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Technical Report
NREL/TP-6A20-54217
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Contract No. DE-AC36-08GO28308

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Prepared under Task No. BZ11.3003

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Acknowledgments

The Biomass Scenario Model development and analysis is sponsored by the U.S. Department of Energy (DOE) Biomass Program, under DE-AC36-08GO28308. We thank Zia Haq and Sheila Moynihan of DOE for supporting this effort. We also thank Mary Lukkonen and Scott Gossett of the National Renewable Energy Laboratory (NREL) for assistance in editing the manuscript; Laura Vimmerstedt, David Hsu, and Debra Sandor of NREL; Dana Stright of Lexidyne, LLC for assistance with database management; and especially Steve Peterson of the Peterson Group, the primary developer of the Biomass Scenario Model.

List of Acronyms

AEO	Annual Energy Outlook
BAM	Biomass Allocation Model
BASE	Biomass Allocation and Supply Equilibrium
BAU	business as usual
bgy	billion gallons per year
BREW	bulk chemicals from renewable resources
BSM	Biomass Scenario Model
CHP	combined heat and power
DOE	U.S. Department of Energy
ECN	Energy Research Centre of the Netherlands
FREE	Feedback Rich Energy Economy
GCAM	Global Change Assessment Model
GHG	greenhouse gas
GTAP	Global Trade Analysis Project
IMAGE	Integrated Model to Assess the Global Environment
kg	kilogram
ktoe	kilotons of oil equivalent
kWh	kilowatt-hour
MARKAL	Market Allocation Model
MMBtu	million British thermal units
MSW	municipal solid waste
Mt	million metric tons
MW	megawatt
NEMS	National Energy Modeling System
NERC	North American Electric Reliability Corporation
NREL	National Renewable Energy Laboratory
PE	polyethylene
PHA	polyhydroxyalkanoates
PLA	polylactic acid
POLYSYS	Policy Analysis System
PURPA	Public Utilities Regulatory Policy Act
ReEDS	Regional Energy Deployment System
RFS	renewable fuel standard
RPS	renewable portfolio standard
SEDS	Stochastic Energy Deployment System
SRWC	short rotation woody crops
Tg	teragram
TIMER	Targets Image Energy Regional Model
USDA	U.S. Department of Agriculture

Executive Summary

The Biomass Scenario Model (BSM) is a system dynamics model developed by the U.S. Department of Energy (DOE) as a tool to better understand the interaction of complex policies and their potential effects on the biofuels industry in the United States. However, it does not currently have the capability to account for allocation of biomass resources among the various end uses, which limits its utilization in analysis of policies that target biomass uses outside the biofuels industry. This report provides a more holistic understanding of the dynamics surrounding the allocation of biomass among uses that include traditional use, wood pellet exports, bio-based products and bioproducts, biopower, and biofuels by (1) highlighting the methods used in existing models' treatments of competition for biomass resources; (2) identifying coverage and gaps in industry data regarding the competing end uses; and (3) exploring options for developing models of biomass allocation that could be integrated with the BSM to actively exchange and incorporate relevant information.

The review of existing models (Section 2) provides an overview on how competing demands for biomass are currently represented; these models do not include the dynamic interaction among biomass end users as a primary focus. There are models that specifically deal with the competition for biomass, but they are predominantly optimization models either with a limited time horizon or an incomplete pool of competitors for biomass. In terms of the current industries that consume biomass resources (Section 3), it is clear that federal and state regulations are a critical driver of growth, as has been the case in the biopower and biofuels industries. It is conceivable that the wood pellet and bioproducts industries could consume a larger portion of the biomass resource pool in the future, but to what extent that occurs depends largely on domestic and foreign policies' promotion of these technologies. In order to more fully explore the competition for biomass resources, complementary modeling pathways are developed in Section 4. A basic, standalone system dynamics model that explicitly models biomass allocation among end users is explored as one option. An alternative involves coupling the BSM with the Regional Energy Deployment System (ReEDS), a linear programming optimization model for the electric sector. This coupling provides a proof of concept that system dynamics and linear programming models can be successfully coupled to provide more accurate supply curves. As would be expected, the competition for biomass resources results in lower amounts of biopower in ReEDS than model runs without competition. However, when competition exists, the renewable portfolio standard (RPS) policy on the power side helps to increase biomass supply, which benefits the fuel sector. Effectively, there is a higher biomass supply with a lower price with an RPS policy than without the policy.

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1 Introduction

The Biomass Scenario Model (BSM) is being developed by the U.S. Department of Energy (DOE) as a tool to better understand the interaction of complex policies and their potential effects on the burgeoning biofuels industry in the United States. While originally created to showcase the cellulosic biofuels industry, the model has recently been expanded to also include advanced conversion technologies and biofuels (i.e., conversion pathways that yield biomass-based gasoline, diesel, jet fuel, and butanol). The BSM uses a system dynamics modeling approach (Bush et al. 2008) built on the STELLA software platform (isee systems 2010) to model the entire biomass-to-biofuels supply chain. The system dynamics framework provides a platform for exploring the relationships and feedbacks among the key players in a system, illustrating possible interactions under different scenarios. Main components of the BSM are shown in Figure 1.

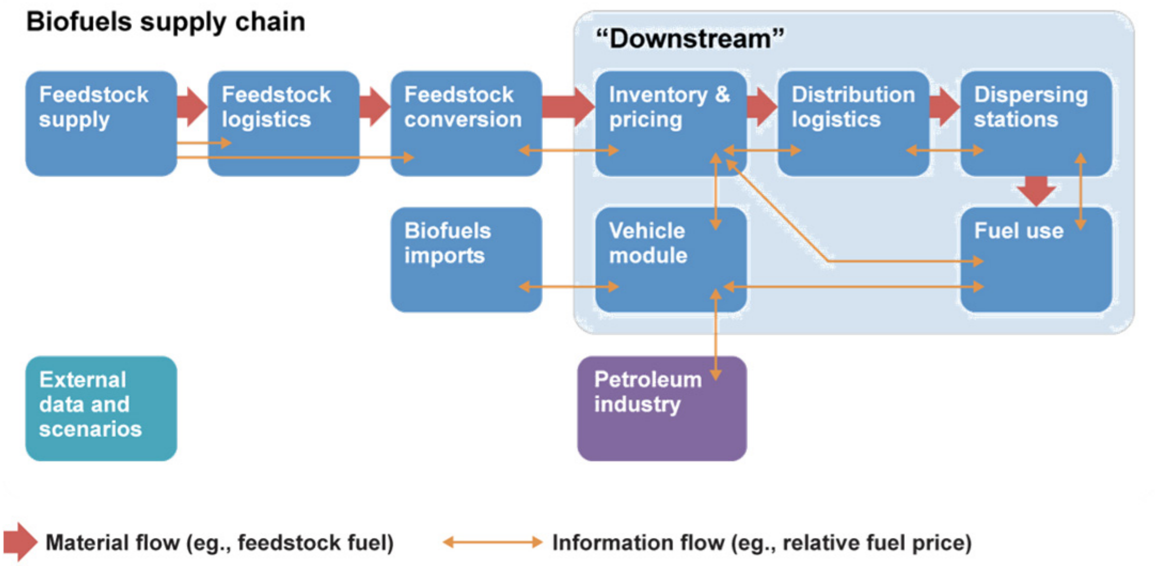


Figure 1. Architecture of the Biomass Scenario Model

The biomass end-use competition modeling project was initiated in an effort to make the BSM account for the alternate sectors that demand biomass feedstock, other than biofuels; the results of this project are reported here. Currently the model assumes that all available feedstock can be consumed by domestic biofuels production, which is unrealistic in many scenarios. Other end users of biomass include traditional heating, bio-based products (such as chemicals and bio-based plastics), exports, and biopower production. To address this discrepancy, we explore the treatment by existing models of biomass competition in order to examine if existing approaches could be utilized in the BSM and research the other end users of biomass to determine which should be included as competing demands to biofuels. We also pursue two different methods for incorporating competition for biomass feedstocks into the BSM: creating a standalone system dynamics model and coupling the BSM with an established linear programming optimization model representing the electric sector called the Regional Energy Deployment System (ReEDS). This report aims to describe the unique demands for biomass along with developing options for addressing the lack of competing demands in the BSM.

2 Existing Models' Treatment of Biomass Competition

There are a number of existing models that account for how end users compete for biomass feedstocks. We conduct a review of these models to understand their relative advantages and limitations in addressing biomass competition. In order to better understand the different methodologies for modeling biomass competition, we look at existing models, paying extra attention to their assumptions and algorithms. If there is a model that is comprehensive in terms of technique and products competed, a similar algorithm could be implemented in the BSM. In addition, we could collaborate with the model's analysts to link the models if the methodologies are compatible. Many of the models are disqualified because they are not are not based on system dynamics methodologies. A subset of these models is discussed below, focusing on the similarities and differences. None of the models allocates biomass in a manner that explores the dynamic interactions among the demanding uses. Appendix A discusses each of these models in more detail.

Many of the models are very large in scope and, therefore, are not intended to model the biomass allocation question in detail; they focus on more macro issues. An example of this type of model would be the Energy Information Administration's National Energy Modeling System (NEMS) (EIA 2009b). It is built to answer questions about the entire energy supply and demand picture, from macroeconomics to residential use. Detailed representation of how biomass resources are allocated is not a major analytic objective of this model. Other models do address the biomass allocation issue as the central focus. Examples include the Biomass Allocation and Supply Equilibrium (BASE) model (Ruth et al.) and the Biomass Allocation Model (BAM) (Morrow 2008). The BASE model was built to determine how biomass resources would be allocated among mature biomass markets at a single point in time, and with all technologies assumed to be fully commercial, for different conversion methods and end products including ethanol, butanol, pyrolysis gasoline, pyrolysis diesel, Fisher-Tropsch diesel, and biodiesel. The BAM competes biomass between co-firing at existing coal-fired power plants and cellulosic ethanol production.

In terms of methodology, a variety of techniques are employed by the different models. Most of the models profiled in Appendix A are optimization models. The RESolve model (Stralen 2010) and the NEMS model both iterate among the different end products to find equilibrium between supply of biomass and demand for the product. The SimBioSys model also finds equilibrium, but equilibrates the cost of producing the end product with the price of a reference technology and then determines the corresponding demand (Kalt 2011). The BAM maximizes total revenue from all end users, subject to consumption and production constraints, and finds the resulting production of cellulosic ethanol and electricity from co-firing. The Global Change Assessment Model (Clarke and Luckow 2011) and the BASE model both use an iterative calculation and a logit function to assign shares to each end user, based on the price of the end product. While all of these methods represent valid ways to model the allocation of biomass resources, many of them would be impossible to implement in a system dynamics framework. For example, system dynamics does not find an equilibrium point, but rather comes close to equilibrium through the pricing dynamics of supply and demand, and so would not employ iteration to find equilibrium.

The only model that utilizes system dynamics methodology, the Stochastic Energy Deployment System (SEDS), is a model of the entire energy system that competes biomass among electricity, biofuels, and hydrogen but does not have biomass allocation as a primary focus (Henrion et al.

2010). The model has been developed more to identify high level impacts of policy implementation, such as change in petroleum use, carbon emissions, or consumer expenditures. SEDS uses a first-come, first-served approach so that existing facilities are guaranteed to have adequate biomass supplies before any biomass is available for additional development.

While these models have different approaches and methodologies, it is readily apparent that most of them rely on static or semi-static supply curves derived from various versions of the Policy Analysis System (POLYSYS) (The University of Tennessee 2011). With the release of the *U.S. Billion-Ton Update* (U.S. Department of Energy 2011), the modeling community has the opportunity to address the need to standardize the set of biomass supply curves used in BAM. Still, the use of any such static annual biomass supply curves allows for biomass production and capacity addition to develop independently from the other restraints or conditions that may be under consideration in a particular simulation. In particular, there is no dynamic feedback to change the actual supply curves when system conditions are altered.

3 Competing for Biomass Resources

Humans utilize 6 billion metric tons of biomass annually. Food consumption accounts for 62% (about 3.7 billion metric tons) of use, while wood consumption for energy, paper, furniture, and construction uses 33% (2 billion metric tons). The remaining 5% (300 million metric tons) is consumed for other non-food purposes, including energy (excluding wood), chemicals, clothing, plastics, and other man-made fibers (Shen et al. 2009). In the United States, the number of markets utilizing biomass resources has been increasing. The major players consist of traditional thermal biomass use; exports, typically to Europe; bio-based plastics and bioproducts; biofuels; and biopower. The following is an overview of each of these competitors.

3.1 Traditional Use and Thermal Biomass Use in the United States

3.1.1 Background

The use of biomass, particularly wood, for thermal energy represents one of the oldest demands for biomass, mainly for heating and cooking. Today, traditional use of biomass accounts for 14% of world energy usage, which is similar to the level of electricity consumption. However, most of this demand is in developing countries where traditional use of biomass accounts for 35% of primary energy usage (Balat and Ayar 2005), and more than 75% of primary energy usage in these countries lies in the residential sector (Victor and Victor 2002). The general trend in developed countries has been a reduction in the amount of biomass used for residential purposes since the industrialized era began; the United States has followed this trend. However, the use of biomass for thermal energy in industrialized countries has expanded beyond traditional modular use to include large-scale heating plants capable of heating large buildings and complexes of buildings and supplying heat for industrial processes.

Compared to other developed countries, the use of biomass for heat in the United States is much less than its use of biomass for electricity generation. In 2003, the United States consumed 727 kilotons of oil equivalent (ktoe) of biomass to produce useful thermal energy while consuming 6,078 ktoe of biomass to produce electricity. Europe consumed 6,978 ktoe of biomass, including municipal solid waste (MSW), to produce useful thermal energy while consuming 5,663 ktoe of biomass as electricity (ABS Energy Research 2009). In Europe (particularly due to Sweden and other Nordic countries), the use of biomass for heat is much higher with 68% of biomass use going toward residential heating and 12% going toward process heating applications. Scandinavian countries make extensive use of biomass-fired district heating plants that provide heat to nearby buildings from a central large-scale boiler. Biomass boilers can also be used to heat large buildings or institutions.

In the United States, the overall use of biomass has been increasing since 2000, mostly for biofuels in the transportation sector with smaller increases in the industrial sector, as shown in Figure 2. Residential use of wood and wood-derived fuels, primarily wood pellets, accounted for 12% of total energy produced from biomass in the United States in 2008 (EIA 2009a).

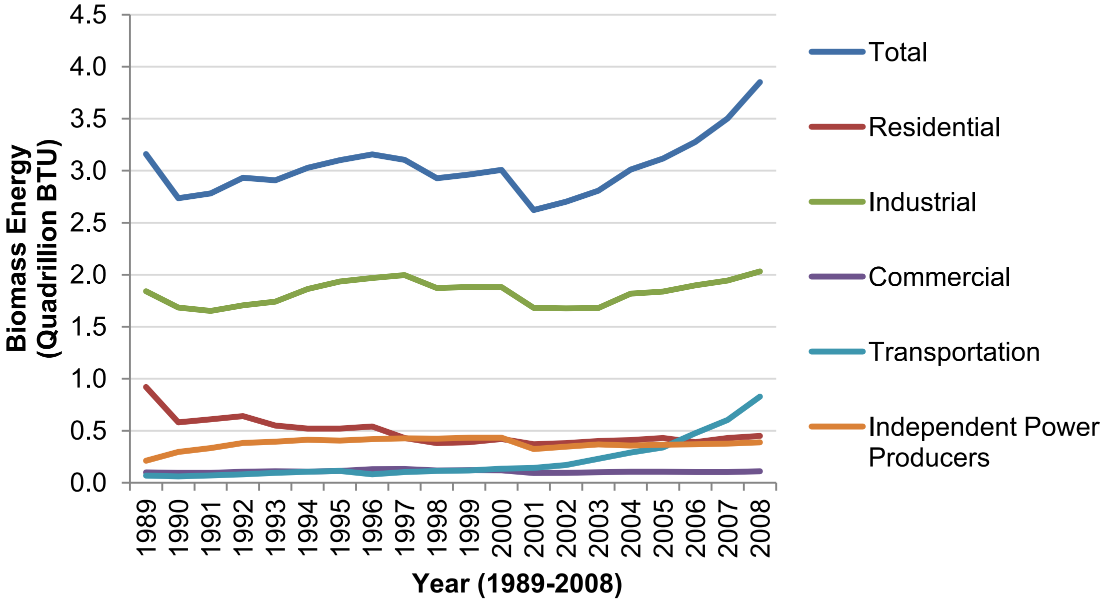


Figure 2. United States biomass consumption from 1989–2008 by sector

Source: EIA 2010b

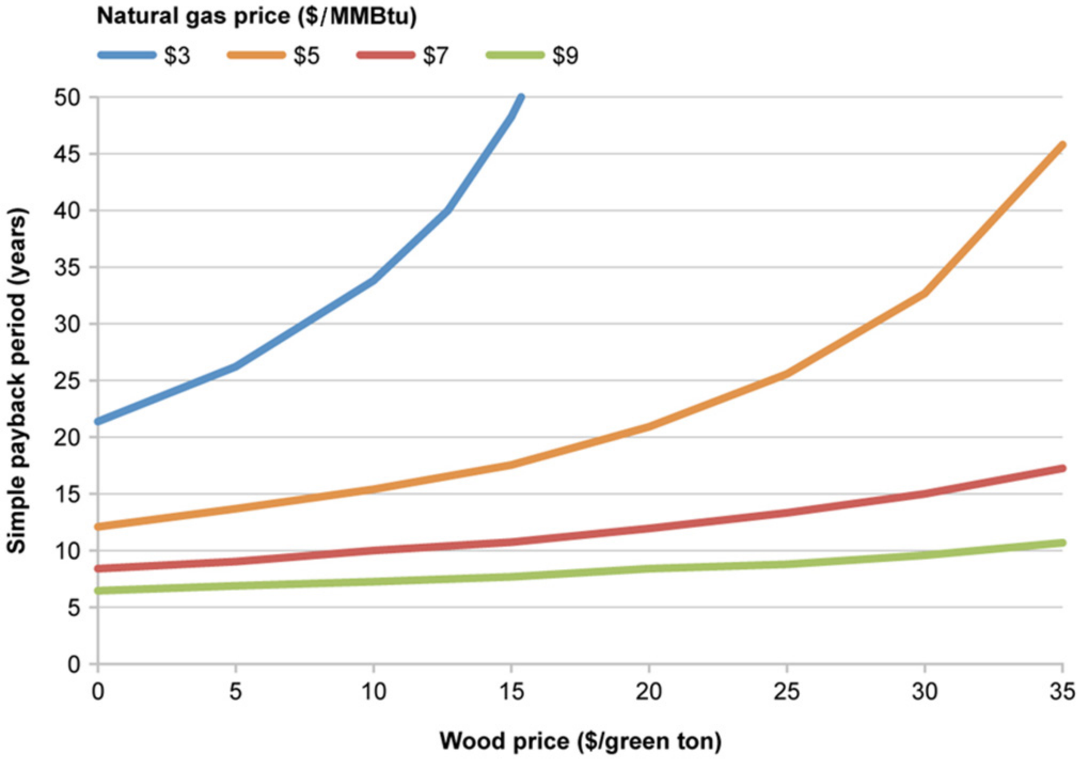
The industrial sector is the biggest consumer of energy from biomass, consuming 52% of total energy produced from biomass in 2008, with 91% of that energy consumed as thermal energy. Most of this thermal energy is produced in combined heat and power (CHP) plants in industries that process products derived from biomass; in particular, paper/lumber mills and biorefineries consume 66% and 26%, respectively, of energy from biomass in the industrial sector. Biorefineries and paper/lumber mills consume 100% and 86%, respectively, of their biomass-derived energy as thermal energy (EIA 2010b). The majority of the energy used by paper and lumber mills is produced onsite from CHP plants that can provide approximately 60% of the total energy required by the mills (ABS Energy Research 2009). The feedstock used is generally wood and derived fuels that include black liquor, forestry residues, and other waste products from the manufacturing process. In biorefineries, the energy consumed is from waste heat produced during the refining process. In both industries, thermal energy use does not increase the demand for feedstock because the energy comes from onsite waste products of the industries. The residential sector remains the only sector that significantly uses biomass only for heat, but, as shown in Figure 2, the amount of energy from biomass used has been relatively constant for the past 10 years.

