Competitiveness of Biomass-Fueled Electrical Power Plants

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ABSTRACT

One way countries like the United States can comply with suggested rollbacks in greenhouse gas emissions is by employing power plant fueled with biomass. We examine the competitiveness of biomass-based fuel for electrical power as opposed to coal using a mathematical programming structure. We consider fueling power plants from milling residues, whole trees, logging residues, switch grass, or short-rotation woody crops. We do this using a combined model of the agricultural and forestry sectors.   We find that the competitiveness of biomass depends in a key way upon the success of research in developing improved production methods for short rotation woody crops without great increases in costs.

Competitiveness of Biomass Fueled Electrical Power Plants

The United States is involved in international negotiations regarding greenhouse gas emissions. Proposed agreements, such as the Kyoto Accord, involve rollbacks in greenhouse gas emissions measured in terms of carbon dioxide(CO_2) equivalents. One large source of CO_2 is the burning of fossil fuels (accounting for a little more than 1/3 of the U.S. emissions via a U.S. Department of Energy estimate) . In turn electricity generation emits a large proportion of U.S. CO_2 (coal usage alone accounts for over 25% - Kopp). Compliance with the proposed agreements could make it desirable to reduce electricity generation related emissions. Possibilities for doing so are to increase fuel efficiency, use substitute fuels which do not emit as much CO_2, or use substitute fuels which, when burned, yield emissions which do not count against agreement emission levels. Biomass energy falls into the last class.

Biomass energy arises through forest or agricultural production. A biomass fired power plant emits CO_2 into the atmosphere, but biomass plant growth removes atmospheric CO_2 through photosynthesis, fixing it into the biomass. Consequently, fueling a power plant with biomass as opposed to fossil fuels means that rather than digging carbon-based fossil fuels out of the ground and emitting new CO_2 into the atmosphere, that we are both emitting and absorbing carbon and thus reducing long-term emissions compared to coal fueled generation. Kline, Hargrove and Vanderlan indicate that conversion to biomass fueled power plants would reduce net emissions by 95%.

The basic concept is that a power plant would be located in proximity to a source of biomass. The biomass would be brought into the power plant and burned as a feed stock to generate electricity.

As electricity demand grows and older plants reach the end of their useful life, there is a potential for biomass-based plants to be put into service. The question is: how competitive are such plants with traditional coal-based alternatives when the full costs of biomass production, assembly, hauling, handling, and any differential firing costs are considered?

In this paper we examine the competitiveness of biomass-based fuel for electrical power as opposed to coal. This is done through economic modeling using a mathematical programming structure. We will consider fueling power plants from milling residues, whole trees, logging residues, switch grass, or short-rotation woody crops.

Basic Requirements for an Assessment Methodology

Assessment of biomass fuels competitiveness for power plant operation mandates the use of an assessment methodology which encompasses a number of aspects of the agricultural and forestry sectors. Here we overview a number of considerations. In the next section we present technical details on how these conditions are entered into our analysis.

First, if forestry byproducts (from the processing of saw logs into lumber and other products) are used to generate power, one must have a framework which depicts the quantity available of those byproducts, assembly cost and current usages. For example, milling residues are an important input to pulp and paper production, thus expanded use of milling residues for power would alter the demand for pulpwood or the supply of pulp for paper production. This, in turn, might cause an expansion in pulpwood acreage or a rise in paper prices. In addition, if saw log byproducts are made more valuable by power plant use, then this would alter the economic value of harvested forests and might stimulate additional forest harvest and/or altered costs of wood products. One also needs to account for additional resources required to collect, haul, and replace the nutrients associated with logging residues. Thus, a relatively complete look at the question requires a forestry framework that considers alterations in forest product prices and timber harvest patterns including land use, time of harvest, resources used, and costs of harvest.

Second, biomass can arise through diversion of agricultural lands to create short-rotation woody crops (such as poplar and willow) or switch grass for power generation. Usage of lands to raise power plant biomass would require diversion of existing crop, pasture, grazing or forested lands into biomass cultivation and in turn might stimulate transformation of such lands into agricultural production. Simultaneously shifts in production might alter agricultural commodity prices. These things considered, examination of the biomass alternative requires consideration of agricultural production, agricultural prices, capabilities of lands if planted to biomass products, and the allocation of land between forestry and agriculture.

Third, complete modeling of the agricultural and forestry issues noted above raises yet a wider set of issues. For ease of exposition we discuss these under the topics of : (i) dynamics; (ii) aggregate scope; (iii) product substitution; (iv) land base; (v) regionality of production; (vi) other forestry issues; (vii) agricultural issues, and (viii) energy issues.

Dynamics – Modeling of land allocation between forestry and agriculture requires simultaneous consideration of decision frameworks which operate on different time scales. Most agricultural decisions have time horizons of less than a decade. Most forestry decisions involve three or more decades. One has to model the tradeoff between current agricultural costs and returns versus current costs and future forestry returns. Such modeling requires explicit consideration of the time value of money - discounting.

