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International bioenergy synthesis-Lessons learned and opportunities for the western United States

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ABSTRACT

This synthesis examines international opportunities for utilizing biomass for energy at several different scales, with an emphasis on larger scale electrical power generation at stand-alone facilities as well as smaller scale thermal heating applications such as those at governmental, educational, or other institutional facilities. It identifies barriers that can inhibit bioenergy applications, and considers international cases of successful bioenergy production with a focus on Europe and Brazil. Based on the review of international bioenergy applications, important ecosystem service issues having relevance to western U.S. forests are discussed, including hazardous fuel reduction, community development, and sustainability of the wood products industry.

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1. Introduction-environmental benefits of bioenergy and its potential as an ecosystem service

For the purposes of this paper the term "biomass" is used as shorthand for "woody biomass" and refers to organic material from woody plants, especially trees, that is not otherwise utilized in conventional wood products. Biomass thus includes small stems, branches, twigs, and residues of harvesting and wood processing that could potentially be made available for conversion into energy products. This definition is consistent with usage in the Woody Biomass Utilization Strategy recently published by the U.S. Forest Service (Patton-Mallory, 2008). In addition, biomass can be obtained from non-forest sources such as urban waste, which often includes recycled wood, garden trimmings, and other types of biomass.

Although a plentiful supply of such biomass is available in western U.S. forests (Rummer et al., 2003), challenges remain to find economically viable uses given the high removal costs and relatively limited markets for this material. Because the cost of harvesting and transporting biomass is often several times the final value of products obtained, a key challenge for natural resource managers is to find markets and products that will offset at least part of these costs while providing other benefits such as reducing wildfire risk. Important ecosystem services (defined later) are also provided through removal of biomass having little commercial value for lumber or other wood products.

Global carbon dioxide (CO_2) levels and temperatures have increased dramatically during recent years, with CO_2 levels now approaching 380 parts per million (ppm) vs. pre-industrial levels of about 280 ppm (Intergovernmental Panel on Climate Change, 2007). Most of the observed global warming over recent decades appears to have resulted from increased greenhouse gas concentrations in the atmosphere. Although the combustion of biomass, either as biofuels or during conversion into bioenergy, results in a range of combustion products and gases, as does combustion of coal and other fossil fuels, biomass can be regrown to sequester the CO_2 produced through combustion. Thus, forest biomass sources have the potential to be carbon-neutral (Wahlund et al., 2004).

World-wide, forests serve as an important carbon sink, absorbing about 25 percent of CO_2 emissions (Nabuurs et al., 2000). Other estimates indicate that forest and land management decisions could effectively reduce net carbon emissions by 10-20 percent through the year 2050, and that the greatest potential for sequestering carbon is in tropical and sub-tropical forests (Union of Concerned Scientists, 2007). In Europe, boreal forests are estimated to have relatively little carbon sequestration ability while Mediterranean forests have a greater ability to sequester carbon (Nabuurs et al., 2000). Use of forest fuels for bioenergy can potentially negate the effects of carbon sequestration by quickly releasing CO_2 upon combustion, although the newly released CO_2 can be sequestered by trees in forests or plantations established for that purpose. In addition, incorporation of carbon into durable

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products such as lumber and engineered wood items allows for long-term net carbon sequestration. Unmanaged carbon sequestration, such as in overstocked, small-diameter stands, can result in increased wildfire risk and reduced biodiversity. Thus, global forest management objectives must be formulated to consider tradeoffs between biomass as a potential energy source vs. the storage of carbon in living forests and in durable wood products.

Forest-based mitigation of global warming can occur through three strategies (Union of Concerned Scientists, 2007):

- Conservation of existing forests to avoid emissions associated with forest removals.
- Sequestration by increasing forest carbon absorption capacity through forest management options designed to increase biomass.
- Substitution of sustainable biological products in the place of fossil fuels and non-biological products such as aluminum and concrete.

Ecosystem services can be defined as *the benefits people obtain from ecosystems,* and can include provisioning services (e.g., food, water, timber, and fiber), regulating services (e.g., flood control, water quality, and carbon sequestration), cultural services (e.g., recreational, aesthetic, and spiritual benefits), and supporting services (e.g., soil formation, photosynthesis, and nutrient cycling) (Millenium Ecosystem Assessment, 2005). Ecosystem services have also been defined as "components of nature, directly enjoyed, consumed, or used to yield human well-being" (Boyd and Banzhaf, 2007). In forests, economic benefits derived from ecosystem services can be broadly grouped into two categories: extractive goods, which include timber, hunting, and non-timber products, and non-extractive goods and services, which include water supply and quality, soil quality, carbon sequestration, biodiversity, and recreation (Rose and Chapman, 2003). Costanza et al, (1997) estimated the value of the earth's ecosystem services conservatively at US$ 33 trillion per year.

2. International bioenergy production and applications

Many nations have already made substantial gains in using biomass for energy, and have committed to lowering greenhouse gas emissions through the Kyoto Protocol or other initiatives. As of 2004, bioenergy production for heat, electricity, and liquid fuels accounted for close to 14 percent of global energy use (Parikka, 2004). However, the potential sustainable use of biomass energy globally is estimated to be about 30 percent, more than double the current level.