3.1.2 Biomass Thermal Systems and Cost

The two types of energy conversion technologies that are used for biomass thermal and CHP systems are direct combustion systems and gasification systems. Direct combustion systems are the most common and have the most mature and commercially available technologies. A few gasification systems are commercially available, while more advanced two-stage gasification system technologies are in developmental or demonstration stages (Peterson and Haase 2009). The continued development of gasification technologies may increase the market appeal of biomass thermal systems due to their relatively lower emissions and higher efficiency in comparison with fossil-fuel-based technologies, but new gasification options are likely to have a greater effect on electricity and CHP markets because they are more regulated to require the reduction in emissions that gasification produces. Generally, biomass boilers can tolerate the greater impurities created during the direct combustion process and do not require the specialized fuels or low moisture content that gasification systems need.

The fuel costs for biomass thermal systems are competitive with fossil fuel costs, but the payback period of the system heavily depends on both the cost of the fossil fuel and the cost of the biomass replacement (Peterson and Haase 2009). Since natural gas is another major option for thermal heat, the economic competitiveness of biomass feedstocks depends on the cost of natural gas, which can have a volatile price. Also, the availability and price of biomass feedstocks vary from region to region. These factors make the economic feasibility of biomass thermal projects difficult to generalize. In most cases, the projects with the greatest economic potential are retrofitting fossil-fuel-based boiler systems and installing systems in new construction.

In Figure 3, the simple payback period is shown for a 3 million British thermal units (MMBtu) per hour system with an installed cost of $850,000. Table 1 shows the cost of fuels per MMBtu of energy produced.



$$\textit{Simple payback period} = \frac{\textit{Incremental capital cost}}{\textit{Incremental annual costs}}$$

Annual costs include O&M and fuel

Figure 3. Simple payback period versus the price of wood

Note: The graph is for a 3 MMbtu/hr system with an $850,000 installed cost. The different curves represent different costs of natural gas (Peterson and Haase 2009).

Table 1. Cost of Fuels

Source	Units	User Cost per Unit ($/unit)	Efficiency	Btu/Unit	$/MMBtu
Chipped biomass	Green ton	$50.00	75%	13,500,000	$4.94
Wheat straw bales	Ton	$55.00	70%	14,000,000	$5.61
Natural gas	Therm (10^5 btu)	$1.00	85%	100,000	$11.76
Wood/agricultural pellets	Ton	$130.00	80%	15,000,000	$10.83
Hardwood pellets	Ton	$185.00	80%	16,600,000	$13.93
Fuel oil	Gallon	$2.25	85%	135,000	$19.61
Propane	Gallon	$2.25	85%	91,600	$29.30
Electricity	Kilowatt-hour (kWh)	$0.10	100%	3,413	$29.30

Source: Peterson and Haase 2009

3.1.3 U.S. Policies and Market Obstacles

The United States does not use much biomass for thermal energy in industrial, commercial, or residential applications and does not have policies that encourage its use. A few regional "Fuels for Schools" programs exist, which help fund transitions from using fossil-fuel-based boilers to biomass-fueled boilers. These programs have been limited in success and have not led to sweeping changes in the use of biomass for thermal energy. U.S. energy policy has focused on promoting renewable energy in electricity and fuels but has not promoted renewable thermal energy sources as prominently (Biomass Thermal Energy Council 2010). Much of the growth of biomass for heating in Europe has been a result of meeting the European Union's "20-20-20" goal of 20% reduction of greenhouse gas (GHG) emissions by 2020, and thermal energy from biomass is seen as a significant way to reach this goal in the short term (European Climate Foundation et al. 2010). Without policies that specifically target GHG emissions, U.S. energy policies do not encourage the growth of biomass as a source of thermal energy.

The availability of biomass is a barrier to the implementation of biomass heating systems. Because transporting feedstock over long distances can be costly, large biomass heating plants need to be located near a source of feedstock. The use of biomass for thermal energy is most applicable in areas that both have nearby access to wood feedstocks and have colder climates (ABS Energy Research 2009). As a result, many organizations, especially trade organizations related to the timber industry, have promoted thermal energy use in the northeastern and western United States (Nicholls et al. 2008). However, neither of these regions currently has many thermal biomass plants.

Another barrier to the growth of biomass for thermal energy is the lack of tradition of using biomass for heating. One of the reasons cited for Scandinavian countries' large use of heating districts and other biomass-based heating systems is their cultural use of wood for heating (ABS Energy Research 2009). The United States has a more established tradition of using fossil fuels instead of biomass for heating.

3.1.4 Conclusion

The United States makes limited use of biomass for the production of thermal energy apart from heat produced in CHP plants and as waste heat from forestry-related industries, although there are some small-scale efforts in the northeastern and western United States. Lumber mills, paper mills, and biorefineries produce the most thermal energy from biomass, but this energy is created from waste products and does not greatly affect demand for biomass energy. Although residential use of biomass is primarily for the production of heat, it is only a small part of the use of biomass and has not changed much in the last 10 years. Across all sectors, the demand for biomass solely for the production of thermal energy is small. Without more incentive to switch from other energy sources, it is doubtful that the share of biomass for heating will increase significantly in the future. The European Union has climate goals that have increased the use of newer, high efficiency biomass plants for useful thermal energy, but U.S. policies have focused on the electric and fuel sectors. A shift toward policies that directly regulate GHG emissions might create more demand for biomass thermal facilities because of their potential to reduce emissions and the cost competitiveness of biomass feedstocks relative to fossil fuels.

3.2 Wood Pellet Exports

Wood pellets are compressed wood particles used primarily as fuel. As the cost of fossil fuels increase and carbon emissions become an increasing concern, wood pellets are being targeted as a possible near-term solution for meeting energy needs, particularly in Europe. As a means of reducing carbon emissions, European nations, especially Sweden and the Netherlands, use wood pellets in co-fired coal electricity generators as well as in the residential, commercial, and industrial sectors for thermal needs. Internationally, the wood-pellet industry is still largely considered an immature industry.

Wood pellets are a low-cost renewable resource that burn more cleanly than regular firewood. Approximately 69% of the raw material used for pellet production comes from sawmill residues, 14% from furniture and millwork residues, 16% from pulpwood and logging residues, and 1% from urban wood. The raw material is compressed under high pressure and temperature into wood pellets. This compression results in a higher energy density and lower moisture level than wood in its raw state, which reduces transportation costs (Spelter and Daniel 2009). The current price of wood pellets is about $230 to $300 per ton (Crowe 2011), which corresponds to about $0.049 per kilowatt-hour (kWh). This includes the capital cost, plus the cost of screening, drying, grinding, pelleting, cooling, storing, and transporting the pellets.

The production and utilization of wood pellets for home heating and co-firing in existing coal plants in the United States has grown significantly in the past two years. Overseas, the extraordinary demand for wood pellets has encouraged countries to look to the United States and Canada for supply. Much of the production growth in the United States, particularly the Southeast, can be attributed to European demand. The European Union’s concern with carbon emissions, along with high oil prices, has resulted in an increase in the export of wood pellets from North America (Grbovic 2010). Europe has been burning wood pellets in cogeneration plants to meet the requirement that 20% of total energy consumption be supplied by renewable energy sources by 2020. In 2008, the United States began exporting to Europe, beginning with about 85,000 tons of wood pellets to the Netherlands. In 2009, exports rose to nearly 30%, with 534,679 tons of the 1.8 million tons produced exported to Europe, corresponding to $53 million. The main export destinations within Europe have been the Netherlands, Belgium, and Sweden.

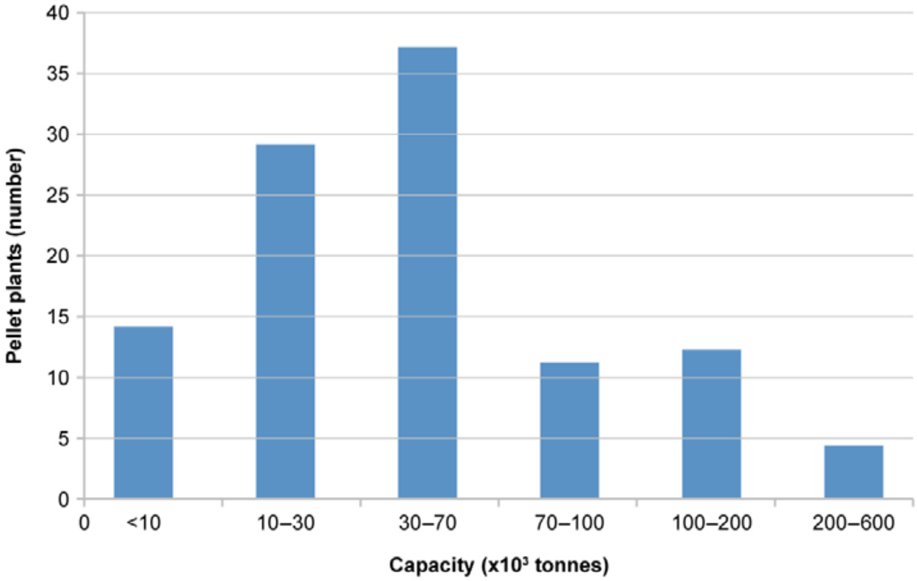


Figure 4. Distribution of pellet plants by capacity size in 2009

Source: Spelter and Daniel 2009, p. 2

There are just over 100 producers of wood pellets in the United States, concentrated mainly near international ports in the Northeast and Southeast, where pellets can be exported at a competitive price. Most of the producers are smaller plants, as shown in Figure 4, and depend on mill residues from other industries. The South represents the largest share of U.S. wood pellet capacity with 46% of the total production in 2009, followed by the Northeast, the West, and the Midwest, with 24%, 16%, and 14%, respectively, of the national wood pellet production (Spelter and Daniel 2009).

Due to the European Union's "20-20-20" goal, the export of wood pellets to European countries is expected to increase through 2020; in response, new production facilities are being planned in the southeast region of the United States, and existing facilities are ramping up production: quantities in the Southeast have increased from nearly zero in 2004 to close to 2 million tons in 2010 (Spelter and Daniel 2009). In addition to a convenient location for exporting the pellets, these plants benefit from proximity to forest plantations. Plants can obtain their wood supply from the selective thinning of nearby forests in addition to residual raw materials from other wood industries (Georgia Biomass 2010). Figure 5 illustrates the production capacity by region through 2009. Green Circle Bioenergy in Cottondale, Florida, is currently the highest-producing wood pellet facility in the world, producing 560,000 tons of pellets in 2010; this could be surpassed by Georgia Biomass, operated by a subsidiary of RWE Innogy, which opened in May 2011 and has a production capacity of 750,000 tons annually (Norris 2011). This facility is anticipated to be at full capacity in fall 2011 and is solely dedicated to European exports.

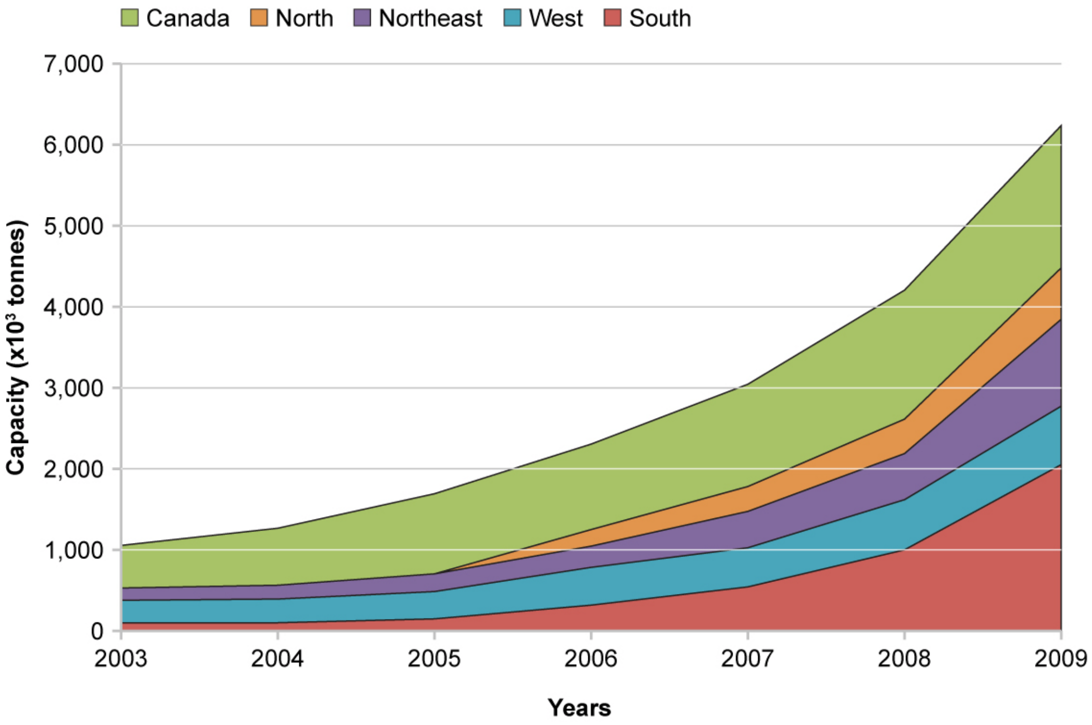


Figure 5. Wood pellet capacity by Canada and regions in the United States

Source: Spelter and Daniel 2009, p.3

A report by the United States Department of Agriculture (USDA) emphasizes the potential for growth in the use of pellets for home heating but cautions that high demand from biopower plants could destabilize the U.S. pellet industry because it is immature (Spelter and Daniel 2009).

3.3 Bio-Based Plastics and Bioproducts

3.3.1 Background

The production of bio-based products, particularly plastics and chemicals, seeks to address increased oil prices, expectations of oil scarcity, and environmental concerns. There are many reasons why switching from petroleum-based products to bio-based products is viewed in a positive light. Some bio-based products are biodegradable, which is desirable from a waste perspective. With increasing oil prices and supply disruptions, using biomass as the feedstock to plastics and chemicals could ease the unpredictability of raw materials prices and increase energy security. In addition, eliminating the environmental concerns that accompany extraction, transportation and processing crude oil could be seen as a positive attribute by countries with environmental regulations.

The term “bio-based products” refers to products that come from biological feedstock, whereas the term “bioproducts” refers to products that are biodegradable but may not be from bio-based feedstock. Though research on bio-based plastics and chemicals began in the 1860s, activity decreased in the 1950s after the discovery of petroleum’s use as a synthetic polymer (Shen et al. 2009). While most plastics and chemicals are currently petroleum-based, they could potentially be made from biomass (Sanders et al. 2007). Bio-based feedstock use is expected to increase as petroleum becomes scarcer and environmental concerns increase. The amount of increased production of bio-based products depends heavily on the price and availability of petroleum, the continued development of production processes, and the price of biomass feedstock (Patel et al. 2006).

3.3.2 Current Global Use of Bio-Based Chemicals and Plastics

The current use of bio-based plastics and chemicals is small compared to the overall use of petroleum-derived plastics and chemicals and to the overall use of biomass: only 1.3% of all plastics were bio-based in 2007 (Shen et al. 2009), and 3% of all chemicals were bio-based in 2009 (Vijayendran 2010). In 2007, 20 million metric tons (Mt) of bio-based polymers[1] were created from biomass (Shen et al. 2009). As a comparison, 365 Mt of biomass were used to produce wood and paper. Production of emerging bio-based plastics was only 0.36 Mt of plastic in 2007 and an additional 3 Mt of mature cellulosic polymers (including cellulosic fibers) were produced; demand for mature cellulosic polymers is not expected to grow as quickly as demand for emerging bio-based plastics. The yield of plastics from biomass feedstocks varies greatly among end products, ranging from 0.971 kilograms (kg) of biomass per kilogram plastic produced for bio-based thermoplastics to 5.06 kg of biomass per kilogram plastic produced for polyhydroxyalkanoates (PHA) (Dornburg et al. 2003). The yield for polylactic acid-based plastics (PLA), 1.74 kg of biomass per kilogram of plastic produced, is used in this report to convert quantities of plastic into approximate quantities of biomass because PLA is currently and is projected to continue to be one of the most common bio-based plastics. Using this yield factor, the production of 3.36 Mt of bio-based plastics consumed 5.85 Mt of biomass in 2007. While bio-based plastics and chemicals are in early stages of development with low demand, they both have a large potential to meet future plastic and chemical demands, with corresponding increases in biomass feedstock demands.

Although plastics have only been used on a large scale for approximately 60 years, the demand for plastic products has grown rapidly. Plastics currently account for 6% of all bulk materials in Europe (Shen et al. 2009). Between 1971 and 2004, plastics had an average annual growth rate of 5.9% worldwide and continue to be substituted for other bulk materials. The vast majority of these plastics and chemicals are petrochemical-based, though only about 2.2% of petroleum consumed annually in the United States is used for the production of petrochemicals (EIA 2010c); almost 4% of oil worldwide is used to produce non-energy resources (Cherubini 2010).

3.3.3 Biorefineries

To manufacture most bulk chemicals, oil refineries generally produce platform chemicals such as naphtha from which many other chemicals and plastics can be derived. These chemicals are separated out when crude oil is processed, but a significant change in the production of fuels could affect the ability or cost to produce petrochemicals. Currently, most bio-based chemicals and fuels are produced in single-production chains and do not take advantage of available processes to produce more than one end product (Cherubini 2010). It is expected that biorefineries will follow the same development pattern as oil refineries and will start to combine processes to make coproducts, including fuels, chemicals, and plastics, from a single input feedstock (Vijayendran 2010). These biorefineries will help increase the value of products that can be produced from a given feedstock. There is also the potential to integrate processes to

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[1] "Bio-based polymers" includes non-food starch (75% of supply, excluding starch for ethanol fuel), cellulose polymers, plastics, and alkyd resins.

create platforms for plastics and chemicals from biofuel refineries; for example, cellulosic or starch ethanol could instead be used to produce polyethylene.

3.3.4 Projections and Potential of Bio-Based Chemicals and Plastics

The projected production capacity and technical potential for substitution of petroleum-based products are high for both plastics and chemicals. There are two major strategies to replace petrochemical products: produce bio-based products that are chemically identical to current petrochemical products or produce products that are functionally equivalent for some or all of the uses of a current petrochemical product. The maximum technical potential for both types of substitution for all petrochemical-based plastics consumed in 2007 is 90% (Shen et al. 2009). This substitution is not available in the short- or medium-term because of scale-up time, but it shows the longer-term potential for bio-based plastics. Based on company announcements worldwide and the current 3 Mt of mature bio-based plastics, the capacity of emerging bio-based plastics is projected to grow from 3.36 Mt of plastic in 2007 to 6.45 Mt in 2020 (from 1.3% to 2.6% of 2007 plastic consumption). However, if plastic continues to replace other bulk materials as it has in recent years, the relative percentage of plastics that are bio-based will be much less. Starch plastics, PLA, bio-based polyethylene (PE), and bio-based epoxy resins expect the most growth. Figure 6 shows a range of predictions for the use of bio-based plastics until 2020 in Europe.