Forest decisions include harvest age. Most agricultural decisions involve a relatively fixed harvest age. Forest harvests can vary over several decades depending on growth and anticipated market conditions. Thus, on the forestry side harvest age needs to be a variable.

Land shifts between agricultural and forestry along with consideration of harvest age decisions force us into a multi year framework. Multi-year modeling coupled with the inevitable fixed time frame of any practical representation raises the issue of boundary conditions in the initial and terminal time periods. Initial conditions specify the location of current land use and the age structure of the forest inventory. Terminal conditions are needed to reflect the valuation of standing trees at the end of the explicitly modeled time period along with the land remaining in agriculture at the end of the model time representation.

Technical change, demand growth and resource base alteration are relevant. Agricultural demand and productivity have grown over time. For example, corn yields have exhibited more than a two percent annual growth rate. Forestry demand grows with GDP while agricultural demand grows with domestic and world population.

Aggregate Scope -- A major set of conceptual issues involves the scope of the analysis. Certainly when dealing with the U.S. agricultural and forestry sectors, one must consider prices to be affected by the quantities produced and aggregate land allocation decisions. Trade modeling is also important involving forest products imports (primarily from Canada), along with log and agricultural exports and imports.

Product substitution -- Modeling in the agricultural and forestry sectors requires substantial attention to product substitution. Lumber and plywood are substitutes in many uses. Substitution is also common in agriculture, particularly among livestock feedstuffs.

Land base -- When land transfer is an important issue, then so must be land quality. Many forested tracts are not suitable for agriculture due to topography, climate, soil quality etc. Limits must be incorporated on the quantity of land that can transfer. Furthermore, when forested land moves into agriculture, costly grading and stump removal activities may be undertaken.

Regionality of production -- Forestry and agricultural production are geographically diverse. Conditions in different areas imply different product mixes, and different potential for economic activity, biomass growth and land transfer. Thus an explicit geographic scope is desirable.

Other forestry issues -- Numerous other issues could be mentioned. The following are especially significant and influence our approach: (i) the influence of industrial versus nonindustrial land ownership on forest performance and management; (ii) management alternatives varying from rather intensive systems to "leave it alone and let it grow" approaches each yielding different mixtures of products and species; (iii) public ownership of forest lands and associated harvest programs; and (iv) the existence of pulp, fuel wood, lumber, and plywood uses.

Agricultural issues -- Among many other issues, the following are especially significant and affect our approach: (i) production of both crops and livestock; (ii) existence of processing possibilities; and (iii) agricultural use of water, labor, purchased input, grazing, pasture and crop land factors of production.

Energy Sector Issues -- The final conceptual element involves the depiction of energy sector power generation. New power plants will be built as existing plants are retired or energy use grows.

Therefore the potential for penetration of new plants into the energy sector coupled with the cost of production of converting biomass products into energy and production/hauling costs for biomass products must be modeled. To gauge competitiveness relative to coal, we need to model biomass input to the point in the process of power plant energy generation where the two fuels are fed into the burners.

Sector Level Model of Forestry and Agriculture

Most of the above conceptual features are present in a model we developed for other purposes. We call that model the **F**orest and **A**gricultural **S**ector **O**ptimization **M**odel (hereafter called **FASOM**). Here we overview the basic structure and assumptions of FASOM and the modifications needed to undertake a biomass competitiveness analysis.

Basic Structure of FASOM

Several major strategies were followed in FASOM development. First, we deal with forest products at the log level which simplifies forest product substitution modeling. Second, we adopt a price endogenous modeling scheme, as has been done in a number of agricultural and forestry sector analyses (including Adams and Haynes; McCarl and Spreen), because the market decisions being modeled may involve large changes in the aggregate output of products and the use of factors. Third, we use a net present value based version of the price endogenous approach following the approaches in Spreen et al. or Sedjo and Lyons. Fourth, we substantially draw from other efforts. In particular, we rely heavily on the TAMM saw log (Adams and Haynes; Haynes, Adams, and Mills), NAPAP pulp and paper (Ince) and ATLAS forest inventory models for forestry along with the ASM (Chang et al., McCarl et al.) model for agriculture. The mathematical structure of FASOM is summarized in Table 1 (variable definitions are in Tables 2 and 3).

FASOM has three components. Forestry is depicted by the variables QF, EX, NF, and TF; agriculture by A, QA, and Z; and land transfer by LTA and LFA. The agricultural component represents typical annual activity during a time period (decade). The forestry and land transfer components portray total activity during a decade. The objective function places agriculture and forestry on a common timing basis in that the agricultural objective function coefficients are multiplied by an expansion factor (efa) which is the net present value of a dollar received in every year of the time period.

The objective function maximizes the net present value of the integral of the demand curves less the integral of the supply curves. The curves are dynamically dependent and are updated based on gross domestic product projections and extrapolations of past consumption growth. Values of terminal inventories in both sectors are recognized.

Equations (2)-(4) control forest processes. Equation (2) balances forest product consumption with production. Equation (3) forms the estimate of terminal forest inventory under the assumption that forest management from the last period onward is a continuous repetition of the last period's management strategies (see the discussion below and that in Adams, Alig and McCarl). Equation (4) limits timber harvest plus retention beyond the model time horizon of existing forests to the initial inventory.