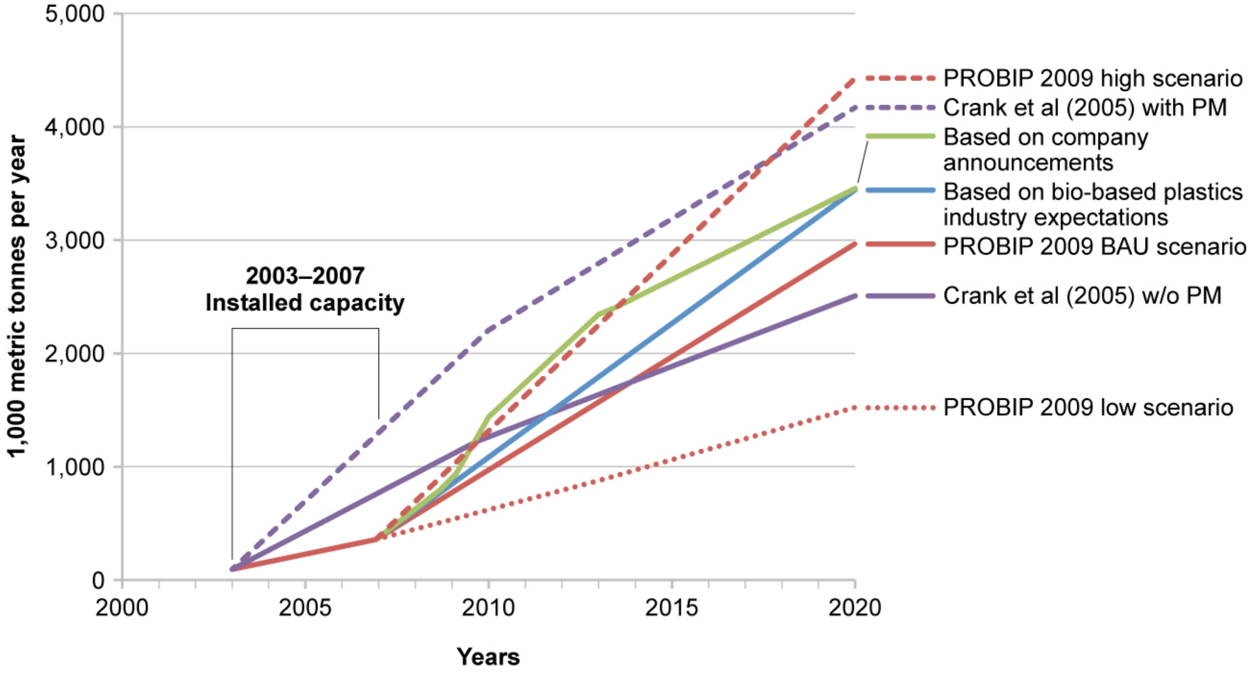

Figure 6. Predictions of the European consumption of bio-based plastics in 1,000 metric tons per year

The Crank et al. (2005) study looked at scenarios with and without policies and measures, and the PROBIP study by Shen et al. (2009) examined scenarios based on specific types of bio-based plastics. These projections may be a bit high because they are based on bio-based plastic company expectations. Even with high growth scenarios, the amount of biomass required for plastic products will be small compared to the need for biomass for fuel and energy markets.

Assuming the same 1.74 kg of biomass per kilogram of plastic produced yield factor, 5.85 Mt, 9.26 Mt, and 11.2 Mt of biomass would be used for bio-based plastics in 2007, 2013, and 2020, respectively (Table 2). At the maximum technical substitution potential of 2007 plastic production (90%), 375 Mt of biomass would be required to produce bio-plastics.

Table 2. Emerging and Mature Bio-Based Plastics Produced and Biomass Consumed Globally in 2007 and Projected Levels in 2013 and 2020 Based on Company Announcements

	2007	2013	2020
Bio-Based Plastics Produced (Mt)	3.36	5.32	6.45
Percent of Total Plastic Production in 2007 (245 Mt)	1.3%	2.2%	2.6%
Biomass Consumed (Mt)	5.85	9.26	11.20

Source: Shen et al. 2009

So far, bio-based plastics have competed successfully in niche markets where clients are willing to pay an environmental premium and in applications where their biodegradability is a significant advantage, such as agricultural films and some product packaging (DiGregorio 2009). For market share of bio-based products to increase rapidly, they need to compete directly with petrochemical-based products.

Expectations for bio-based chemical production growth are similar. The proportion of bio-based bulk chemicals to all bulk chemicals could grow from the current 3% to be as high as 15% in 2025 (Vijayendran 2010). In 2000, Europe produced approximately 70 Mt of bulk chemicals and almost none of that was bio-based (Patel et al. 2006). According to the medium- and long-term opportunities and risks of the biotechnological production of bulk chemicals from renewable resources (BREW) project from Utrecht University, the projected European production of bio-based and total organic chemicals in 2050 for low, medium, and high growth scenarios is 4.8 Mt, 26.2 Mt, and 113.1 Mt, respectively. The three scenarios differ in their assumptions about the growth of total organic chemical consumption and economic factors that affect the production of bio-based chemicals. High growth of bio-based chemicals assumes that there is substantial technological breakthrough in bioprocessing, major progress in downstream processing, high fossil fuel prices, and low fermentable sugar prices. All of the data from the BREW project is based on European production of bio-based chemicals. The European market for bio-based chemicals is expected to grow more rapidly and gain a larger percentage of worldwide production capacity for bio-based plastics and chemicals than any other region, so it can be seen as the upper-bound of production in other regions (Shen et al. 2009).

The technical potential for substitution in the chemical industry is similar to the potential for bio-based plastics. The high technical potential of substitution allows the possibility that a large quantity of biomass could be consumed to produce bio-based chemicals; however, like bio-based plastics, it is unlikely that this substitution potential will be reached in the next few decades because of high costs and scale-up time. In particular, the BREW Project's assumption that fermentable sugar prices will remain at relatively low levels is unlikely to come to fruition if bio-based chemicals are produced at the high scenario levels. The price would be driven up by the increased demand for those sugars from bio-based chemicals and other bio-based products such as fuel (Patel et al. 2006). However, the price of oil has followed the medium and high scenarios, which would result in more bio-based products. Because the BREW project includes large growth projections for PHA, PLA, and ethanol, which can be used as platform chemicals to produce other bulk chemicals or bio-based plastics, quantities of biomass required individually for bio-based plastic and chemical projections requires further analysis.

Table 3. European Production of Organic and Bio-Based Chemicals in 2000 and Projected Production in 2050 for Low, Medium, and High Scenarios of Growth with Assumptions for the Projections

		2000	2050		
			Low	Medium	High
Projection Assumptions	Production of All Organic Chemicals (Mt)	70	70	150	300
	Bio-Based Chemicals (Mt)	0	4.8	26.2	113.1
	Price of Crude Oil ($/barrel)	$25	$30	$66	$83
	Price of Fermentable Sugar ($/ton)	$76–$260	$432	$216	$76
	Annual Growth of Chemical Market (%/year)	--	0%	1.5%	3%
	Year Advanced Technologies Become Available	--	Never	2040	2020
Substitute Starch-Based Chemicals	Land Use for Starch-Based Chemicals (Mha)	--	1.0	--	38.2
	Crop Yield (Mt/Mha)	--	9.1	--	9.1
	Quantity of Biomass Consumed (Mt)	--	9.1	--	347.6
Substitute Lignocellulose-Based Chemicals	Land Use for Starch-Based Chemicals (Mha)	--	0.4	--	15.6
	Crop Yield (Mt/Mha)	--	7.6	--	7.6
	Quantity of Biomass Consumed (Mt)	--	3.04	--	118.6

Source: Patel et al. 2006

3.3.5 Conclusion

High oil prices, expected scarcity of oil, and environmental concerns are the major driving factors in the development of bio-based plastics and chemicals. Many barriers still exist to the large-scale implementation of bio-based products, but there is a high technical potential for substitution. The demand for biomass feedstock from bio-based products appears to be low for the short- and medium-term future compared to food and energy feedstock demand. The current consumption of oil for non-energy use is only 4% of worldwide oil consumption and 2.2% of U.S. oil consumption; it seems unlikely that the demand for biomass from bio-based chemicals and plastics will increase to a greater percentage compared to the amount of biomass demanded from fuels or food. However, total plastic and chemical use is expected to grow greatly as it replaces other bulk materials and developing countries' demands increase; this change could cause more competition for petroleum and increase interest in and use of bio-based plastics.

Currently, little research has been done on the quantity of biomass required to produce bio-based products. More emphasis has been focused on the technical substitution potential of bio-based plastics and chemicals and the penetration of bio-based plastics and chemicals into petrochemical-based product consumption. Much of this research has been centered on Europe and is based out of Utrecht University. The studies have largely ignored the issue of biomass requirements and have assumed that the demand for biomass caused by bio-based chemicals and plastics will not be significant compared to other uses. If bio-based plastics did approach their technical substitution potential, the biomass consumed would be greater than the amount of biomass currently consumed outside of food and wood. The substitution of bio-based products depends heavily on the prices of oil and biomass (Shen et al. 2009). If oil prices are high and the price of fermentable sugar is low or if there are favorable policies, bio-based chemicals and plastics could begin to be substituted for petrochemical products. However, this scenario appears unlikely in the next few decades.

3.4 Biopower

3.4.1 Background

Biopower is defined as the use of biomass to generate electricity (U.S. Department of Energy 2010). At over 11 megawatts (MW), it is second only to hydropower in generating capacity among renewable energy sources in the United States. Some noted benefits of using biopower include the following: cleaner source of fuel than coal based on life cycle analysis; increased diversity of the U.S. energy supply; additional and diversified jobs for rural economies; and storable energy that can be used on demand.

The three main methods of using biomass for electricity generation are direct combustion, co-firing, and gasification. Direct-firing uses biomass as the sole fuel in a power plant furnace. These plants have an industry average efficiency of 25% (Wang et al. 2010). Since these plants rely solely on feedstock, they often have smaller generating capacities. The second method, co-firing, replaces some amount of coal in an existing power plant furnace with biomass, generally between 5% and 30% by mass (Ciolkosz 2010). With proper tuning, levels of efficiency in co-firing plants are comparable to all-coal firing, which are typically around 35%. The third technology, gasification, involves heating the biomass until it results in a flammable gas. This "biogas" can then be purified and used in combined cycle power generation systems, which can be up to 60% efficient (U.S. Department of Energy n.d.). Of the three, co-firing is projected to be the process with the most economic potential to meet growing energy demands in the near term, while gasification may hold more potential in the future as the technology costs decrease. Additionally, another common application for biopower is in CHP plants for both thermal and electrical energy (covered in more detail in Section 3.1). The use of biomass for electricity is growing in the United States and at even greater levels in Europe, and biopower trends and projections suggest continued growth.

3.4.2 Current Biopower Capacity and Generation

Biopower began to grow rapidly in the United States due to the establishment of the Public Utilities Regulatory Policy Act (PURPA) of 1978, which guaranteed that utilities would buy small electricity producers' surplus electricity. This legislation, along with various state incentives, led to generation capacity growth from under 4,000 MW in 1981 to over 8,000 MW by 1990, as well as $15 billion of investment and 66,000 new jobs (Bain and Amos 2003). Growth began to slow in the 1990s when the PURPA agreements began to expire and feedstock costs were high due to inadequate infrastructure**.** Since 1990, the summer generating capacity from biopower has grown by over 3,000 MW[2] (see Figure 7), though it still accounts for just over 1% of the generating capacity across the electric power market in the United States.

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[2] Summer capacity is used because it is generally lower for most U.S. power generators due to the higher ambient temperatures that stress the electric-generating systems.

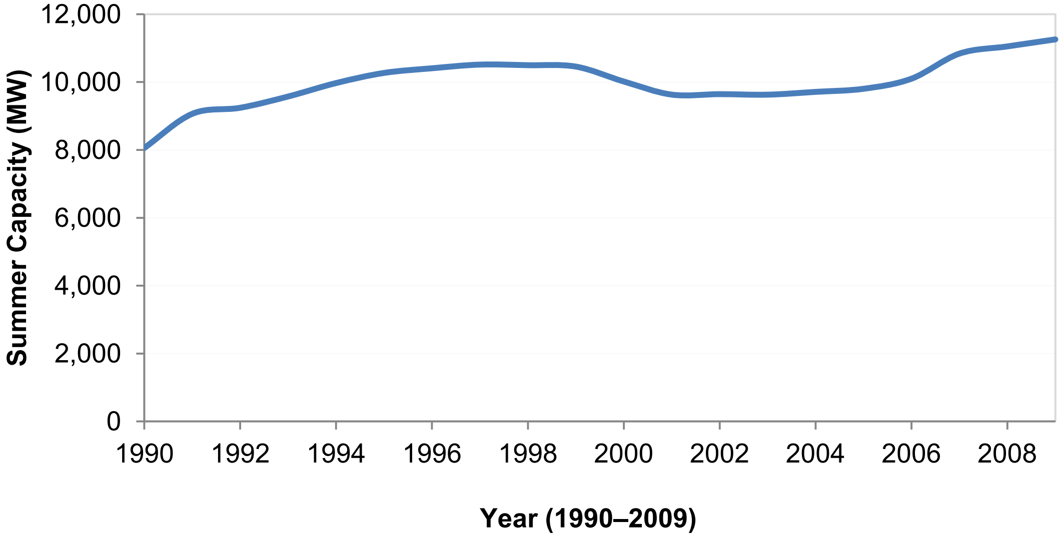

Figure 7. Biomass-derived summer capacity in the United States, 1990–2008

Source: U.S. Energy Information Administration 2010a

3.4.3 Prospects for Biopower Expansion

The Annual Energy Outlook (AEO) (U.S. Energy Information Administration 2011) forecasts that, overall, biopower generation will increase to nearly four times the current level by 2020, as seen in Figure 8. Co-firing accounts for nearly all of the growth, while dedicated plant generation is projected to remain comparatively stagnant.

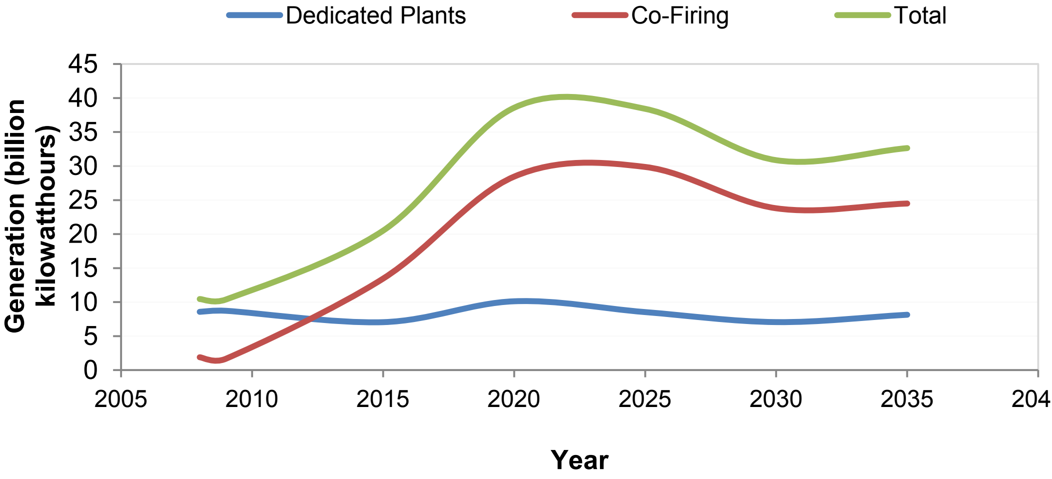

Figure 8. Projections for biopower generation broken up by generating technology, 2008–2035

Source: Energy Information Administration 2011

There are two major variables influencing the growth of biopower in the United States. The first is whether or not renewable portfolio standards (RPS) exist at the state level (Energy Information Administration 2011). Currently, 28 states and the District of Columbia have RPS requirements, while four additional states have non-mandatory goals. States with RPSs typically set targets for the overall renewable energy percent of the electricity sales they desire by a certain year, as well as specific provisions, such as a target goal for a specific technology (such as wind, solar, or biopower). Renewable energy requirements can have a substantial impact, as Europe has shown. The European Union has set a 20% renewable energy goal by 2020, with specific targets for individual countries**.** Because much of this goal is expected to be met with co-firing, this increased demand has directly influenced the growth of wood pellet production capacity in the United States and Canada. (For more information about exports, see Section 3.2.)

The second factor influencing biopower growth is the amount of available feedstock and feedstock transportation infrastructure in the region (U.S. Energy Information Administration 2011)**.** Areas such as the Southeast and California have been able to use substantial shares of their biomass resources. For example, California uses residues from mills, forests, agricultural waste, and urban waste (Bain and Overend 2002) for biopower, which accounts for about 3% of their annual electrical generation (EIA 2010a). Other areas lack the natural resources and infrastructure for feedstock transportation needed for competitive expansion of biopower (Bain and Overend 2002).

3.4.4 Conclusion

Biopower, both co-firing with coal and dedicated biomass plants, has historically been a major source of renewable electricity in the United States, though continued expansion of biopower capacity remains heavily dependent on local factors such as availability of biomass and policy drivers. Biopower capacity is expected to expand only if governmental policies promote renewable generation and specifically include biopower. Additional capacity expansion in the near-term is expected to manifest as co-firing at coal-fired power plants.

3.5 Biofuels

3.5.1 Background

Many countries have adopted aggressive programs to develop and deploy renewable energy for economic, environmental, and energy security reasons (Kerr 2007a; Kerr 2007b). In addition to being the world's largest producer of ethanol, the United States is the world's second largest consumer of crude oil and the second largest GHG emitter (behind China on both accounts). An average of 20,680,000 barrels of oil per day was consumed in the United States in 2007, which amounts to approximately 24% of the 2007 worldwide oil consumption (EIA 2009a). In the United States, burning fossil fuels to accommodate transportation is responsible for the emissions of roughly 5,720 teragram (Tg) carbon dioxide-equivalents annually (U.S. Environmental Protection Agency 2009; EIA 2008). Because the United States is responsible for a disproportionate amount of global oil consumption and GHG emissions, significant improvements in renewable fuels use by the U.S. transportation sector will have far-reaching global implications for petroleum availability and atmospheric carbon dioxide level increases. In the United States, significant research attention has been directed toward bioethanol derived from both first- and second-generation feedstocks (starch and lignocellulosic biomass, respectively), with ethanol derived from the former being produced at an industrial scale both in the United States and throughout the world. Cellulosic feedstocks, such as agricultural and forestry residues, perennial grasses, woody crops, and MSWs, are advantageous because they do not necessarily compete directly with food, feed, and fiber production and are envisaged to require fewer inputs (e.g., water, nutrients, and land) as compared to corn and other commodity crops. Globally, ethanol production has increased dramatically over the last five years. In 2008, worldwide ethanol production exceeded 64 billion liters, 53% of which was produced in the United States using corn grain as the main feedstock and 38% in Brazil using sugarcane as the main feedstock (Licht 2008).

3.5.2 Prospects for Biofuels

Legislation to help curb oil consumption and GHG emissions is beginning to take hold in the United States at both the state and federal levels (California Air Resources Board 2008; U.S. Congress 2007). For example, the 2007 renewable fuel standard (RFS), which is mandated in the Energy Independence and Security Act, is intended to spur the growth of advanced and cellulosic biofuels industries by promoting research in these areas and mandating aggressive market penetration targets. These targets culminate in the year 2022 with a minimum[3] annual production volume of 36 billion gallons per year (bgy) of renewable fuel, including targets of 16 bgy from cellulosic materials, 4 bgy from "advanced biofuel," and 1 bgy from biomass-based diesel (U.S. Congress 2007). Though a minimum target level is not established in the bill, the remaining 15 bgy of renewable fuel will most likely come from corn grain-based ethanol because the industry is well established in the United States and is on track to meet, if not exceed, this production volume within a few years.

Although the use of renewable transportation fuels is increasing, commercial production of these fuels is fraught with serious logistical issues; top among them is sustainable feedstock availability and capital-intensive biorefining facilities. In a recent report by the DOE, the estimated potentially available biomass in the United States ranges from 0.6 to 1.0 billion dry tons in 2022 and 0.7 to 1.3 billion dry tons in 2030 (DOE 2011), depending on feedstock prices. Such levels of biomass harvesting and collection will likely require significant improvements in feedstock logistics to ensure the long-term economic feasibility of installed refineries and continued investment in the industry.

3.5.3 Conclusion

Starch- and cellulosic-based ethanols are the most likely near-term biofuels; the former is already produced at an industrial scale and has a firm foothold in the marketplace as a fuel additive and petroleum substitute. Cellulosic-based ethanol and other cellulosic biofuels must clear several significant hurdles before their market position is secure. For example, for the cellulosic biofuel industry to develop, a year-round, dependable, low-cost source of cellulosic biomass needs to be available to the biorefineries. National resource assessments suggest that there is potential to supply enough biomass to meet long-term energy policy goals; however, these estimates are based on modeled projections of biomass supply in response to price signals (Perlack et al. 2005; DOE 2011). Cellulosic biomass is currently not collected or grown at a large scale in the United States. Before producers are willing to allocate land to production of cellulosic biomass, a market for cellulosic biomass must be in place. Therefore, government intervention, in the form of subsidies and other incentives, would likely be needed to build industrial momentum.

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[3] The targets for each year are subject to EPA review and can be reduced at the administrator's discretion.

4 Pathways for Accomplishing Competition Implementation in the Biomass Scenario Model

Developed to examine the complex interactions of policies and their effects on the biofuels industry, the BSM does not currently account for biomass competition from other end users and assumes that all biomass resources are available for conversion into biofuels. In this section, we explore how to best incorporate biomass competition into the BSM. We investigate three pathways: development of a new biomass competition model that is purpose-built to connect easily with the BSM; use, in parallel with the BSM, of an existing electricity-sector capacity-expansion optimization model with biopower representation; and integration of an existing system dynamics electric-sector model with explicit representation of biopower. This final option was explored but not completed at this time, though it remains of interest for future work (see Appendix B).

The first pathway to meeting the goal involves building a standalone model containing components that can communicate seamlessly with the BSM (discussed in Section 4.1). This model, built in STELLA, does not intend to include a detailed representation of the fuel and power sectors. Instead, it is designed to look at aggregate dynamics and can be used for identifying general trends in the competition for biomass. When run as a standalone model, it can highlight possible scenarios that should be investigated further in more complex models, such as ReEDS.

The second pathway (Section 4.2) is to couple the BSM, a system dynamics model, with ReEDS, an established linear programming optimization model representing the electric sector that is used especially for renewable generation analysis under different scenarios (Short 2011). The differing modeling techniques complicate communication between the two models. We provide a proof-of-concept for overcoming the different modeling methodologies and open a wide range of possibilities for future analyses, including the generation of supply curves.

4.1 Standalone Model

4.1.1 Modeling Method Choices

Initial scoping efforts identified three main model components to be addressed: biomass allocation among end uses, capacity expansion for competing uses and biomass feedstock, and end-use demand. Because each of these three components could itself be the subject of a lengthy and detailed modeling effort, the benefits and shortcomings of various modeling approaches were carefully evaluated, primarily based on the simplicity and general robustness of the approach, as well as the ability to extend the formulations and join the final model into the BSM in a seamless fashion. These results are summarized in Table 4.

Table 4. Modeling Alternatives

Model Component	Approach	Description	Methodology Employed
Biomass allocation among end uses	Proportional allocation scheme (i.e., logit function)	Uses a concept of relative utility (end-use price) to distribute available biomass among competing end uses utilizing a logit choice formulation.	Chose the profit maximization allocation scheme because our focus is on understanding optimal mix of end uses and feedstock given prices.
	First-come, first-served allocation scheme	Allows existing facilities to consume available biomass, with new uses and demand competing for any remaining resources.	
	Profit maximization allocation scheme (i.e., production function)	Allocate resources based on the principle of maximizing individual firm profitability; a commonly employed method in microeconomic models.	
Capacity expansion for competing uses and biomass feedstock	Exogenous approach	Use external scenarios to drive simple capacity scenarios for the biomass, biopower, and biofuels industries.	Used the endogenous, highly aggregated approach so that we could model the dynamics of capacity expansion without the added complexity of modeling individual firms.
	Endogenous, highly aggregated approach	Model the end-use industries where firms are homogeneous so only one firm is modeled and then multiplied by the total number of firms.	
	Endogenous, highly disaggregated approach (i.e., agent based models)	Model the end-use industries explicitly where firms are heterogeneous thus having distinct characteristics.	
End-use demand	Detailed endogenous representation	Represent in high detail the endogenously generated dynamics in each of the end-use sectors.	Allowed the user to switch between simplified endogenous and aggregate exogenous scenarios. It is exceedingly straightforward and extensible to add simple feedbacks to the simplified endogenous scenario.
	Aggregate exogenous scenario	Create a basic time-driven demand scenario.	
	Simplified endogenous representation	Use base end-use demand projections and then: 1. Apply a price elasticity factor to arrive at final demand scenarios, or 2. Utilize a cross-price elasticity of demand formulation that would compute end-use demand as a function of changes in prices for competing outputs (i.e., those not generated from biomass).	

Note: Employed methodologies are shaded.

4.1.2 Model Description

The primary goal of the biomass competition model is to create an elegantly simple representation of key decisions and industry dynamics that allows the relative impacts of different policy schemes to be analyzed. In addition, since this is an exploratory modeling effort, an emphasis is placed on formulations and approaches that are different than those employed by the BSM. The final product combines a number of different modeling techniques, rendered using the STELLA simulation environment, into one model. Figure 9 shows the main components of the model and their interconnections at an aggregate level.

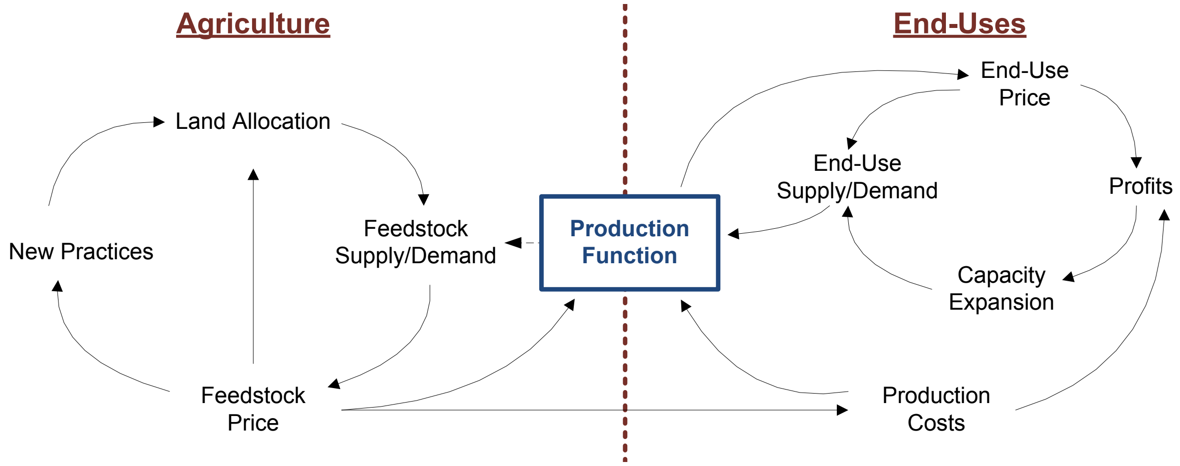

Figure 9. Basic components of the biomass competition model

4.1.2.1 Land Allocation

The land allocation portion of the model incorporates a few key formulations from the BSM, some that have been taken "as is" and some that have been modified for the purposes of simplicity in the biomass competition model.

1. An "accounting structure" tracks available agricultural land that could be dedicated to cellulosic crops if economic conditions (i.e., feedstock prices) warrant a reallocation of arable acreage.
2. An adoption or diffusion dynamic captures the number of farmers (on a percentage basis) who are employing new agricultural practices that allow for cellulosic feedstocks to be grown, harvested, and transported.
3. An increasing yield over time (to simulate learning and technological improvements) occurs for agricultural residues and herbaceous crops, which comes from the reference case run in the BSM.
4. Forest residues are calculated using the implied supply curve from the BSM, in which feedstock supply (from forest residues) is simply a function of feedstock price. This formulation is independent of any other factors (e.g., industry maturity, advances in technology, or time horizon) influencing this source of feedstock supply.

The combination of land allocation, farm yields, new practice conditions, and price-based supply curves results in the calculation of total quantity of feedstock produced per time period (broken out by feedstock type). This feedstock supply in combination with feedstock consumption determined by the production function allows for feedstock inventory dynamics to be captured.

4.1.2.2 Production Function

Production functions are often utilized in microeconomics to relate quantity of output to different combinations of factor inputs. In the context of the biomass competition model, the relationship between the quantity of bio-outputs (biofuel, biopower, or bio-based products) produced and the quantity of feedstock (by feedstock type) consumed needs to be established. The Cobb-Douglas formulation is a specific case of a production function relating inputs to outputs, expressed in the form:

$$Y_i = A_i {B_{ij}}^{\alpha_{ij}} \qquad [1]$$

where

Y_i = the production of the end-use product

A_i = the technology-scaling factor

B_{ij} = the amount of feedstock consumed by each end use

α_{ij} = the output elasticity of end use given a change in feedstock.

The subscript i denotes end-use product (biopower, biofuels, or bio-based product), and the subscript j denotes feedstock type (agricultural residues, forest residues, herbaceous crops, or woody crops). In effect, this form of the Cobb-Douglas production function establishes a two-dimensional matrix relating the quantity of various feedstocks needed in order to produce different types of end-use products, given prevailing technological conditions as well as the sensitivity/elasticity of outputs to varying quantities of inputs.

The system dynamics framework employed in the biomass competition model is not suited for optimization of static mathematical calculations, so additional steps were needed to extend the basic Cobb-Douglass production function into calculations for output prices, demand, and ultimately feedstock allocation. For any end-use product i, a basic profit calculation can be established (as shown in Equation 2).

$$\Pi_i = P_i Y_i - (F_i + V_i Y_i + P_0 B_i) \qquad [2]$$

where

Π_i = the profit derived from the economic activity

P_i = the prevailing price of the end-use product

F_i = the fixed costs associated with production

V_i = the variable costs per unit of production

P_o = the price of the biomass input

B_i = the quantity of biomass consumed.

Combining [1] with [2] allows for a profit maximization calculation to be established, subject to the constraints on output established by the Cobb-Douglas production function. The exact mathematics of this translation are beyond the scope of this paper, but the optimization process returns expected output prices, as well as the allocation of feedstock by end-use product, subject to any additional constraints on feedstock supply and market feedback mechanisms (see subsequent sections). Utilizing the Cobb-Douglas production function, combined with an associated profit maximization formulation, allows for base quantities of inputs (feedstocks), outputs (end-use products), and output prices to be established. A more traditional system dynamics modeling framework can then use these values to capture how market and industry dynamics will evolve over time in response to changing macroeconomic conditions.

4.1.2.3 Feedstock Price and Inventory

Using an extension of a common system dynamics formulation, the model establishes a balancing feedback loop between feedstock inventory dynamics and feedstock price. First, an initial feedstock price is established (using a model initialization year from the BSM) that through a series of calculations determines the quantity of feedstock supply and demand. Any imbalance between feedstock supply and feedstock demand will, through the model simulation, result in changes to the feedstock inventory over time (see Figure 10). As feedstock inventory deviates from its desired levels, the feedback component is formulated to affect feedstock price in the opposite direction. In other words, feedstock inventories that are above their desired levels will cause feedstock price to fall (thus decreasing supply, increasing demand, and bringing inventory back in line). Conversely, low feedstock inventories will send a signal to increase feedstock prices, which force supply to rise and demand to fall, thus helping inventory to return to desired levels.

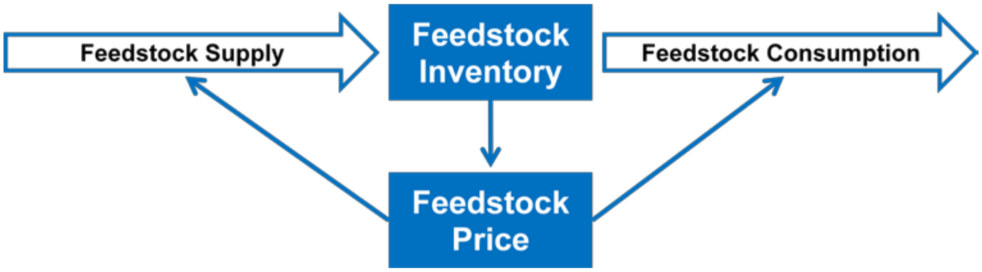

Figure 10. Balancing feedback mechanisms for feedstock price and inventory in the biomass competition model

The mathematics of the feedstock price formulation includes a feedstock inventory elasticity factor that can be used to tune the “responsiveness” of feedstock price to changes in feedstock inventory, as well as a dynamic concept of a desired feedstock inventory level that is scaled based on changing feedstock demand. In general, however, the model utilizes the concept of balancing feedback to relate feedstock supply, demand, and inventory in a dynamic fashion.

4.1.2.4 End-Use Demand

The biomass competition model currently has two separate mechanisms for determining output demand. A simple switch in the STELLA code allows for either of these two end-use demand formulations (endogenous or exogenous) to be used in the calculations. The first formulation utilizes a simple price elasticity variable in which end-use demand is a function of the change in prevailing output prices (relative to initial or baseline values), subject to a sensitivity or elasticity metric. This formulation allows for end-use demand to be determined endogenously but ignores some of the real-world dynamics of substitution and price comparisons between bio-outputs and their traditional alternatives.

The second mechanism for determining end-use demand is to utilize exogenous forecasts from AEO 2011 (U.S. Energy Information Administration 2011) and employ substitution effects between biopower/biofuels/bio-based products and their fossil-fuel-based competition considering their relative prices. These formulations typically include a cross-price elasticity of demand calculation, where the change in demand for biofuels, for example, is expressed as a function of the change in price of fossil fuels. The functional form of this relationship includes a sensitivity or elasticity metric, which is often held constant but can in fact be changing over a time interval (particularly in evolving marketplaces where the substitutability of competing products has not yet stabilized). This cross-price elasticity factor can be derived from analysis of AEO 2011 data and incorporated directly into the biomass competition model. Finally, end-use demand is determined exogenously from AEO 2011 data and the elasticity of substitution between biopower/biofuels/bio-based products and the alternatives are applied to the data.

4.1.2.5 Product Price/Inventory

The model's approach to product price and inventory dynamics in the end-use sector mirrors that employed in the feedstock formulations. In this case, however, the initial product price is derived from the production function. This base price is subsequently impacted by product inventory levels as they deviate from target values. Similar feedback mechanisms exist that then determine product demand based on the adjusted product price (again, using an explicit price elasticity) and product supply (as computed based on operating capacity in the industry, which itself results from profit metrics stemming from prevailing prices). In this manner, the model establishes a similar set of balancing feedback mechanisms that serve to link product price to supply, demand, and inventory, as seen in Figure 11.

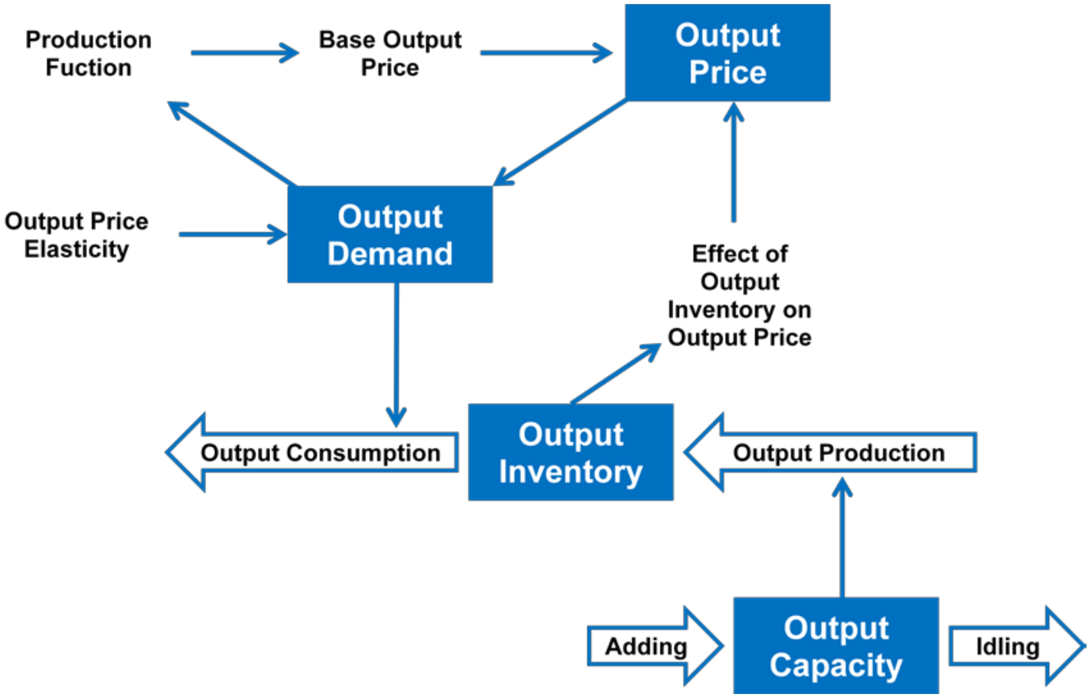

Figure 11. Balancing feedback mechanisms for product price and inventory in the biomass competition model

4.1.2.6 Capacity Expansion

The capacity expansion portion of the model is inspired by basic microeconomic principles but applied at the aggregate or industry level. Suppliers in any dynamic marketplace face two basic production decisions: adding capacity in order to increase production and subtracting/idling capacity in order to curb output. The model breaks the former decision into two different categories: restarting previously idled capacity and constructing new facilities when no slack capacity remains to be restarted.

This model uses industry profit margin, defined as the ratio of gross profits to total revenues, as the driving force behind capacity changes. If profit margins are too low (relative to an average or expected value), producers will see fit to decommission plants, thus decreasing industry capacity in an effort to increase profit margins up to acceptable levels. If the industry is operating at profit margins above expected levels, then previously idled plants will be put back into commission and new facilities will be constructed. Through this balancing feedback mechanism, the addition and subtraction of capacity works to move industry profit margins into acceptable ranges, even in the face of changing marketplace dynamics or shocks to the system, as seen in Figure 12.