Equations (5)-(6) control land allocation and transfer. Equation (5) balances forestry land uses with supplies in each period. Land uses include new forest plantings, conversion to agriculture, and conversion to other uses. Land supplies include land freed up by harvest of existing or new forests and land converted from agriculture. Equation (6) controls annual agricultural land use by period, ensuring current land use is less than the initial inventory plus all lands converted in from forestry in all periods up to and including this one less land shifted to forestry.

Equations (7) - (8) balance agricultural production with consumption and agricultural factor use with supply. Agricultural yields and factor usage vary by decade with historical trends in yield growth and input/yield interrelationships extrapolated. Equations (9) provide nonnegativity conditions.

Elaboration on Key Model Components

The foregoing model description was very aggregate; literally thousands of further details go into the complete empirical specification. The remainder of this section summarizes some of the most important of these considerations. Adams, Alig, and McCarl provide details on the forestry part of the model while Chang et al. and McCarl et al. provides details on the agricultural part and Adams et al. provides further FASOM documentation.

A FASOM solution reflects price and quantity equilibria established in each period where producers and consumers have perfect knowledge of market conditions in all periods (see McCarl and Spreen for a mathematical exposition of these points). Given knowledge of prices, producers act so as to maximize the net present value of timber and agricultural investments. Equivalently, land migrates into the sector that promises the highest net present value of future returns considering costs of use conversion and land movement limits. Model size and numerical complexity required aggregation to an

11 region basis (Figure 1). Thus all modeled activity occurs within these 11 regions.

FASOM Structure in Typical Decade

A simplified overview of one decade in FASOM is illustrated in Table 4. The forest sector describes the planting and harvesting of timber (logs) on private lands in U.S. regions and foreign trade in logs. Harvests of forest lands are differentiated by whether the stand is "existing" or "new", where "new" depicts stands that were planted during the explicit model time frame and existing refers to those in the initial inventory when the model starts up. The agricultural sector depicts crop and livestock production and product processing using water, labor, and AUM grazing inputs as well as primary product trade. The sectors are linked through land transfer activities and constraints. The "new forests" row in Table 4 is the counterpart of equation (5) in Table 1. This row constrains the area of new forest stands to the sum of areas harvested from existing and previously planted new stands, adjusted for land exchanges with agriculture. This row is present in every decade as illustrated in the more dynamic tableau in Table 5 which shows a two decade version of FASOM emphasizing the forest sector and illustrating the inter-period linkages. We employ a nine-decade projection period to keep the problem size manageable and because results in the first five decades were not materially affected by 9, 10 or 11 decades. Of course, results in decades closer to the end were sensitive to this choice, but these are so heavily discounted that they have little impact on the aggregate results.

Table 5 reveals several things about the forest sector portion of FASOM. The harvest timing decision is endogenous. Consider the first three variables: an existing stand can be cut in the first decade, the second decade, or "never." The "never" designation indicates that a stand's production enters the terminal value equation, which values stands that are harvested beyond the explicit model time horizon. When a stand is harvested the decision is made whether to reestablish with trees or shift the land into agriculture. Simultaneously, land can be shifted into forestry from agriculture. When new stands are established, the decision is made whether to harvest them in a subsequent decade or "never." The objective function comprises the present value of the quantity dependent integrals under the forest product demand curves less the costs of harvesting, reestablishment, intermediate timber management, and any land transfer. Thus, the overall objective function includes the net present value of forestry welfare in the first decade plus the net present value from the second, plus the net present value of the terminal inventory (a perpetual annuity beginning at the end of the explicit projection period).

In the agriculture component, the original long-term equilibrium form of ASM (McCarl et al) was used to represent typical activities in each decade (see the next section on the ways the sectoral time frames are meshed). Demand and supply components are updated between decades by means of projected growth rates in yield, input usage, domestic demand, exports, and imports. The FASOM agriculture component uses constant elasticity functions to represent domestic and export demands as well as factor and import supplies. It simulates the production of 36 primary crop and livestock commodities and 39 secondary, or processed, commodities. Crop and livestock production compete for crop pasture and grazing land as well as labor and irrigation water at the regional level. More than 200 production possibilities (budgets) represent agricultural production options in each decade. These include field crop and livestock production. The field crop variables are also divided into irrigated and non-irrigated. In the first two decades, the production solution is required to be within a convex combination of historical crop mixes, following McCarl, but is free thereafter.

Dynamics and Terminal Conditions

A feature of FASOM which merits separate discussion involves meshing the dynamic nature of the sectors coupled with the terminal conditions. A fundamental problem in terms of modeling by FASOM is that agricultural commodities come and go largely in a single decade; however, forest processes can take has long as 5 or 6 decades. In order to model these processes in the context of forestry/agricultural land use and land exchange, a model was needed which represented decisions that could be made in each time period including transfer of lands. Within each decade in FASOM, forest management decisions depict the choice as whether to harvest a stand or leave it alone. Further in each decade newly harvested lands can be replanted to forest or migrated out to agriculture. Also agricultural lands can be moved into forest production. FASOM includes agriculture activities for each decade depicting regional crop and livestock mix as a function of decade-specific land availability and agricultural demand.