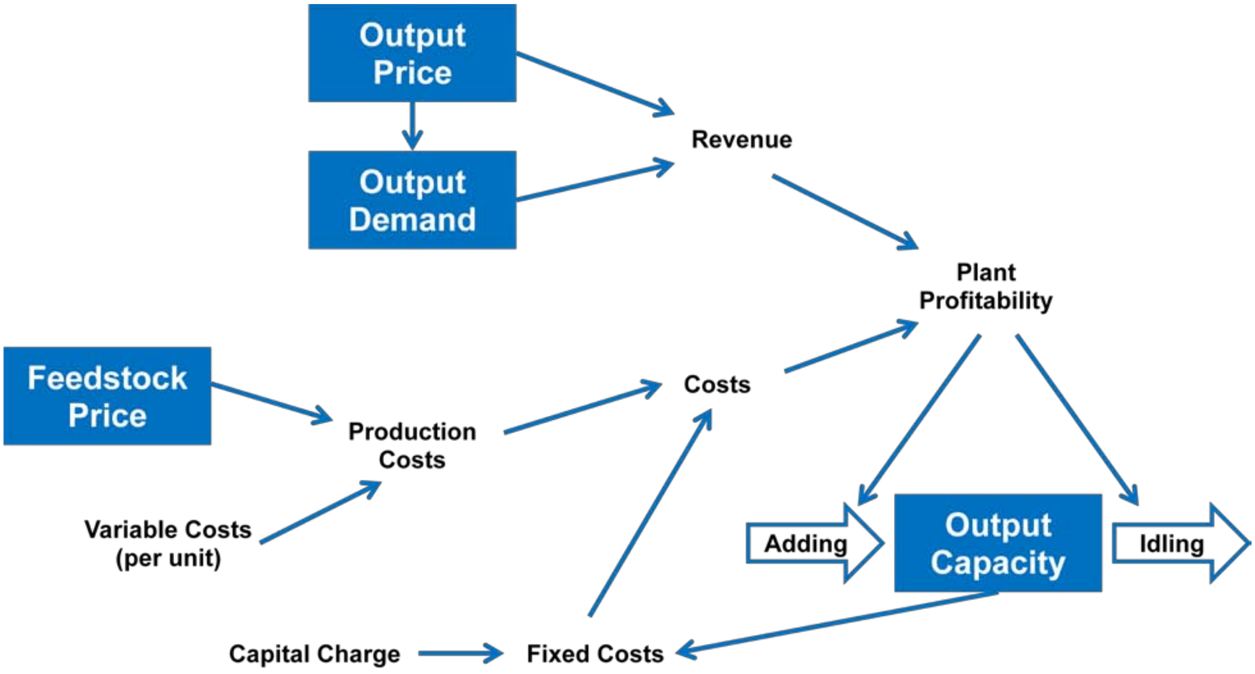

Figure 12. Balancing feedback mechanism for capacity in the biomass competition model

The model calculates gross profit in a very basic manner by taking the algebraic difference between revenues and costs. The former is driven by production volumes and output prices, while the latter is broken up into raw materials, variable costs, and fixed costs. Although more complex financial calculations are certainly possible (and even perhaps desirable in the longer term), this simple approach allows for the exploration of the response of the formulation to a wide range of scenarios.

4.1.3 Insights from Model Development

The model-building process allowed us to verify that an “operational abstraction” of the detailed BSM feedstock supply/logistics, providing a minimum structure required to handle build-out of biomass resource over time and matching biomass production to downstream demand dynamics, is possible. We also verified that Cobb-Douglas production functions (and associated elasticity formulations) can be successfully connected to system dynamics formulations of physical conversion parameters, such as feedstock throughput and plant capacity-addition dynamics. The varied price/inventory relationships in the model can handle fuels/products that require inventory, along with electricity, which effectively has no inventory in the model. The price/inventory/supply/demand dynamics result in a high degree of feedback between model sectors and can potentially lead to instabilities in the simulation.

In general the simplified model has formed a laboratory for understanding (1) dynamics of biopower/biofuel/bioproduct uses for feedstocks and (2) simplified market/pricing dynamics that can be fed back into more complex simulations such as the BSM. If we choose to pursue completion of this model, the next steps are to perform rigorous model testing and calibration, undertake scenario and parameter analysis, and further elaborate the insights generated from the modeling effort.

4.2 Coupling with ReEDS

4.2.1 ReEDS Model Description and Modification

ReEDS is a power generation capacity and transmission expansion model of the national electric sector (Short 2011).[4] Through a highly discrete regional structure, explicit statistical treatment of the variability in wind and solar output over time, and consideration of ancillary services requirements and costs, ReEDS is able to explicitly model issues associated with variable renewable resources that many other models address through more general assumptions. It provides a detailed treatment of electricity-generating and electricity-storage technologies and specifically addresses a variety of issues related to renewable energy technologies, including accessibility and cost of transmission, regional quality of renewable resources, seasonal and diurnal generation profiles, variability of wind and solar power, and the influence of variability on the reliability of the electrical grid. ReEDS, a linear program, minimizes the 20-year present value total system cost to build new capacity as well as operate the system. It performs this optimization in two-year increments, stepping from the present to 2050 in a recursive dynamic algorithm.

Among the power generation technologies represented in ReEDS, there are two types of power plants that rely at least in part on biomass for fuel: dedicated biopower plants and coal plants that co-fire with biomass. Dedicated biopower plants are assumed to rely strictly on biomass feedstock for fuel. For biopower, ReEDS does not explicitly distinguish between direct combustion power plants and integrated gasification combined cycle plants. Instead, the cost and heat rate assumptions for new plants in a given year can be representative of a mix of plant types. ReEDS also includes the option to build new coal/biomass co-fired plants or to retrofit existing coal plants to co-fire biomass. In either case, a maximum of 15% of the electricity output is

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[4] ReEDS, developed by NREL’s Strategic Energy Analysis Center, is designed to analyze the critical energy issues in the electric sector, especially with respect to potential energy policies such as clean energy and renewable energy standards or carbon restrictions. More information on the model can be found at www.nrel.gov/analysis/reeds.

allowed to be derived from biomass fuel due to the boiler's engineering consideration. ReEDS does not include the option to completely "re-fuel" a coal plant or retrofit the pre-existing coal plant to fire 100% biomass fuel. Upon being retrofitted to co-fire biomass, a plant retains the same heat rate.

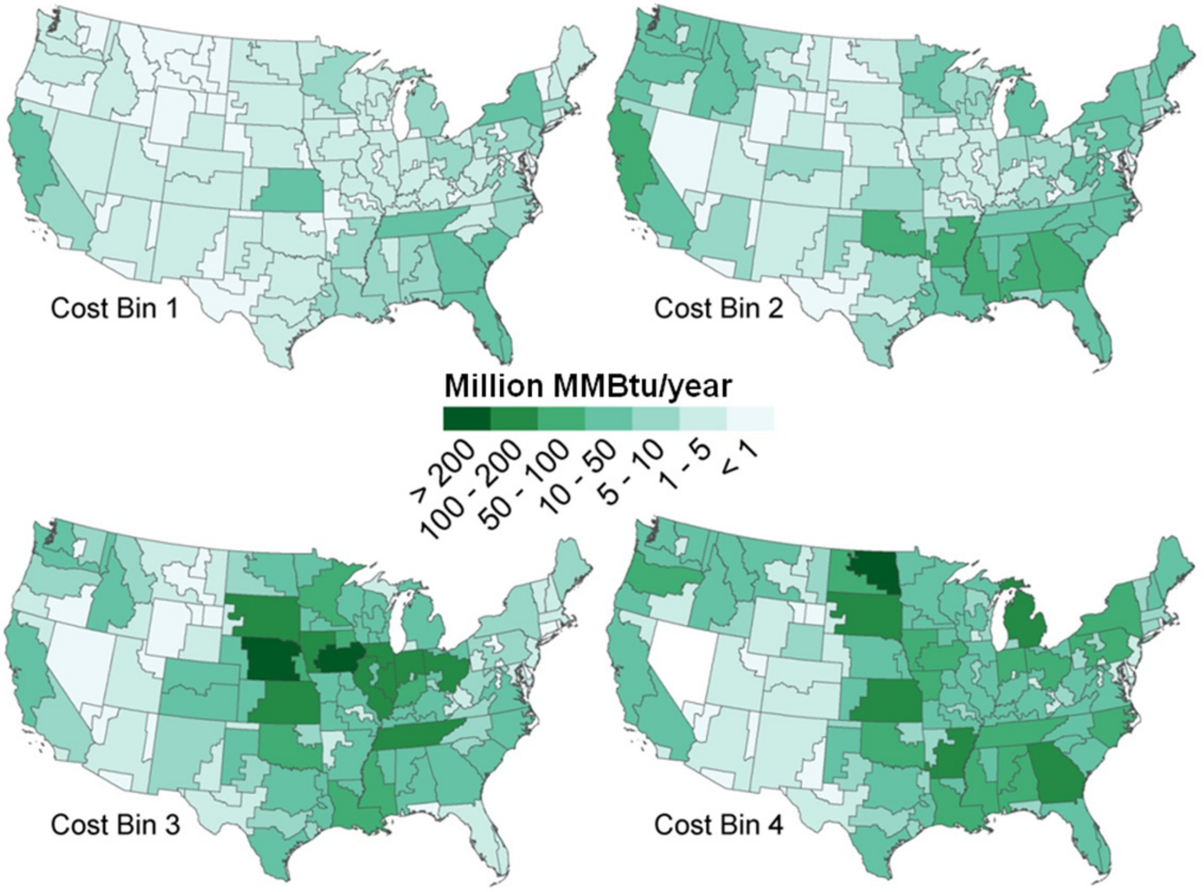

Figure 13. Biomass feedstock supply curve with default cost bins: $1.64/MMBtu, $2.46/MMBtu, $3.27/MMBtu, and $4.09/MMBtu

Figure 13 shows the annual supply curves for the biomass feedstock (Walsh et al. 2000) that has been disaggregated to the balancing area level (Milbrandt 2005). The available feedstock is divided into four cost bins with the following default prices: $1.64/MMBtu, $2.46/MMBtu, $3.27/MMBtu, and $4.09/MMBtu[5] ($26.24/ton, $39.36/ton, $52.32/ton, and $65.44/ton, assuming 16 MMBtu/ton). Though no price escalation is assumed by default, a user-defined annual price increase or decrease can be applied. The feedstock in the supply curve is comprised of urban and mill waste, forest and agriculture residues, and dedicated crops. Dedicated crops reside predominantly in the two most costly bins of the supply curve. ReEDS does not currently treat competition for biomass feedstock between the electricity sector and other sectors (e.g., transportation), although the user-defined reduction in feedstock resource could be used to represent such competition.

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[5] Unless otherwise noted, all dollars are in 2009 dollars.

4.2.2 Coupling Process

The goal of coupling the BSM and the ReEDS model is to take advantage of the unique capabilities of each model while also addressing a shortcoming in each model: biomass feedstock supply needs to be competed among multiple sectors. In the fuel and power sectors, the same feedstock supply can be used for either fuel or power, but not both simultaneously. To capture this competition, the following approach was used to couple the BSM and ReEDS model. As previously stated, the ReEDS model does not account for the fuel sector at all, and the BSM does not account for the power sector dynamically. These shortcomings allow one particular sector in each model, power or fuel, respectively, to dominate the market demand without allowing the feedstock producer and the end-use consumer to see the full marginal price of the competed biomass feedstock. The lack of competition is illustrated in Figure 14. If only one sector is represented, the equilibrium point (i.e., the intersection of the supply and demand curves) would be lower than the equilibrium point with competition.

To model the competition between the sectors there would ideally be continuous feedback between the models. However, ReEDS models time in discrete two-year steps, solving for equilibrium during each time period, whereas the BSM represents time continuously without the imposition of equilibrium assumptions, allowing for transients and other non-equilibrium effects. Nevertheless, the coupling process implemented as part of this study and outlined below takes a first step towards fully integrating the two models to communicate effectively in order to provide an improved alternative to the existing approach.

4.2.3 Approach

The approach to couple the BSM and ReEDS models is conceptually straightforward, though not without weaknesses. The BSM continuously generates a hypothetical biofuel demand curve and a hypothetical total biomass supply curve; though these curves change moment-to-moment in the simulation due to dynamic interactions among variables, snapshots are exported to data files for every USDA Farm Production Region and applicable year. The total biomass supply curves are developed by looking solely at the producers (e.g., growers) and conditionally positing different price points to find the level of biomass production that would occur at that price. A similar methodology is used to develop the biofuel demand curves, which are derived independently from the supply curve and are based on the prospective utilization of biofuels conversion plants given potential price points. Although the BSM's supply and demand formulations do not rely on supply or demand curves as input data, such curves can be derived from the BSM and passed along to ReEDS.

If the total biomass supply curve and the biofuel demand curve for a given moment in time and USDA Farm Production Region are extracted (Figure 14) from outputs of the BSM, then an effective net supply to power curve can be easily derived for the biomass supply available to the power sector (Figure 15). Calculated using a simple script external to the BSM, this net supply curve can then be input into ReEDS between the appropriate two-year optimization period (Figure 16). ReEDS can then run its optimization routine and output the marginal price for biomass feedstock. Given this input price as an initial starting point for the next period, the BSM arrives at the production and demand infrastructure that could potentially be built during the two-year period. The BSM then provides a new total biomass supply curve and a biofuel demand curve as outputs for that instance in time. The process repeats every two years until 2050.

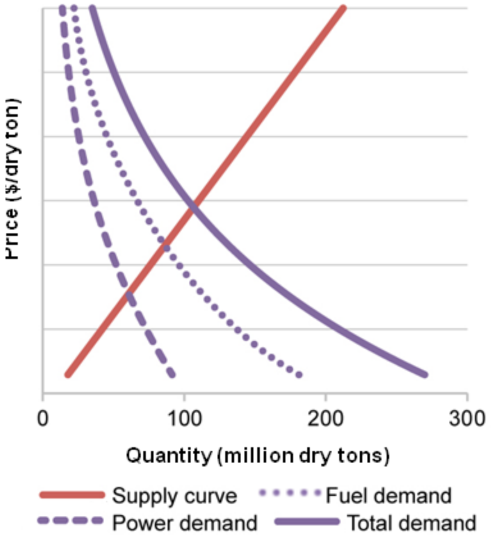

Figure 14. Representative supply and demand curves for biomass

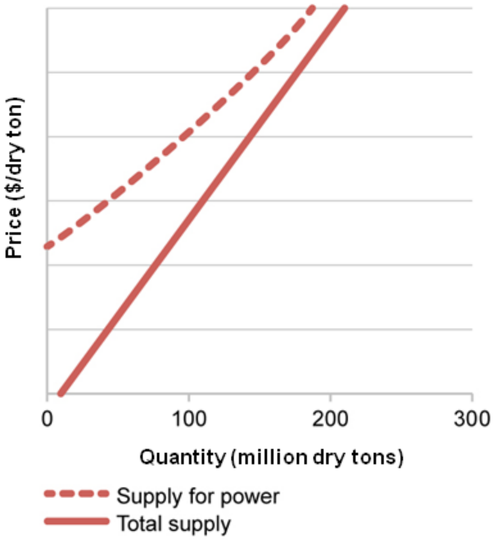

Figure 15. Representative supply to biopower curves for biomass

The approach developed in this study allows for some interaction between the fuel and power sectors, but it is not fully synchronized. To comprehensively model the competition, the routine requires a tighter, more frequent feedback than just every two-year time step; consistency between the two models during every time step should be achieved by iterating in ReEDS to correspond to the smaller delta time in the BSM in order to pass the supply and demand information between the models more frequently so as to near convergence. This interaction, however, would significantly increase the computational complexity of the coupling process and was not explored during this experiment.

The most significant drawback of the current scheme is the assumption of using the same prices and supply and demand curves for the entire two-year period: the BSM is faced with prices that are stepwise constant for each two-year period but then jump or drop suddenly between the two-year periods; similarly, ReEDS is faced with supply and demand curves that jump or drop every time step. The sudden changes in these quantities can introduce spurious transients into the dynamic model (the BSM) and hinder smooth growth of the biofuels or power industry.

4.2.4 Results

Three scenarios were designed and implemented to investigate the effects of coupling the ReEDS model and the BSM. This section presents the results; however, it is important to note that this was a proof-of-concept feasibility study, and as such, the methodology for these cases could be improved.

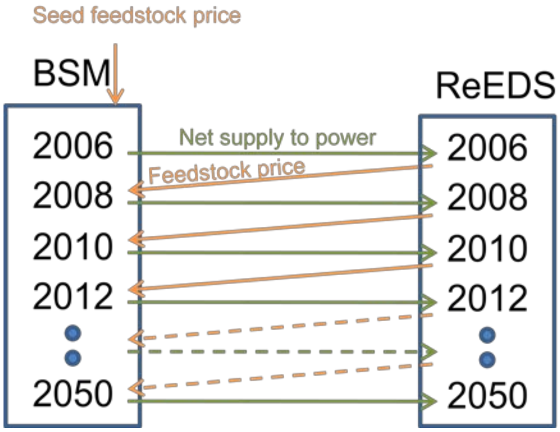

Figure 16. The coupling model between the BSM and ReEDS implemented in this program

4.2.4.1 Coupling Scenarios Considered in this Program

We selected three readily available scenarios to emphasize the interaction between the fuel and power sectors as it relates to biomass feedstock demand (shown in Table 5). They are exploratory scenarios adapted from existing scenarios within each of the models.

Table 5. BSM – ReEDS Coupling Scenarios Considered in this Program

Case	ReEDS	BSM
1 – Business as Usual (BAU)	BAU	BAU
2 – Renewable Portfolio Standard (RPS)	80% RPS*	BAU
3 – RPS No Coupling	80% RPS*	Static total supply curves

*80% RPS by 2050 with a linear path from 2010–2050.

The business-as-usual (BAU) scenario corresponds to a case where a national-level carbon-reduction policy is not enacted in either the power or fuel/transportation sectors. Existing state-level RPSs are included in the model but only lead to a small deployment of renewable or clean energy technologies. The RPS scenario corresponds to a national-level constraint on the amount of electricity that must come from renewable energy technologies. Both the BAU and RPS scenarios employ the model communication structure shown in Figure 16. The "RPS no coupling" scenario corresponds to a case where the total supply of biomass is available to the power sector; the fuel sector is ignored and assumed not to exist. The RPS no coupling scenario is similar to the default ReEDS model as it does not account for the biofuel demand when considering the biomass feedstock supply or price. To improve the consistency between the RPS and RPS no coupling scenarios, the supply curve used by the ReEDS model in the RPS no coupling scenario was developed in an independent BSM scenario.[6] It was then passed statically to ReEDS. This feed-forward structure is where "total supply" is calculated initially for all years by running a full simulation using the BSM and then it is passed to ReEDS, as depicted in Figure 17.

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[6] The 80% RPS case only applies to the power sector. Therefore, the assumptions regarding the fuel sector demand curves within the BSM are the same as the BAU scenario.

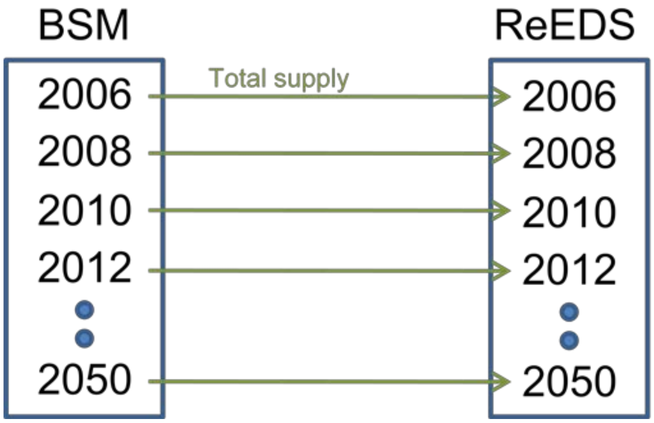

Figure 17. Depiction of the feed-forward approach for the “RPS no coupling” scenario

4.2.4.2 Power Sector Results

The amount of biomass consumed by the power sector is dependent on the policy enacted. Under the BAU scenario, biomass is primarily used in conjunction with coal to co-fire existing power plants to meet state RPS requirements or reduce sulfur dioxide emissions. It is only economical to co-fire in a few locations so the total amount of biomass used in this BAU scenario is minimal. Under the RPS scenario, however, biomass becomes more attractive as it receives the added benefit of counting towards the renewable generation required by the RPS. In these cases, dedicated biopower plants, as well as co-fired plants, become more common. The power capacity and generation growth under the different scenarios can be seen in Figure 18. To give some perspective, the generation from biopower is 0.13%, 5.66%, and 8.32% of the total electricity demand in 2050 for the BAU, RPS, and RPS no coupling scenarios, respectively. The results show that coupling the models effectively reduces the generation from biomass. This reduction stems from the competition between the fuel and power sectors, which drives up the marginal price of the biomass feedstock and should thus reduce the demand in each of the two sectors.

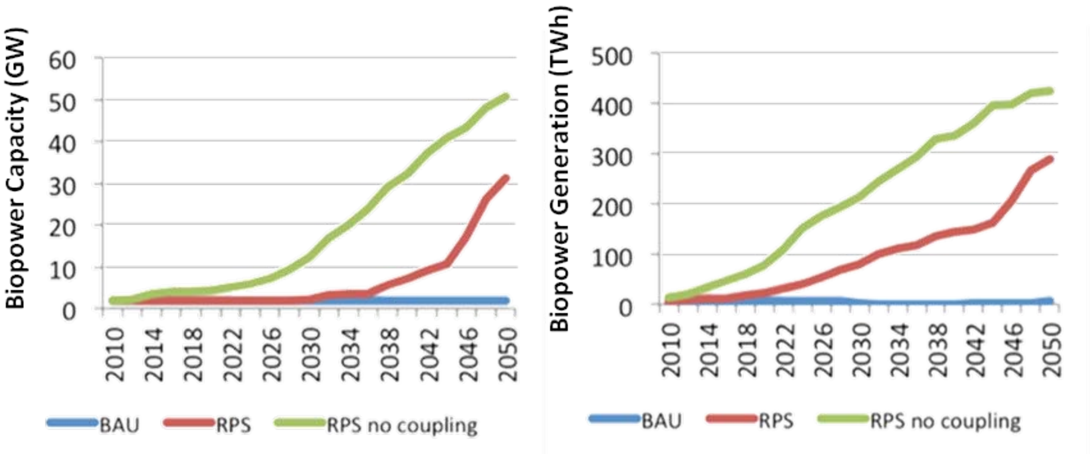

Figure 18. Biopower (dedicated and biomass portion of co-fired) capacity (left) and biopower generation (right) for the three scenarios

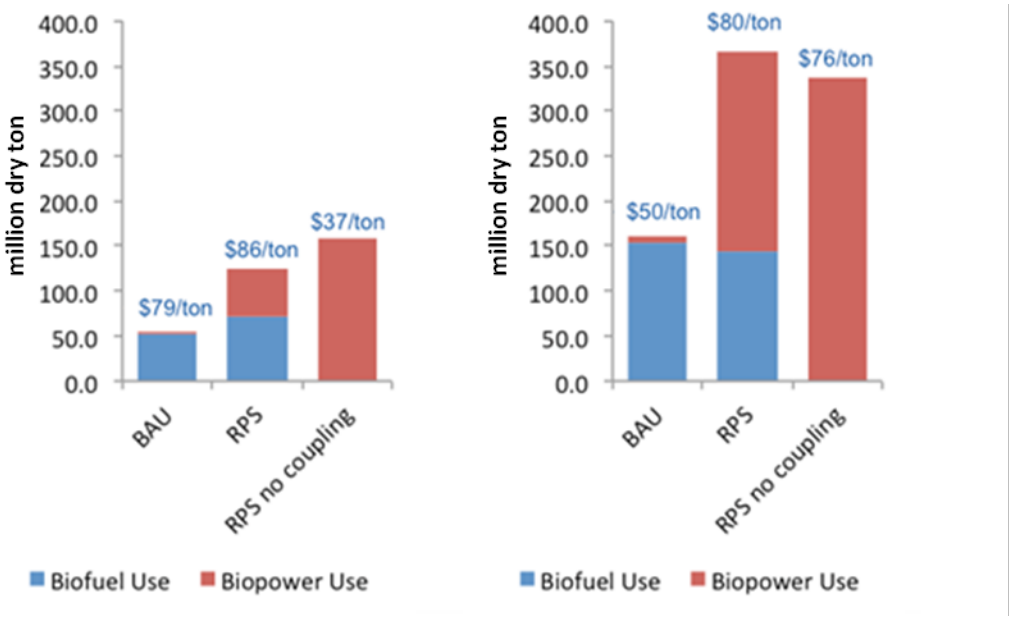

Figure 19. Biomass consumption for the fuel and power sectors in 2030 (left) and 2050 (right) for the three scenarios

Note: The demand-weighted marginal biomass feedstock approximate price is above the bar.

Under an RPS scenario, a significant amount of biomass feedstock, 200 million dry tons by 2050, is used in the power sector. The quantity in dry tons of biomass consumed in 2030 and 2050 by the fuel and power sectors is shown in Figure 19. The figure illustrates an interesting finding as well as insight into the purpose of coupling the two models. The fuel sector consumes almost the same amount of biomass in both the BAU and RPS scenarios. This result is reiterated in Figure 20 on the national and regional levels.

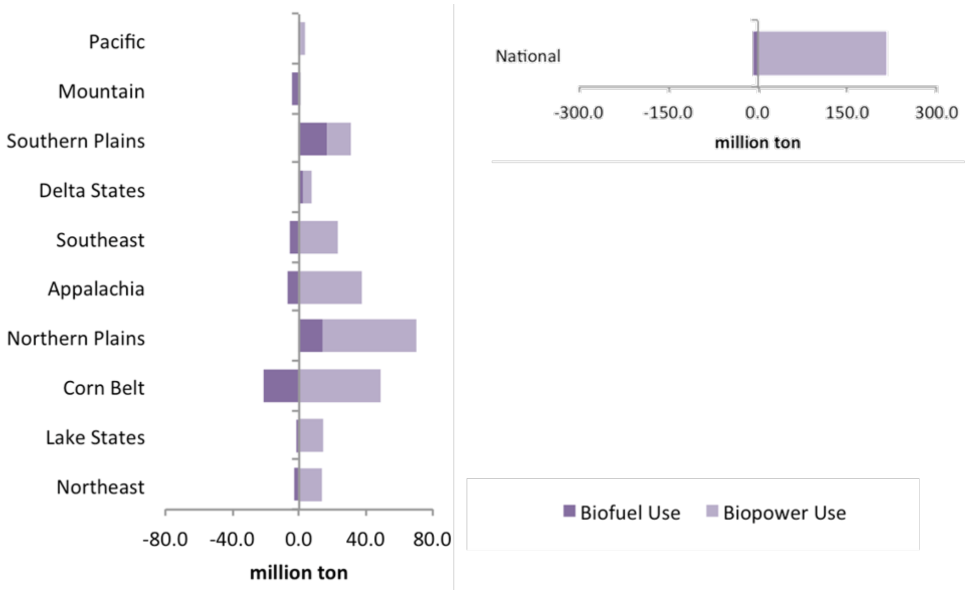

Figure 20. Change in biofuel consumption (RPS scenario minus BAU scenario) at the regional (left) and national (right) levels (2050)

Fuel usage is a function of both fuel sector demand and total biomass supply. On the demand side, the RPS scenario shows that the fuel sector is relatively inelastic to biomass feedstock prices below about $100/dry ton. This price should not be seen as a magic number; rather, the inelasticity could be an artifact of how the biofuel demand curves are developed within the BSM (discussed in Section 4.2.5).

The other factor affecting fuel usage is the total biomass supply. The RPS scenario only implements a power sector policy, which leads to more demand for biomass in the power sector. This increase in demand from the power sector drives up the marginal price of biomass, which spurs investment on the supply side.[7] The growth in investment on the supply side increases the total supply available to both the power and fuel sectors. Increased supply allows the fuel sector to demand more biomass at a cheaper price (see Figure 21). In other words, the investment on the supply side shifts the biomass supply curve so that more feedstock is available in a lower price bin. The additional lower-cost supply is available to both the power and fuel sectors. The net effect of the increased demand in the power sector is that the biofuel sector can get feedstock for the same price. This result is slightly counter-intuitive because competition typically leads to a decline in demand for both sectors, which are competing for the same supply. This intuition, however, does not account for the fact that the supply side sees greater demand and higher price as incentive to build more infrastructure to increase profits.

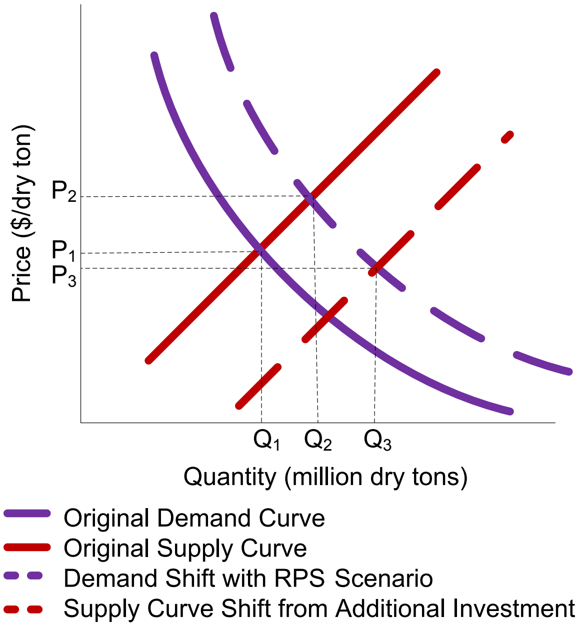

Figure 21. Biomass feedstock demand and supply shifts in the RPS scenario

By coupling the models, the competition between the fuel and power sectors could be explored. Although the methodology was not without its shortcomings, coupling the two models produced

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[7] The agricultural residue and energy crop biomass supply curves are determined endogenously in the BSM through the dynamics of farmers' decision making, land allocations, crop markets, and farmers' transitions to new agricultural practices. However, forest and urban residue curves are determined exogenously through the POLYSYS model and fed as inputs into the BSM. Higher feedstock prices signal the farmers to change their planting behavior while more forest and urban residues can be provided at higher prices. For more discussion on how the BSM determines feedstock supply see Newes et al. 2011.

useful insights. The preliminary results show that the RPS could cause an increase in demand in the power sector, but the feedback between consumers and suppliers also allows the total feedstock supply to increase through time due to the coupling. The BSM also indicates that the fuel sector is potentially inelastic in the price regime below about $100/dry ton. These two factors, more supply and inelastic demand, allow the fuel sector to demand a similar amount of biomass in both the RPS and BAU scenarios. Without the coupling, the power sector would have consumed more biomass for a lower price that would not have been reflective of the competition between the power and fuel sectors.

4.2.5 Possible Next Steps/Opportunities

This effort represents the first coupling between the BSM and ReEDS models. The approach used to couple the models should be considered as only a proof-of-concept design intended to demonstrate feasibility of the process and to show the relevance of the results; it is not without shortcomings. With appropriate time and support, refinements to the model could remedy some of the existing issues, discussed below, in order to perform a wider range of analysis with greater confidence. Even so, the new capabilities from this approach could be applied to analyses that could not be performed with either model alone. For example, it is now possible to combine an RPS analysis for the power sector with an RFS analysis for the fuel sector. Since this exercise was a proof-of-concept analysis, only a few, readily available scenarios were examined. Specifically formulated scenarios for particular questions of interest can be developed and utilized for future analyses, providing more confident and meaningful results.

One refinement would be to address the regional difference between the BSM and the ReEDS models. The BSM uses 10 USDA regions to model the supply and demand of feedstock, whereas ReEDS builds capacity at 134 balancing areas. As a result, a single USDA region encompasses multiple balancing areas in the current coupling methodology. This mismatch between USDA regions and balancing areas allows ReEDS to build biopower capacity near the load but use biomass feedstock from anywhere within the co-located, and much larger, USDA region. This issue could be remedied by creating a disaggregation algorithm to divide the supply available at the 10 USDA regions into the 134 balance area regions in ReEDS.

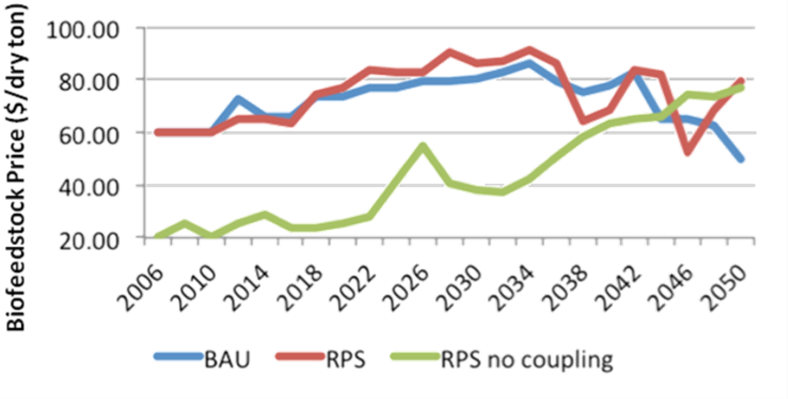

Figure 22. The national average biomass feedstock price for the three scenarios

Another issue concerns the structure of the feedback between the BSM and ReEDS models. While feedback exists between the two models, it does not occur within the same time period (as shown in Figure 16). As a result, equilibrium between total demand and total supply in ReEDS is reached over multiple periods (rather than within a single period), leading to instability of the system. This issue becomes apparent in the oscillations that occur in the national average feedstock price (Figure 22). These oscillations occur because the feedback from the power sector demand during one time period spurs investment on the biomass supply side during the next time period. But this investment in supply overshoots the demand, leading to oscillations in the national feedstock price over time. The oscillations are to be expected as the models approach convergence; however, they would ideally occur within the same optimization time period in ReEDS and as such would neither influence future periods nor be observable to the user. The magnitude of the oscillations is influenced by the size of the discrete biofuel supply bins, which are an inherent characteristic of the linear programming optimization technique.

The stability of the system could be improved by introducing intra-period feedback between the BSM and ReEDS model such that the models are more closely linked during each time period, as shown in Figure 23. Smaller quantization steps in the supply bins would also be helpful. The trade-off for these improvements in stability is computation time, as the ReEDS optimization and interaction with the BSM would now need to occur multiple times during each time period.

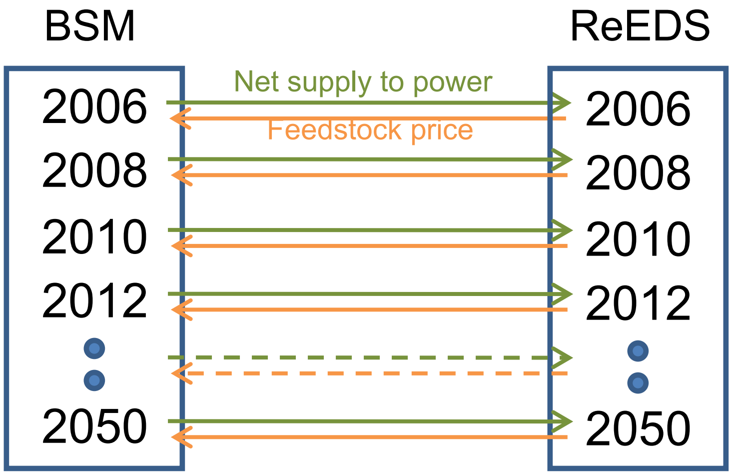

Figure 23. An improved feedback approach for coupling the BSM and ReEDS model

Additionally, the formulation of the demand and supply curves within the BSM needs some refinement. The BSM develops a supply and demand curve for a single point in time with the infrastructure in place at that point in time. This leads to interesting behavior near the head and tail of the supply and demand curves and leads to the relative inelasticity of the demand in the price regimes below $100/dry ton. In contrast, ReEDS is a long-term expansion planning model, which would ideally utilize longer-term supply curves. There is no obvious solution to this issue, although it might be possible to modify the structure of the BSM to provide a more compatible supply curve. Once this is further investigated, the BSM will have the capability to generate a library of supply and demand curves for a wide range of scenarios. This library could then be made available to other interested parties in the biomass allocation modeling community.

5 Conclusions

Our analyses show that the two main competitors for biomass resources continue to be biopower and biofuels, though the existence and character of federal and state regulations is critical to their future prospects. The other end uses, including traditional use, exports, and bio-based products, do not currently demand a large portion of the biomass market and are not projected to drastically increase their market shares. In particular, existing thermal energy production from biomass in the United States relies heavily on waste products, and biomass demand from heating is relatively small and unlikely to increase greatly. However, the demand for wood pellet-based heating in Europe is growing so it is possible that the exports of biomass-based products for heating will command a higher share of the domestic biomass market. Although some scenarios indicate that bio-based products, such as bio-plastics or bio-acrylics, could demand a large fraction of the overall biomass resource in the future, those scenarios depend on assumptions of substantial technological breakthroughs and are highly uncertain at this point; scenarios that include market and technical barriers suggest only minor demand for biomass resources from these products.

Our comparison of the existing models that include biomass allocation highlights that most of them are using static or semi-static supply curves that are typically derived from various versions of POLYSYS. The publication of the *U.S. Billion-Ton Update* (U.S. Department of Energy 2011) provides an opportunity for the modeling community to standardize the set of supply-curve inputs used for biomass allocation modeling. Overall, we find that none of the models treat the competition for biomass resources in a dynamic manner. We have demonstrated the feasibility of using either a pure system dynamics model (the biomass competition model discussed in Section 4.1) or a hybrid system dynamics and linear programming model (the BSM-ReEDS model discussed in Section 4.2) to generate dynamically varying supply curves—a new capability added to the BSM as a direct result of this coupling exploration—that are fully responsive to the scenario under consideration. Such coupled models allow the joint exploration of RPS and RFS scenarios in a self-consistent manner. Initial indications are that competition for biomass among different end-use sectors often spurs more rapid addition of biomass-production capacity, compared to the case where biomass demand comes from a single sector. We also see a tendency for biofuels to dominate biomass supply unless aggressive RPS policies are in place.

This report presents a foundation on which to build a more complete understanding of the competition for biomass resources. Based upon the review, model development, and exploration of model coupling, we are now in a position to explore the interaction of RFS and RPS policies and their effect on biomass supplies. We have taken initial steps towards methods that will allow the BSM to account for the competing uses of biomass.

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Appendix A: Models that Include Biomass Allocation Logic

There are a number of existing models that account for end-use competition of biomass resources. The following section focuses on their respective methodologies and not on the different scenarios that they have simulated or the results generated.