The decade by decade representation of agricultural land use relies on ASM (Chang et al., McCarl et al.) which represents longer run agricultural activities in a typical year. This typical year agricultural model was meshed with the multi-decade forestry model by first establishing a different agricultural model in each decade updated according to technical change and demand growth. FASOM then takes the nine decade specific ASM model objective function components and multiplies each by a decadal discount rate and by the net present value factor of a constant annuity for the time frame each of the nine models represents (generally 10 years).

The other aspect of the dynamic issue with respect to merging the forest and agricultural models involved terminal conditions. In the Pacific Northwest particularly where 60 year rotations are not uncommon the modeling framework had to reflect the fact that 40 years into the model any forests planted possibly would not be ready for harvest by the end of the explicit time period. As a consequence we needed to reflect terminal valuation of existing forest stands. This was done through the adoption of von Mantel's formula (Davis and Johnson) for the yield of a fully regulated forest, (i.e. one which produces equal periodic harvest). That formula estimates perpetual and continual harvest for each forest type as the summed ending volume across all ages of stands times two divided by the harvest age. The sum of these over all forest types was then subjected to a demand curve times the net present value for an infinite annuity giving a perpetual value of maintaining that forest inventory structure forever.

The treatment of forest terminal conditions necessitated parallel treatment of the perpetual value of land staying in agriculture beyond the model time frame. This was done by multiplying the objective function coefficients of the last periods' agriculture activity not by the net present value factor for a decade but rather by the net present factor for continual annuity at that price. Thus, when one reaches a decision in later time periods of the model whether to move the land into agriculture or reforest it one faces in both cases estimates of the net present value of future returns of the land remaining in that use forever.

Adding Biomass to FASOM

The depiction of biomass production and power plant use in the FASOM model required that several new production possibilities be added:

1) diversion of mill residues from traditional pulp and paper or other uses;
2) collection of logging residue or harvest of whole trees for chipping, and shipment to a

power plant;

3) production and hauling of switch grass and short rotation woody crops for biomass

4) treatment of power plant use of biomass to the point where the energy in biomass is on an equivalent basis with the energy from coal; and

5) treatment of the possible use of wood chips from short rotation woody crops for pulp and paper production.

Each is covered below.

Diversion of Milling residues to Biomass-- Consideration of milling residue diversion to power generation required model treatment of milling residue commodities. In earlier FASOM versions milling residues were treated as an exogenous revenue source with the pulpwood demand curve exogenously adjusted for the presence of dedicated residues. We removed the credit and expanded the pulpwood demand, and then allowed the model to endogenously determine the allocation of the hardwood and softwood residues to biomass power and pulp plants.

Chipping logging residues and whole trees for feedstocks **—** Previous versions of FASOM only depicted forest harvest for conventional uses, that is, hauling harvested timber to saw log or pulp mills. We added possibilities for collecting logging residues or hauling off whole trees. Both were depicted as harvested and then chipped for transfer to biomass-based power production. Estimates were made of the yield of chips using the TAMM/ATLAS model.

Adding Switch Grass and Short Rotation Woody Crops **–-** The forestry biomass commodities discussed above involved modifications of existing commodity usage or diversions of the products from existing production systems. Thus, actual production information was available on yields, input costs, and hauling costs. However, this was not the case with respect to switch grass and short rotation woody crops. Only experimental and relatively small demonstration unit production has been ongoing. In addition, technological innovations are possible in the raising of these crops since historically they have not been the subject of much yield-enhancing research. We used information from studies at the Oakridge National Laboratories pertaining to yields and costs of production (Walsh and Graham; Graham et. al.). The Oakridge experimental data include estimated production budgets between now and 2020 with and without research investments. These data show static yields and costs without research investments. Under research investments they forecast a 1.8% annual growth rate in switch grass yields, 3.3% for willow, and 4.9% for poplar. The budgets also show modest cost increases associated with the yield increases.

The Oakridge budgets only consider farm-level production yields and costs. Movement of the products from fields to farms also needed to be portrayed. This was done following French. Namely, given a rectangular road system, a per square mile density of biomass production of 0.2, a plant requirement of M tons of biomass, and a yield per acre in BTUs (Y),

French derives that the average hauling distance (D) in such a case as:

$$D = 0.4714 \cdot \sqrt{\frac{M}{640 \cdot 0.2 \cdot Y}}$$

In turn we estimated hauling cost per trip using the formula 38+D, then divided that by load size to get cost per ton. We computed D for M equal to the tons of each biomass crop required to fuel a 100 megawatt[1] power plant for a year or approximately seven trillion BTUS. This produced location and crop specific hauling costs which worked out to be between $2.50 and $4.00 per ton.

Poplar and Pulp -- Cheap poplar supplies that are suitable for fueling power plants could also be used for pulp production. A preliminary analysis showed under the Oakridge technology assumptions that poplar may be competitive in the hardwood pulp market, although only the nonbark part is practically usable as pulp. Thus, we included the possibility of moving poplar to pulp use, where 75% was usable for pulp and the remaining 25% (the bark portion) available as burnable biomass.

Biomass plant market penetration and cost differentials –- Based on the desires of the U.S. Department of Energy (DOE) and Environmental Protection Agency (EPA) personnel guiding the inquiry, it was assumed during the study that the biomass would only be used in new plants designed to handle it. There was a maximum potential by year for biomass penetration into the electrical energy market. They then gave us an estimate of market penetration due to phase out of obsolete power plants and new power plants as documented in Tunure et al.[2] We then considered the differential costs of burning biomass in a new plant designed to use biomass as opposed to a new plant designed to use coal. However, DOE and USEPA personnel recommended we use a zero differential. Thus, after accounting for costs of production, and transportation we treated BTUs from wood chips, switch grass, and coal as perfect substitutes.

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[1] Only part of the energy in the biomass is actually converted to electricity. Due to conversion efficiency of less than 50%, more than half of the BTU's from biomass are lost when converted to electricity.

[2] Mark Shenkel and Ira Shavel at ICF along with Bob Shackleton and Steven Winnett at USEPA were especially helpful.

Results

Three fundamental questions will be examined with the model.

1) How competitive is biomass production in comparison with coal?
2) What biomass feed stocks are used when biomass prices fall in the competitive ranges with respect to coal price?
3) How sensitive are the results to variations in the yield and cost assumptions resulting from agricultural research enhancements?

Before discussing these results let us give a little information about the model and solution process.

Model Size and Solution Characteristics

FASOM is set up and solved in GAMS (Brooke, Kendrick, and Meeraus). The model was initially set up with explicit integration under linear demand and supply curves in forestry and constant elasticity curves in agriculture. This resulted in a nonlinear programming problem, with in excess of 800 nonlinear variables, 120,000 total variables, and 9,500 constraints. MINOS (Murtaugh and Saunders) had substantial difficulty reaching a solution so we formulated a separable programming version (Baumes and McCarl). We also discovered that logging residue and whole tree harvest (the presence of which tripled the biggest part of the model, that for tree harvesting) were not competitive under any scenarios. Thus we dropped those activities. The resultant model has 71,200 variables and 9,750 constraints. Solutions for a set of 18 scenarios took 6 days with MINOS5, 18 hours with OSL, and 6 hours with CPLEX. We now routinely solve with an advanced basis in CPLEX and get a solution for each scenario in under 30 minutes total time.

Competitiveness Analysis

Competitiveness was examined by looking at the cost per trillion BTUs (TBTUs) of delivered energy feedstock for production in 2020, with and without incorporation of the Oakridge assumptions on yield enhancing and cost altering biomass crop research innovations. A supply curve was generated by systematically increasing the quantity of biomass feedstock required nationally and solving FASOM. The resultant solution generates biomass at a minimum cost including not only the direct production costs of the biomass, but also costs from land and commodity use that reflect the opportunity costs for use of these items in other enterprises. Thus, for example, land prices in willow production would rise as more and more willow is planted because that land is being diverted from other uses. The composite cost of production is reflected in the shadow price on the biomass feedstock requirement equation. These shadow prices are the costs of providing the biomass feed stock and were tabulated for runs with and without research improvements.

The resultant data appear in the first two columns of table 6 (note the last 4 columns give numbers that will be discussed in the sensitivity section below). For comparison and perspective purposes note that a 100 megawatt power plant (hereafter called a CMW plant) requires about seven TBTUs and that the coal price in dollars per million BTUs is projected to fall in a range between $1.05 and $1.69 /MMBTU in 2020 (DOE, Tunure et. al.) with a midrange value of $1.37/MMBTU.

The results show that biomass-fueled power is not very competitive without research innovations or subsidies. Coal prices need to be above the midpoint of the projection range before any is competitive without subsidy. At the upper limit of the coal price range around 100 CMW plants could be built. With research-based innovations the result is different; about 20 plants can be built at the low end of the range , 200 at the mid range and 500 at the upper extreme. Technological development in the short rotation woody crops is a key input to the feasibility of biomass-based power plants if they are to be operated without massive subsidies.

Feedstock Choices

***With Technology* –** An inexpensive initial biomass supply is realized at the first two TBTU steps due to poplar being grown for pulp which creates a cheap byproduct. Recall that we allow 25% of the poplar grown for pulp (the bark) to go into biomass uses while the other 75% goes into pulp. The cost is so low because the only marginal cost linked to the use of the bark byproduct is hauling cost.

At higher TBTU requirements, northeastern willow production is the primary feedstock with production climbing steadily up to the 3500 TBTU production level. Limited poplar is used in the Lake States. Production of poplar other than for pulp in other regions, milling residues and switch grass do not enter the picture until 4700 TBTUs or 650 + plants are constructed. Costs at that level fall in the noncompetitive range. Logging residues and whole tree chips were never competitive and were dropped from later analysis.