Biomass Allocation Model

The BAM is a linear optimization model for the allocation of biomass between co-firing at existing coal-fired power plants and cellulosic ethanol conversion facilities in the United States at the state level. The model was developed using the solver in Excel by William Morrow during his post-doc research at the National Energy Technology Laboratory (Morrow 2008). Biomass supply curves are provided by POLYSYS. The linear program maximizes total revenue from all co-firing plants and ethanol production facilities subject to the following five constraints:

- Limit total ethanol production to the total rated capacity of the facilities
- Limit total ethanol production within a state to its total gasoline consumption
- Limit the building of corn ethanol facilities by a capacity growth constraint
- Limit the total allocation of biomass to co-firing and ethanol production within a state to the state's ability to grow biomass
- Limit the co-firing rate of a power plant to 20%.

The model estimates both capacity utilization at existing plants, based on the short-term marginal cost of ethanol production without capital costs or tax credits, and capacity expansion to build additional plants, using a long-term marginal cost. The production cost declines with economies of scale, and cellulosic ethanol plant operating costs are assumed to decline over time once the first plant is built.

Biomass Allocation and Supply Equilibrium Model

The BASE model was developed by the National Renewable Energy Laboratory (NREL) as part of the Transportation Energy Futures project for the DOE (Ruth et al.). It finds an equilibrium state of the U.S. transportation and electricity sectors and the corresponding consumption and price of biomass feedstocks. By focusing on mature biomass markets, it identifies how biomass resources are projected to be most economically used in the long term and the resultant implications for GHG emissions and petroleum use. The model does not show transitions to future scenarios or the incremental changes to fuel and power markets. Likewise, it is not intended to simulate near-term markets because they are far from equilibrium due to technological immaturity, growth rate, the number of investors, and lack of resource limitations.

The biomass feedstocks represented in the BASE model include forest residues, short rotation woody crops (SRWC), agriculture residues, switchgrass, corn, soybean, and algae. These feedstocks can be converted to biofuels or electricity. Separate end-use markets are treated in the BASE model, namely the electricity, gasoline, diesel, jet fuel, and bunker fuel markets. For biofuels, the BASE model distinguishes between a variety of feedstock/fuel combinations. Fuels include ethanol, butanol, and pyrolysis gasoline that are competed in the gasoline market and pyrolysis diesel, Fisher-Tropsch diesel, and biodiesel that are competed in the diesel, jet fuel, and bunker fuel markets.

The market equilibrium state is found iteratively and relies on detailed input data of full life cycle costs. Market shares for biomass and its allocation among the different fuels and markets are determined based on levelized costs of energy (fuel or electricity), which account for many of the costs and losses that occur between the farm or field to the end user. These costs include feedstock costs, biomass transport and logistics costs, conversion costs, fuel transport costs, and any assumed cost associated with GHG emissions. The BASE model uses an iterative calculation and a set of logit functions to determine the quantities of biofuel and power that are generated and thus how much biomass is used. The demand for each end-use market is exogenously defined. Logit functions are used to estimate the share of each fuel in each market based on initial estimates of fuel price. Fuel prices are then calculated based on quantities of biomass used, harvesting, conversion, fuel transport, and carbon costs (if desired). If the calculated fuel prices do not match those estimated by the logit function, initial estimates are adjusted and the process is repeated until the estimated and calculated prices match. By sharing the same resource and supply curve across multiple fuels and markets, the BASE model is able to account for coupling dynamics of supply and demand.

These calculated market shares and the associated demands for the biomass feedstocks and other fuels are outcomes of the model. In addition, BASE finds the equilibrium price for the biomass feedstocks (forest residue, SRWC, agriculture residue, and switchgrass) and competing energy sources (natural gas and coal) represented with supply curves. The resultant GHG emissions are broken down by each category in BASE, including by competing technologies and by the separate biomass pathways, independently. Petroleum use in each market scenario is calculated in a post-processing step.

Global Change Assessment Model

The Global Change Assessment Model (GCAM), developed by the Pacific Northwest National Laboratory and the University of Maryland through the Joint Global Change Research Institute, is a partial-equilibrium model of the global industrial and energy system, including agriculture and land use (Clarke and Luckow 2010). GCAM solves for the equilibrium prices in 14 main global regions and runs from 1990 to 2095 in 15-year time steps. Population and gross domestic product are inputs to the model and exogenously specified for each region. Competition among energy sources is simulated using the market share, based on the probability that a certain energy source and technology has the least cost for a given application. GCAM integrates agriculture with land use in a single module. Feedstocks include MSW, agricultural and forest residues, and dedicated bioenergy crops. In GCAM, energy crops (e.g., switchgrass and willow) compete with biomass from waste (usually cheaper) to meet bioenergy demand. Biomass from waste supplies almost all the present regional biomass demand; energy crops usually dominate the feedstock supply portfolio for additional end-use demand (once waste supplies are exhausted) in scenarios with high prices for fossil fuel and carbon. Dedicated energy crops must compete with other uses of land among 15 land uses: pasture, corn, wheat, sugar crops, grain crops, oil crops, miscellaneous crops, fodder crops, fiber crops, bioenergy crops, rice, forests, unmanaged forests, unmanaged land, and non-arable land. End users of biomass include electricity production, biofuels, hydrogen, and direct use (such as space heating of buildings and industry). GCAM adds feedstock transportation costs of \$0.31/gigajoule for all biomass produced.

The amount of each fuel[8] allocated to meet end-use energy demand is based on their prices and elasticities using a logit market share equation. The variance on fuel prices due to factors such as transportation costs and taxes is captured in an energy price exponent. Market share for each of the fuels by end-use energy is computed by the following equation:

$$\mathrm{Share}_j = \frac{b_j \cdot P_{fuelj}^{rp}}{\sum_j b_j \cdot P_{fuelj}^{rp}} \qquad [A\text{-}1]$$

where

P_{fuelj} = the cost of the fuel *j*

r_p = the price exponent that determines the variance of the price distribution

b_j = the base share.

Global Trade Analysis Project Model

The Global Trade Analysis Project (GTAP) is a global computational general equilibrium model that can be used to analyze bioenergy growth and its impacts on the economy (Birur et al 2008). As a general equilibrium model, GTAP solves for the equilibrium of all markets regarding supply and demand in an international setting with bilateral trading allowed. Different versions of the model are built to analyze different questions.

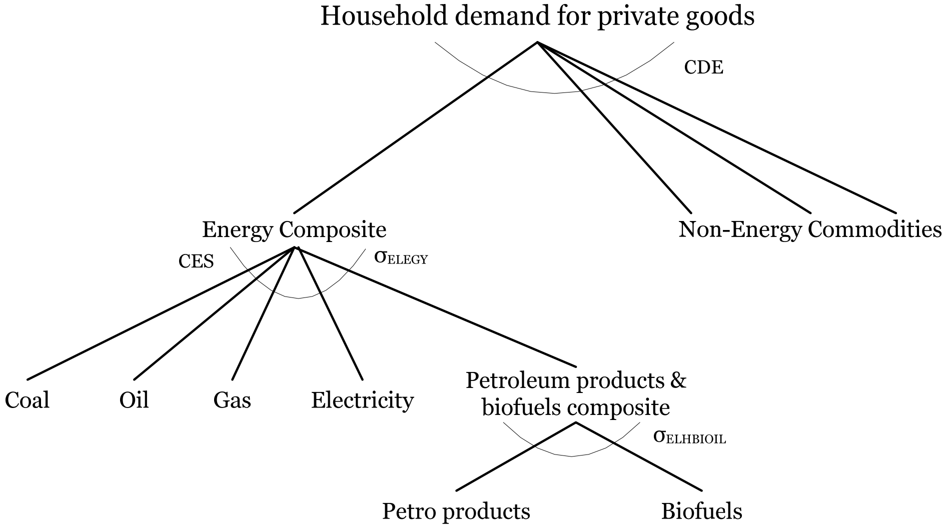

Figure A-1. Structure of consumption side of the GTAP-BIO Model

CDE = constant-difference of elasticities, functional form; CES = constant elasticity of substitution; σ_{ELEGY} = elasticity of substitution among energy commodities and the petroleum-biofuel composite; $\sigma_{ELHBIOIL}$ = elasticity of substitution in the petroleum-biofuel composite.

Source: Birur 2008

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[8] The word "fuel" can denote raw fuel to refined fuel to fuels to be consumed by end users. The logit is repeated for each stage of the fuel transformation.

When the model is modified to analyze biofuels, sugarcane-based ethanol, grain-based ethanol and biodiesel from vegetable oil are considered. Biofuel byproducts are included explicitly in order to include their contribution to revenues. In addition, the electricity sector can include bioelectricity and co-firing of coal-fired power plants. GTAP uses simultaneous equations in a three-tier nested constant elasticity of substitution function (see Figure A-1) to determine the relative activity level of each biofuel. Since the model uses a zero-profit assumption, the demand for biofuels depends on the price of feedstock compared to fossil fuel energy prices.

Market Allocation Model

The Market Allocation Model (MARKAL) is a dynamic bottom-up optimization model that aims at choosing the optimal mixture of technologies and fuels in order to minimize the net present value of the system-wide cost. Some constraints include current and projected technology costs and efficiencies, resource supply costs and competition for fuel across sectors, resource supply constraints, trade costs and constraints, emission limits, and other policies. The 10 biomass feedstocks considered in MARKAL are corn grain, corn stover, agricultural residues, energy crops, forest residues, primary mill residues, urban wood waste, MSW, soybean oil, and waste oil.

Conversion technologies include two pathways: liquid fuels and heat and power. Liquid fuels include ethanol (dry mill, wet mill, and cellulosic), biodiesel (fatty acid methyl ester), and thermochemical (pyrolysis to bio-oil and gasification to syngas). Heat and power includes power generation (biomass gasifcation, coal/biomass co-firing, biomass direct combustion, landfill gas combustion, and waste-to-energy), industrial heat and power (pulp and paper and other industrial heat/steam), and residential heating (wood stoves and outdoor wood boilers).

MARKAL outputs feedstock quantity used by type across the simulation time horizon and utilization by sector of the economy. The model also outputs the feedstock use by region.

National Energy Modeling System

The NEMS, developed by the Energy Information Administration, is a model of the U.S. energy system that aims to reach equilibrium between supply and demand (EIA 2009b). It models all energy sectors of the economy, including the electricity, industrial, residential, commercial, and transportation sectors. It divides the nation into 13 North American Electric Reliability Corporation (NERC) regions. The biomass supply curves for each feedstock and every year at the state level are aggregated at the NERC region level. These curves are obtained from the Oak Ridge National Laboratory, along with the Antares Group and the USDA (Haq 2002). The supply curves take into account agricultural and forestry residues, energy crops, urban wood waste, and mill residues. Forest products consist of salvageable dead wood, logging residues, and excess polewood. The supply curve reflects the delivered price, which includes transportation costs. Figure A-2 shows the supply curve for 2020 for the different feedstock types.

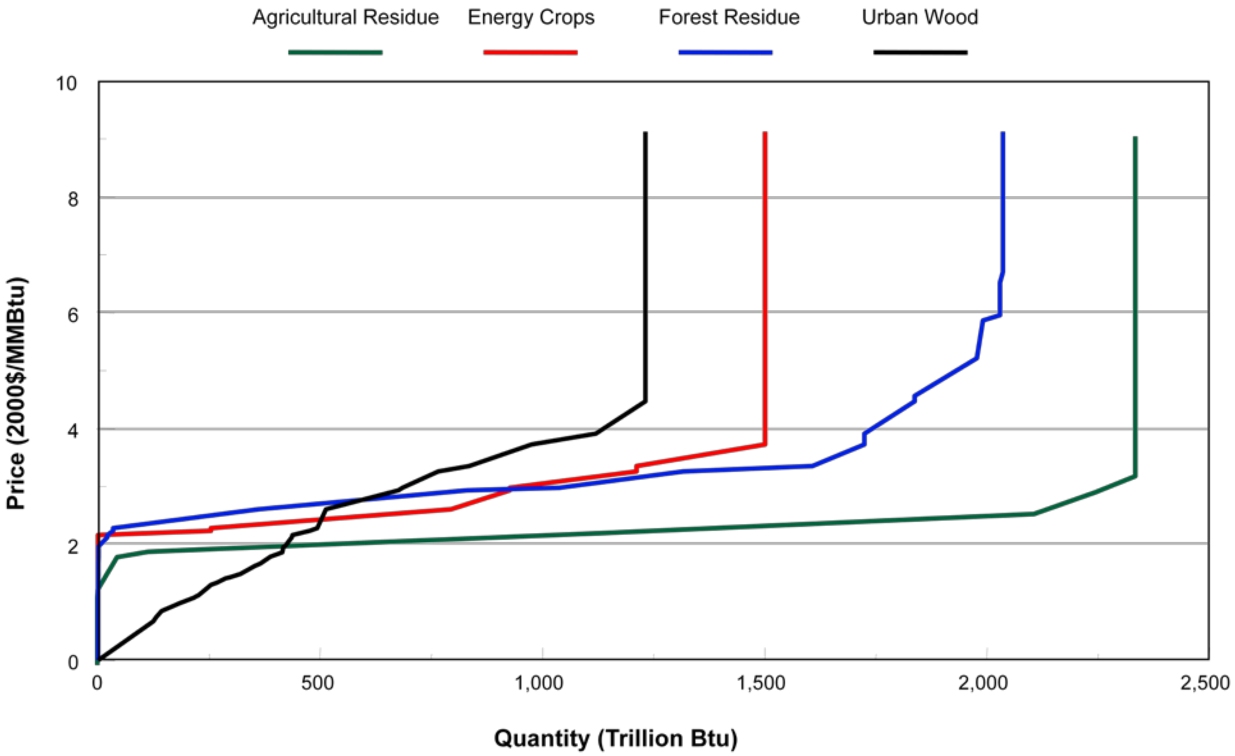

Figure A-2. NEMS 2020 supply curves

Source: Haq 2002

In NEMS, biomass has the following end uses: industrial cogeneration, dedicated biomass, biomass co-firing, cellulosic ethanol, corn ethanol, residential use, and commercial use. The different uses are solved iteratively to reach equilibrium between supply and demand for biomass across sectors. Biomass co-firing is represented in NEMS by assuming that coal-fired capacity can be retrofitted for biomass co-firing up to 5%, without additional capital, operation, or maintenance costs. For modeling purposes, it is assumed that the biomass is comingled with coal, and the mixture is fed into the boiler through the existing coal feed system. Therefore, it is assumed that no new capital expenditure is required.

RESolve Model

The RESolve model was developed by the Energy Research Centre of the Netherlands (ECN) to address the issue of market competition for biomass resources in the European Union in order to meet policy targets (Stralen 2010). It takes into account 30 European countries, allowing international imports of ethanol from Brazil and palm oil from Malaysia. The RESolve model is divided into three models for the different sectors: RESolve-T for the transportation sector, RESolve-E for the electricity sector, and RESolve-H for the heat sector. Each model has a sector-specific demand. The model allocates the biomass among the three sectors in a way that will minimize cost. The biofuel demand is calculated based on biofuel targets, while the bioelectricity and bioheat demands are calculated using renewable energy sources policies and technology costs. The allocation is done within RESolve-T, and the results are fed into RESolve-E and RESolve-H as demand data. This iterates until cost allocations, demand, and potential supplies converge.

In RESolve-E, the following feedstocks are considered: energy crops, forestry, manure, agricultural residues, municipal and industrial waste, sewage sludge, and landfill gas. Several technologies are involved besides biopower, such as wind, hydro, solar photovoltaics, and geothermal. The competition across sectors only occurs for energy crops, forestry residues, liquid manure, and agricultural residues. MSW, industrial solid waste, sewage sludge, landfill, and solid manure are feedstocks used by the power sector only, so their contribution is subtracted from the bioelectricity demand. Biomass technologies considered in RESolve-H are combustion, CHP, digestion, and gasification; technologies that compete with biomass are geothermal, solar thermal, and ambient heat.

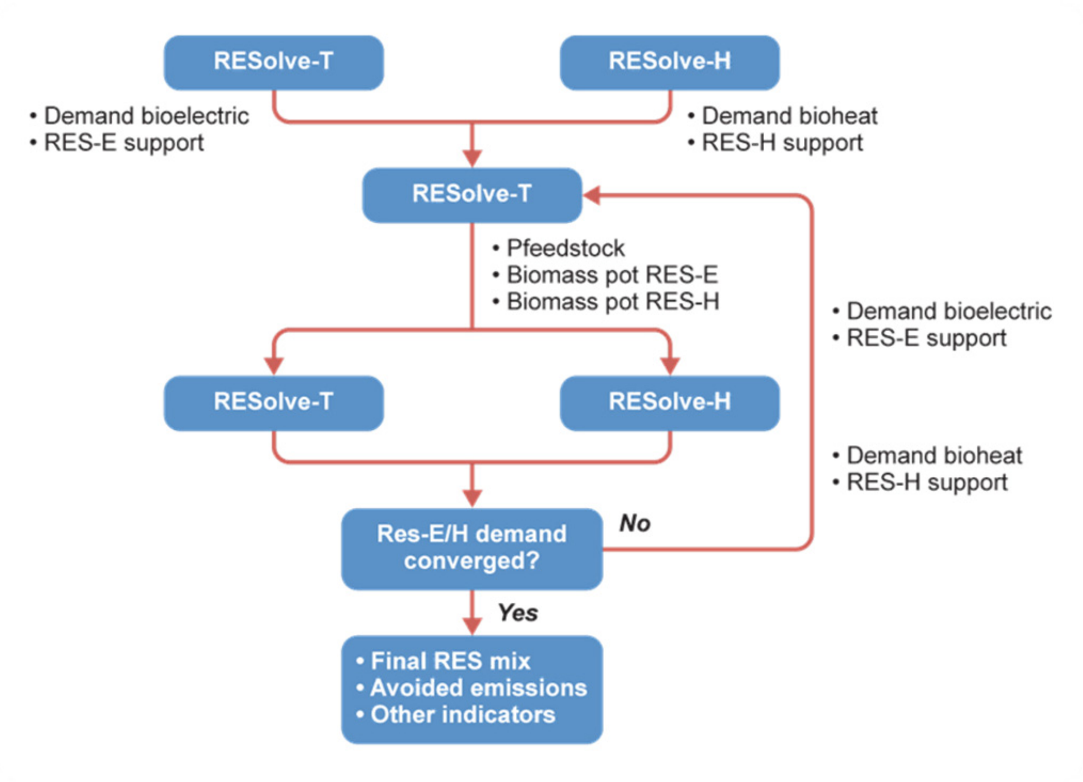

Figure A-3. Biomass allocation: Interaction among the sub-modules

RESolve-T calculates the most cost-effective way to meet the specified biofuel demand given projections of demand, feedstock, conversion, and technological progress and limits on GHG emissions. The transportation module allows international trade of feedstocks and final energy products. The model includes 10 feedstocks (grassy, oil, starch, sugar, woody crops, wood residues, agricultural residues, used fats, used oils, and pre-treated biomass) and 7 biofuels (bioethanol 1st and 2nd generations, biodiesel, bio-Fischer-Tropsch diesel, bio-dimethylether, synthetic natural gas from biomass, and bio-ethyl tertiary-butyl ether).

As mentioned earlier, biomass allocation between the three sectors is done in RESolve-T such that the demand for biofuels, bioheat, and bioelectricity are supplied in the most cost-effective manner. The iterative process happens among the three modules in the following way: The initial bioelectricity demand is calculated in RESolve-E using economic and technological parameters, financial incentives, policies in place, and comparison with costs and potentials of competing technologies. The initial bioheat demand is calculated in RESolve-H based on economic and technological parameters, fuel prices, policies, consumer behavior, and comparison with costs and potentials of competing thermal energy technologies. The bioelectricity and bioheat demands are input into RESolve-T in addition to the biofuels demand assumed within RESolve-T. RESolve-T calculates the feedstock prices per country, technology, and year. The resulting feedstock price and available potential are fed back to RESolve-E and RESolve-H so that a new demand for those sectors is calculated. The iteration process occurs until equilibrium is reached in biomass demand, potential, and price in the three models (see Figure A-3).