***Without Technology* –** These results show dependence on milling residues up to a 850 TBTUs requirement with that usage occurring in the south eastern and south central regions. Willow and switch grass eventually enter the solution but not until 1450 (200+ plants) and 2300 (300+ plants), respectively. Poplar never enters the picture nor do logging residues and whole tree chips.

Sensitivity to Technology Advance Assumptions

The dependence of competitiveness on the Oakridge research innovation assumptions makes closer scrutiny of those assumptions desirable. The rate of yield increase in the Oakridge budgets assumes annual yield growth rates between 2000 and 2020 of 1.8 % for switch grass, 3.3% for willow and 4.9% for woody crops. This may be too high. The annual growth rate of hay yields over the last 20 years has been somewhere around 1%. Corn, cotton, and rice yields have all risen by a little more than 2%. Sorghum yield increases have been about 1.2%, barley about 1.1%, and oats has largely been static. There are reasons to think that a fast growth rate for switch grass and woody crops may occur initially as they have not been extensively cultivated or researched in the past. In the long run, the growth rate would probably decline toward the pattern of increase in other crops. We will examine the issue of lowered yield by cutting the yield enhancement in half. This means willow yields only go up by about 50%, rather than almost doubling, by 2020.

Cost changes are also a factor. Traditionally in agriculture a 1% change in yield has been found to be matched by a 0.43% change in costs (Evenson). The Oakridge budgets for switch grass show cost changes in such a neighborhood. On the other hand the willow and poplar costs increase by less than 10% of the rate of change in yield. Thus, if yield doubled the cost would only go up about 10%. These were felt to be potential underestimates of rates of change in costs. In total three sensitivity runs were designed. The first sensitivity run was an increased cost case, where the cost of the wood commodities was assumed to go up at one-third the rate of change of yield. Thus, if yields doubled, wood cost would go up by 33%. The second assumed the change in wood yields were one half of those in the Oakridge budgets. The third run examined the case with both decreased wood yields and increased costs. In this case the cost went up by one-third the percentage change in yields and the yields went up one-half as much. Switch grass data were left at the Oakridge levels.

The sensitivity run results are displayed in the last three columns in Table 6. They show higher initial costs at low TBTUs because the woody crops becomes more expensive to raise. Second, the competitiveness of biomass other than as a pulp byproduct becomes an issue. The unsubsidized competitiveness vanishes at the low end of coal price conditions, and the potential for power plants at the high end falls, particularly if the yield increments are not realized. Third, in the case of high TBTU requirements in the non cost competitive range results, do not show a lot of effect as switch grass is used and the switch grass data were not altered.

Concluding Comments

The analysis reported here has important implications for the biomass energy issue and offers a useful illustration of the application of operations research tools in the analysis of public policy problems.

First, biomass feed stocks can be a way of altering the emission characteristics of U.S. electrical generation. The competitiveness of biomass depends in a key way upon the success of research in developing improved production methods for short rotation woody crops. Willow in the northeast and poplar for pulp production in the Lake States appear to be the two biggest potential crops. However, the competitiveness of these items depends critically on the development of enhanced yields without great increases in costs. Competitiveness may not be a strict requirement. Rather the government may be willing to subsidize biomass-based power production in order that it might not involve large shifts in costs with associated impacts on the economy at large and/or to reduce costly greenhouse gas emissions. If so, then the short rotation woody crops mentioned above coupled with near-term diversion of milling residues to power may be the best alternatives. Finally note there are a number of issues that we did not cover in the appraisal or the paper. Namely there would be environmental benefits and costs from having biomass powerplants where there might be positive and negative affects on for example wildlife populations, soil runoff, etc. We also did not cover the research investment costs to derive the improved varieties.

Second, we have demonstrated the simulation of market equilibria as effected by environmentally motivated policy using mathematical programming. The FASOM model formulation maximized the net present value of the area under decadal product demand curves minus the area under factor and import supply curves. Many other such analyses could and have been done. Non-dynamic versions of this methodology is common in energy analyses. In other instances, we have used the FASOM model to examine public timber policy, agricultural policy shifts, and carbon sequestration policies among others. Similar models have been used to examine water, soil conservation, and endangered species policy alterations.