SimBioSys

SimBioSys is a model of the Austrian bioenergy sector developed by Gerald Kalt in defense of his Ph.D. thesis at the Institut fur Energiesysteme und Elektrische Antriebe (Kalt 2011). SimBioSys is used to determine how to optimally make use of the biomass resources available. Only the bioenergy sector is simulated in SimBioSys; energy demand not supplied using bioenergy technologies is satisfied by a fossil-fuel-based reference system. Other renewable energy sources are not explicitly modeled so competition between bioenergy and other renewable energy technologies is not considered. The model, developed using the MATLAB (MathWorks Inc. 2010) simulation environment, is based on continuous supply curves for the biomass resources. Financial incentives, such as investment subsidies, premiums, quotas, and feed-in tariffs, are taken into account in the model. The deployment of bioenergy can be done using a cost-based or a demand-based algorithm, depending on the scenario.

Bioenergy supply curves are derived from biomass supply curves, assuming that a single technology is consuming all available supply. In the cost-based approach, the goal is to find the economic potential of a given biofuel-producing technology, ignoring the demand for fuels. The allocation is done by finding the equilibrium between the energy generation cost of a certain bioenergy technology and the cost of the respective reference technology and determining the biomass demand at that point (see Figure A-4) on the supply curve. Reference technologies for biofuels (technology 1) are diesel and gasoline and for biomass-derived substitute/synthetic gas and bio-methane (technology 2) is natural gas. Figure A-5 shows the resource competition. In the first interval from $q_{B,T}$ to $q_{E,T}$, technologies 1 and 2 both compete for the feedstock. In this interval the allocation is given in

$$q_{j,T}^{add,I} = q_{T}^{add,I} \frac{a_j}{\sum_j a_j} \qquad \text{[A-2]}$$

where

a_j = a profitability index

$q_{T}^{add,I}$ = quantity of feedstock in the interval considered.

The quantity of feedstock in the second interval is fully allocated to technology 2, as the cost of the energy for technology 1 at the end of the second period is greater than the cost of the reference technology 1, as seen in Figure A-5.

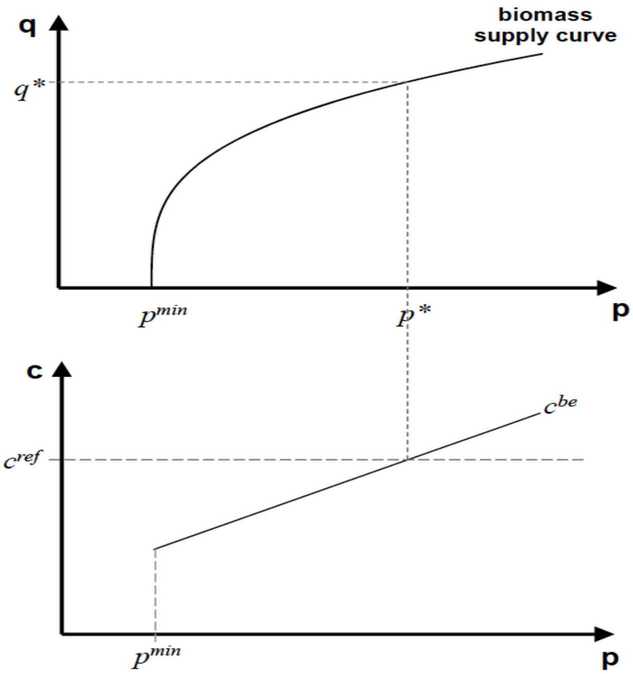

Figure A-4. Determining the economical potential of bioenergy based on a biomass supply curve

Source: Kalt 2011

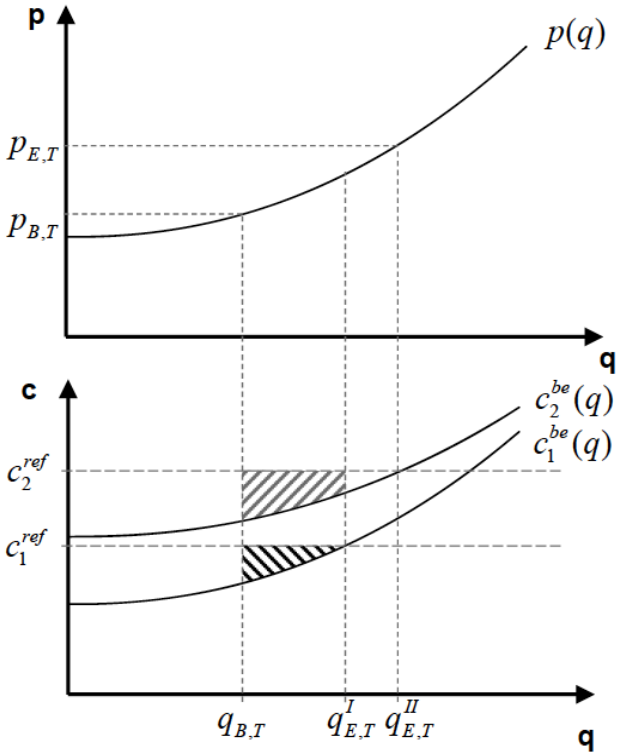

Figure A-5. Resource competition

Source: Kalt 2011

The demand-based approach determines the optimal deployment to meet a certain demand. This approach is used when scenarios involving quotas are being simulated. The linear program minimizes total generation cost while meeting some constraints: total energy demand must be equal to or greater than the given demand, new capacity is only built if it is equal to or greater than minimum plant capacity (leaving some unmet supply until that capacity is reached), total demand for each fuel may not exceed maximum supply potential, and prices of the feedstock are determined by the total demand for that feedstock and by the supply curve.

SimBioSys only models the bioenergy sector. Therefore, energy demand not supplied by bioenergy is assumed to be supplied with the fossil fuel reference technologies. Competition between bioenergy and other renewable sources is not modeled.

Stochastic Energy Deployment System

The Stochastic Energy Deployment System (SEDS) is a stochastic, or non-deterministic, capacity expansion model of the U.S. energy markets (Henrion et al. 2010). Developed by NREL, SEDS simulates how the national markets build and deploy new technologies depending on their costs, performance, and GHG emissions constraints. In SEDS, biomass resource is represented by supply curves generated by POLYSYS. The supply curves (shown in Figure A-6) represent the biomass feedstock price (in $/MMbtu) as a function of demand (in trillion Btu) for each year of the simulation horizon. Because SEDS treats the United States as a single region, variations in biomass costs, production costs, and biofuel demand are ignored. In SEDS, biomass resources are used in biofuels (cellulosic ethanol), electricity, and hydrogen. The competition for end use is done on a first-come, first-served basis so that all existing facilities consume available biomass before the construction of new facilities is considered. This simplifying assumption results in a strong first-mover advantage and dampens opportunities for new technologies to compete with the installed base.

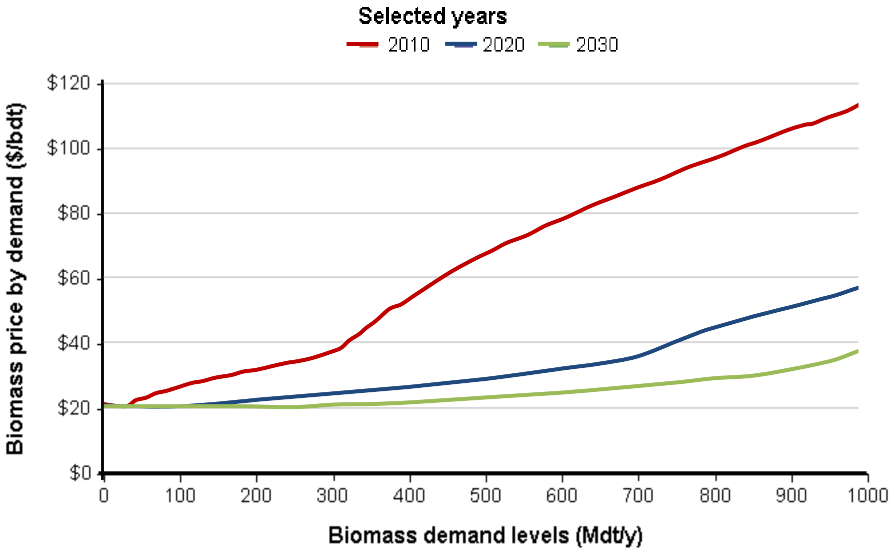

Figure A-6. SEDS annual supply curves

Targets-Image Energy Regional Model

The Targets-Image Energy Regional Model (TIMER) is the energy sub-model of the Integrated Model to Assess the Global Environment (IMAGE), an integrated assessment model developed by the Netherlands Environmental Assessment Agency that analyzes global climate change (Solberg et al. 2007). IMAGE represents economic and demographic developments, the energy industry (TIMER), the terrestrial environmental system, and the atmospheric-ocean system.

The energy demands for fuels and electricity are determined by fuel type (solid fuels, heavy liquid fuels, light liquid fuels, gaseous fuels, traditional biomass, modern biomass, electricity, and secondary heat) from prices and preferences. In TIMER, the energy demands are determined by a recursive optimization function that informs investment decisions on an annual basis using production costs in combination with premium factors such as preferences, environmental policies, and strategic considerations.

The production of bioenergy takes into account the demand for both modern and traditional biofuels. Modern biofuels consumption is modeled considering the biomass use for solid fuels, electricity, and liquid biofuels. The amount of biomass that is used for electricity versus biofuels is calculated by comparing production costs and takes into account fossil fuel depletion dynamics. The percentage of the market that is comprised by traditional biomass is determined as a function of per capita income.

Appendix B: System Dynamics Electricity Sector Models

When exploring the option of joining the BSM with an external system dynamics model, various electricity sector models using system dynamics were identified. While there are numerous other electricity sector models, many of them do not use the system dynamics framework and thus would be difficult to link with the BSM. The Washington State University Western Electricity Model, The Feedback Rich Energy Economy (FREE) Model, and the ENERGY 2020 model are three of the top system dynamics electricity sector models.

Energy 2020 Model

Purpose and Scope of Model

The ENERGY 2020 model (Backus et al. 1995) has been used by state governments and other organizations to model energy demand, supply, prices, and environmental impact. The model was developed from other more specific energy models. The model covers the entire energy sector but still treats each energy source separately. The model is a system dynamics model that runs in the PROMULA simulation system and has separate modules that can be run individually in order to focus on particular aspects of energy. The model is used to gain state- or national-level insights with a time horizon of 3 to 30 years and outputs data on an annual.

Plant Construction Decision and Generation Sources

The ENERGY 2020 model forecasts future electricity loads and prices to determine whether new generation capacity will be built (Backus et al. 1995). The amount of time in the future that is forecasted depends on the type of plant (if a plant takes two years to be built, then the prices and load are forecasted two years into the future). This method attempts to simulate how construction decisions are actually made. There are five options in the model on how to determine what type of plant will be built: market share, future market share, supply curve, generation capacity fraction initiation, and rank order. The market share method is based on consumer choice theory, which includes non-price factors, imperfect information, and marginal cost in the decision process. The future market share method bases the allocation of new generation capacity on a user-specified market share proportion of each generation type. All new construction follows this proportion. The generation capacity fraction initiation method is similar to the future market share method, but the user input proportion of generation capacity is applied to existing capacity as well as new generation capacity. The supply curve method determines plant allocation based on user-specified supply curves for the generation sources. The rank order method makes generation decisions based on perfect knowledge of marginal costs. These methods can be selected in the model. The generation sources included are gas, oil, biomass, solar, wind, hydro, landfill gas, pumped hydro, wave, biogas, MSW, fuel cells, and energy storage. These sources can be selected or ignored in the model.

Electricity Supply, Demand, and Feedstock Prices

Electricity demand is separated by end uses and industry sectors, and it includes energy efficiency investment, which is based on fuel price following a least-cost curve (Backus et al. 1995). The demand in the model is determined causally without the need for an explicit price elasticity and is influenced by the economic module. The demand model uses changes in price to influence the economics of technologies and behaviors that determine demand. The feedstock prices are determined by the supply module in the model and use a depletion factor to keep track of limited resources including land and fuel. An average fuel price is used throughout the year except for heating loads in the winter and cooling loads in the summer. Weather data can be included to examine the differences in heating and cooling requirements in more detail.

Treatment of Biomass

Biomass is treated much like other feedstock sources (Backus et al. 1995). The price is determined by demand for electricity and a scarcity factor that takes into account land use and decreased land availability. Biopower facilities compete with other electricity generation sources and have the same decision process as other electricity generation plants. The model allows for some fungibility between biomass, gas, and coal as electricity feedstock in the short term, which depends on fuel prices.

Policy Implementation and General Model Results

The ENERGY 2020 model has been used frequently for state-level policy decisions, especially in California (Backus et al. 1995). The model has focused on GHG reduction, market deregulation, cap and trade, RPSs, and energy efficiency policies. It is intended to inform decision makers about implications of policies. The model has been widely used because it can be greatly modified to meet the users' needs, including turning various modules on and off.

A Feedback-Rich Energy Economy Model

Purpose and Scope of Model

The FREE model was created by Tom Fiddaman for his Ph.D. dissertation and developed in Vensim (Ventana Systems, Inc. 2011). The model sought to correct issues that Fiddaman saw in the popular Nordhaus climate-economy model, which is a linear optimization model that is available either in General Algebraic Modeling System or Excel (Fiddaman 2002). Fiddaman converted the Nordhaus model into system dynamics. The FREE model (as well as the Nordhaus model) focuses primarily on the climatic and economic implications of energy portfolios rather than energy usage and sources. The model has a global perspective of overall energy use (not only electricity) and is not broken down into regions. The timeframe for the model is from 1960 to 2100 and has been calibrated based on historical data.

Plant Construction Decision and Generation Sources

The FREE model calculates the capital costs required to build new energy generation. The capital cost calculation includes projections of the price of energy and operational costs. The model does not build discrete plants or even plants that are particular to a specific energy use. Energy sources are divided into four types: coal (and other solid fuels), oil/gas, hydro/nuclear, and new renewables (including biomass liquid fuels, wind, and solar). Biomass as a fuel is not specifically tracked. The specific capital requirements associated with each source determine the capacity of each source, but demand determines the utilization of each source thereby limiting the short-term transition among fuel sources. The model assumes that learning will cause nascent technologies that are constructed to decrease in capital cost per unit of energy produced and that the rate of technological progress will not slow to zero. For renewable sources, the capital cost of additional construction increases as more plants are built, forcing later facilities to be built in less ideal locations (Fiddaman 1997).

Electricity Supply, Demand, and Feedstock Prices

The FREE model assumes that there is enough energy supply to meet demand (Fiddaman 1997). However, the model includes a factor for the depletion of non-renewable resources, which will raise the price of fuel and decrease the demand. The utilization of non-renewable sources decreases as the price increases and energy production shifts to renewable sources. Renewable resources do not suffer from this problem but deal with the issue of saturation where the best sites are used up first so the initial investment of capital is higher for additional capacity. The demand for energy is based on a macroeconomic module and the allocation of output from that economic module, which is based on energy produced, labor (exogenous), and technology (exogenous). Labor is determined by projected population growth. The model includes exogenous energy efficiency improvements, which decrease the amount of energy required to get the same economic output.

Treatment of Biomass

Feedstock prices are not explicitly represented in the model and are most greatly affected by depletion of resources and saturation of generation capacity for a particular source (Fiddaman 1997). The model ignores non-energy use of feedstock. Energy produced from biomass is lumped with the "new renewables" category of energy sources. It is assumed that there is enough biomass available for electricity to meet demand. The cost of producing biomass energy is assumed to be the same as other new sources. In general, the model considers biomass to be used for liquid fuel and not biopower.

Policy Implementation and General Model Results

The FREE model includes a carbon tax; an energy tax, which affects all energy sources equally; and a depletion tax, which taxes depleting resources more in order to slow down their depletion (Fiddaman 2002). The model results focus more on environmental and economic outcomes than energy usage and the construction of specific energy sources. The model is used to examine how climate change and changes in energy production affect overall welfare and the economy. The model largely ignores feedstock and does not differentiate biomass or electricity from other energy sources and uses.

Washington State University Western Electricity Model

Purpose and Scope of Model

The Washington State University Western Electricity Model was originally developed under a National Science Foundation grant to combine a system dynamics model with an engineering model in order to gain insight on the economic, environmental, and engineering considerations of the western electricity grid (Dimitrovski et al. 2007). Later versions of the model focused on tracking GHG emissions and implementing environmental policies (Ford 2008). The model examines long-term trends in power plant construction, transmission construction, electricity markets, and electricity generation in the Western Electric Coordination Council system (Dimitrovski et al. 2007). In most analyses, the model is run for a 20-year time period in Vensim. The model was intended to run quickly so that it could facilitate group learning and systems thinking.

Plant Construction Decision and Generation Sources

New generation capacity increases according to an exogenous annual growth rate that can be changed by the user (Dimitrovski et al. 2007). The type of generation capacity built is determined by a logit function where the share of new generation capacity is divided based on the total investor cost of each type of plant. Generation sources with lower costs get a larger share of new generation, but the logit function ensures that even generation sources with higher investor cost gain some market share. The generation sources considered in the model are coal, hydro, wind, nuclear, biomass, and gas combined cycle; however, the model uses conservative assumptions about advanced technologies, and only wind, biomass, coal, and gas combined cycle are considered for new generating capacity. In some versions of the model, gas combined cycle plants with carbon sequestration are introduced in later years. In a simple method to approximate resource variability, wind generation has a higher fixed transmission cost as part of the investor cost calculation. For both wind and biomass generation sources, each additional plant gets more expensive assuming that less ideal sites will be used.

Electricity Supply, Demand, and Feedstock Prices

The amount of electricity generated each month is simulated by calculating the electricity demanded for an average day of that month (Dimitrovski et al. 2007). The load duration curve for each month has the same shape every year, but the amplitude is adjusted according to the retail price of electricity in the model, an initial trajectory of prices, a user-defined elasticity, and a lag time for consumers to change consumption. The shape of demand for each month can be changed by the user. The electricity supplied by each generation source is calculated by supplying electricity from the must run units first and then other peak sources bid in the wholesale market based on their variable costs. The feedstock prices of natural gas and coal are constant throughout the time period, but the feedstock price for biomass increases as more biomass plants are built, assuming that the demand for biomass will raise the price. The model also includes a spot market for thermal energy.

Treatment of Biomass

Biomass power plants are treated simply in this model (Ford 2006). New biomass generation capacity is produced from the same logit function as the other generation sources with the investor cost determining its share of new generation. Biomass plants tend to become more expensive as more units are online and as feedstock prices increase due to increased demand for biomass. The model does not address competition for biomass from non-electricity consumption.

Policy Analysis and General Model Results

The Washington State University Western Electricity Model has been used to analyze production tax credits for renewable energy and the effects of the Senate 139 Cap and Trade (S139) bill (U.S. Congress 2003). The S139 bill implementation in the model did not enforce a firm constraint on the amount of carbon produced but added EIA projections of carbon prices into investor cost calculations (Ford 2008). In general, the market share for biomass, wind, and gas combined cycle tended to increase. Gas combined cycle gained the most ground especially as biomass and wind sources became more expensive. If gas combined cycle with carbon sequestration was introduced to the model, it gained a substantial market share quickly.