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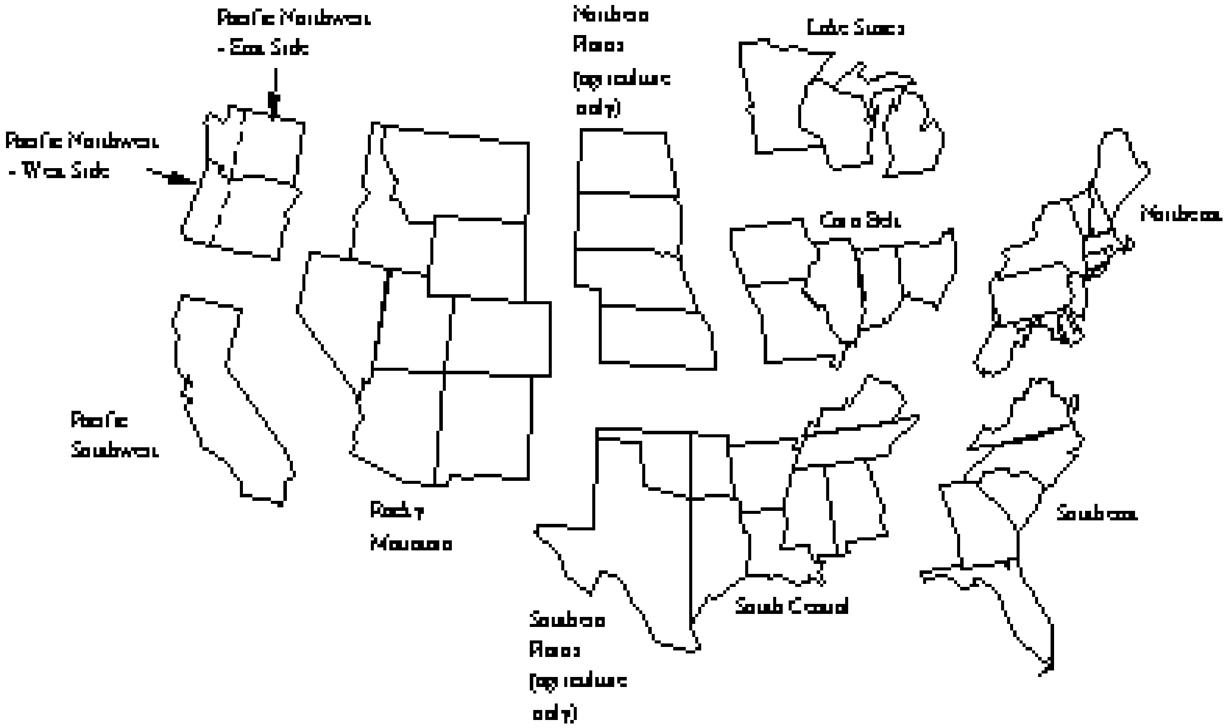

Figure 1 Regions included in FASOM

Table 1: Mathematical Model Description

Panel A Summation Overview

(1) Max $\underset{t'0}{\overset{T}{'}}(1\%r)^{\&t}$ [$m\,pf_t(QF_t)\ dQF_t$ $\&\ ce_t\ EX_t$ $\&\ \underset{k}{'}\ cn_{t,k}\ N_{t,k}$ $\&\ cv_t\ LTA_t$ $\%efa_t$ [$ca_t\ A_t\ \%\ m\,pa_t(QA_t)dQA_t\ \&\ m\ pz_t(Z_t)dZ_t$]] $\%\ (1\%r)^{\&T} m\,pf_T(TF)dTF$

(2) s.t. QF_t $\&yx_t\ EX_t$ $\&\ \underset{k\ k<t}{'}\ yn_{t\&k.k}\ N_{t\&k.k}$ # $excut_t$ for all t#T

(3) $\&xf\ tyx_T\ EX_t\ \&\ \underset{k\ t\%k>T}{'}\ xf\ tyn_{t\&k.k}\ N_{t\&k.k}$ $\%\ TF$ # $excut_{T\%1}$

(4) $\underset{t'0}{\overset{T\%1}{'}}\ EX_t$ # iex_o

(5) $\&EX_t$ $\%\underset{k}{'}N_{t,k}\&\ \underset{kk<t}{'}\ N_{t\&k,k}$ $\%LTA_t$ $\&LFA_t$ # & $landout_t$ for all t#T

(6) $\underset{t(t(<t}{'}$ [$\&LTA_{t(}$ $\%LFA_{t(}$] $\%\ A_t$ # $agland_0$ for all t#T

(7) $\&ya_t\ A_t$ $\%QA_t$ # 0 for all t#T

(8) $\&fa_t\ A_t$ $\%Z_t$ # 0 for all t#T

(9) QF_t , EX_t , $N_{t,k}$, LTA_t , LFA_t , A_t , QA_t , Z_t , TF \$ 0 for all t

Table 2 Variable definitions

Variable	Definition
QF_t	Quantity of forest products consumed in period t
EX_t	Quantity of preexisting forest inventory harvested in period t
$NF_{t,k}$	Quantity of forest land planted in period t and harvested k periods later
LTA_t	Land transferred from forestry to agriculture in period t
LFA_t	Land transferred from agriculture to forestry in period t
A_t	Agricultural production in a typical year during period t
QA_t	Agricultural consumption in a typical year during period t
Z_t	Agricultural factor supply in a typical year during period t
TF	Quantity of forest products in inventory after last explicit time period

Table 3 Parameter definitions

Parameter	Definition
t , t^*	time period in decades
T	Last explicit time period
r	discount rate
$pf_t(QF_t)$	Inverse forest product demand curve in period t
ce_t	Net present value of maintaining and harvesting existing forest in period t
yx_t	Yield from harvesting existing forest in period t
xf	Expansion factor for steady state forest after period T
tyx_{T+1}	Yield of existing forest when not cut during model
$cn_{t,k}$	Net present value of planting, maintaining and harvesting new forest $N_{t,k}$
$yn_{t,k}$	Yield from new forest when planted in period t and harvested k periods later
$tyn_{t,k}$	Yield from new forest when harvest period falls after last explicit period in model
cv_t	Cost of converting forested lands to agriculture in period t
efa_t	Net present value of a $1 annuity over length of ag period t
ca_t	Cost of annual operations in agriculture during period t
ya_t	Yield from annual operations in agriculture during period t
fa_t	Factor use in annual operations in agriculture during period t
$pa_t(QA_t)$	Inverse annual demand for products from agriculture during period t
$pz_t(QZ_t)$	Inverse annual supply for factors to agriculture during period t
$excut_t$	Exogenous timber harvest during period t
iex_0	Initial inventory of forested land
$landout_t$	Net land migration to other uses during period t
$agland_0$	Initial inventory of agricultural land

Table 4. Schematic Tableau of FASOM Model Showing Primary Activities and Constraints and Relation of

Forest and Agriculture Sectors.

		Forestry Variables							Land Transfer		Agricultural Variables									Rhs
		Production		Forest Market				Terminal Value	To Ag	From Ag	Produce Crop	Produce Animal	Process	Water	Grazing	Labor	Demand	Import	Export	
		Harv Exist	Harv New	Demand	Product Sub.	Export	Import													
	Objective	-	-	+	-	+	-	+	-		-	-	-	-	-	-	+	-	+	Max
Forest	Existing Stands	1																		#+
	New Stands	-1	+/-						1	-1										#-
	Log Demand / Supply	-	-	1	+/-	1	-1													#+
	Terminal Inventory	-						1												#+
	Land Transfer Limit								1	1										#+
Ag	Ag Land Balance								-1	1	1	0								#+
	Primary Ag Production										-	+/-	+				+	-	+	#0
	Secondary Ag Production											+	-				+	-	+	#0
	Water										+			-						#0
	Grazing											+			-					#0
	Labor										+	+				-				#0

Table 5. Simplified Tableau Emphasizing Forest Sector and Intertemporal Linkages.

		Decade 1											Decade 2							Forestry Term Value	Rhs
		Forestry						Land Transfer		Agriculture			Forestry		Land Transfer		Agriculture				
		Harvest Existing Stands			Reestablish and Harvest Stands		Forest Dem						Reestablish and Harvest Stand	Forest Dem Ato Ag							
		Cut Dec 1	Cut Dec 2	Cut Never	Plant Dec 1 Cut Dec 2	Plant Dec 2 Cut Never		To Ag	From Ag	Prod	Factor	Dem	Plant Dec 2 Cut Never		To Ag	From Ag	Prod	Factor	Dem		
	Objective	-	-	-	-	-	+	-		-	-	+	-	+	-		-	-	-	+	
	Existing Stands	+	+	+																	# +
	New Stands	-1			+	+		1	-1												# -
	For Prods	-					1														# +
	Ag Land							-1	1	1											# +
	Ag Prods									-		1									# 0
	Ag Factors									+	-1										# 0
Decade	New Stand		-1		-1								1		1	-1					# -
	For Prods		-		-									1							# 0
	Ag Land							-1	1						-1	1		1			#+
	Ag Prod																	-			# 0
	Ag Factors																	+	-1		# 0
	Limit Land to ag							1	-1						1	-1					#+
	Lim Land to For							-1	1						-1	1					#+
	Term Inventory			-		-							-							+1	#+

Table 6. Results on cost per million BTUs of biomass Under Alternative Technology Assumptions

	Production Technology Assumption				
Trillion BTUS of Biomass Energy Produced	With Research Induced Technology	Without Research Induced Technology	With ½ Growth in Wood Yield	With Higher Growth in Wood Cost	With Higher Wood Cost and Lower Yield Growth
	($/MMBTU)				
0	0.00	0.00	0.00	0.00	0.00
7	0.19	1.38	0.79	0.19	1.32
14	0.19	1.40	1.28	0.19	1.32
21	1.03	1.41	1.28	1.17	1.32
28	1.04	1.40	1.28	1.17	1.32
35	1.04	1.42	1.29	1.17	1.33
42	1.04	1.42	1.29	1.17	1.34
49	1.04	1.42	1.29	1.18	1.34
56	1.04	1.41	1.31	1.19	1.34
100	1.05	1.44	1.33	1.20	1.36
125	1.05	1.49	1.34	1.20	1.38
200	1.07	1.51	1.35	1.22	1.40
275	1.07	1.56	1.36	1.23	1.40
550	1.08	1.66	1.37	1.23	1.44
850	1.08	1.69	1.45	1.26	1.51
1450	1.39	1.83	1.66	1.45	1.66
2300	1.45	2.25	1.81	1.60	1.86
3500	1.66	2.42	2.01	1.66	2.01
4700	2.03	2.52	2.08	2.04	2.08
5900	2.12	2.65	2.17	2.15	2.17
7100	2.16	3.06	2.53	2.36	2.52
8300	2.65	3.41	2.80	2.68	2.80
8840	2.74	3.74	2.86	2.76	2.82

Note the coal price is projected to range between $1.05 and $1.69 with a midpoint of $1.37 (DOE, Turnure et al.). Also figures are in 2020 dollars.