Faaij (2006) outlined several conversion technologies for power and heat having bioenergy applications in Europe, including district heating, direct combustion, gasification, and co-combustion of biomass with coal. Several countries in the European Union (EU) are now meeting a substantial portion of their primary energy needs with biomass (i.e. Finland, Sweden, and Austria). Other nations such as Germany and the Netherlands have also made significant progress in bioenergy applications, and will be discussed later in this paper. Bioenergy successes in the EU have been motivated by government incentives for biomass utilization (including financial incentives such as the carbon tax), a willingness to develop and test new technologies, and by strong research and developments efforts. Between 1990 and 2000, biofuel production among EU nations increased about eightfold to a 2000 contribution of about two-third of the total renewable energy production (Faaij, 2006). Other EU nations presently using bioenergy at lower levels have set ambitious goals for the next few decades. For example, Poland, with a bioenergy use of about 4 percent of primary energy, has set a target of 14 percent by year 2020 (Nilsson et al., 2006).

EU strategies for increasing bioenergy use have been documented in two widely cited papers. The White Paper (European Commission, 1997) was adopted to help achieve overall energy policy objectives related to security of supply and competitiveness, and to improve and reinforce environmental protection and sustainable development (Pagernaš et al., 2006). The Green Paper (European Commission, 2000) stated a goal of doubling the share of renewables in the EU 15-12 percent of primary energy use by 2010 (Faaij, 2006). Fig. 1 shows the increasing use of biomass and other renewable energy sources for electricity generation between 1990 and 2003.

EU directives have been used to set targets for renewable energy production, to encourage low-carbon energy production, and to set limits on emissions from biomass combustion or disposal (Faber et al., 2006). Several EU directives have been designed specifically to support biomass for heat and power generation, including the following broad areas: renewable energy sources, emission trading, landfills, and biofuels (Fagernaš et al., 2006). Other EU efforts aimed at limiting greenhouse gas emissions include an EU emissions trading scheme. Initiated in 2005, this program covers all 25 EU nations and is the first international agreement of its kind in the world. EU members set limits on CO_2 emissions from energy-intensive companies, including about 12,000 steel factories, oil refineries, paper mills, cement installations, and power plants having thermal capacities greater than 20 MW (Fagernaš et al., 2006). Close to 45 percent of the EU's total CO_2 emissions are accounted for by participation in this program.

These examples from Europe are significant in that a unified approach to bin-energy production has been established and is seen as a way to clarify the need for bioenergy production while allowing individual nations to capitalize on their strengths. For example, Austria has set a target of 78 percent of electricity to be produced from renewable energy sources by 2010, while Hungary's target is 3.6 percent (Faber et al., 2006).

In this synthesis of international biofuel use we examine several successful ventures, identifying factors that could be potentially adopted for the forests ofthe western U.S., given the resources and

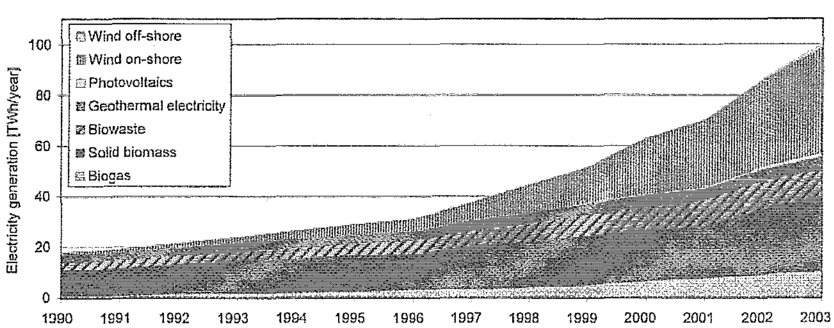

Fig. 1. Trends in electricity generation from renewable energy sources in the EU25 from 1990 to 2003. *Source:* European Commission (2005).

the need to reduce hazardous fuel loads. We do this by considering not only primary energy but also some ecosystem services that can be provided from the biomass resource. We next consider several nations individually, followed by lessons learned for biomass utilization in the western U.S.

2.1. Finland

Fennoscandinavian countries are international leaders at innovative bioenergy applications and national policies are driving much of this innovation. In particular, Finland has developed advanced pellet technologies, district heating systems, and harvesting techniques for whole-tree utilization. Bioenergy use in Finland presently accounts for more than 20 percent of primary energy generation (European Union Barometer, 2007), while renewable energy as a whole accounted for 28 percent of electricity production in Finland in 2001 (Ericsson et al., 2004). Fig. 2 shows the relative shares ofbioenergy for selected European countries in 2000. District heating systems have been widely established, and in 2004, biomass accounted for 7.9 percent of the fuel mix for district heating systems (Ericsson et al., 2004). More than 170 district heating plants had a thermal output capacity greater than 1 megawatt (MW) (European Union Barometer, 2007).

Several important factors have driven increased bioenergy use in Finland. First, an energy and CO_2 tax has been instrumental in making biomass cost-effective as compared to fossil fuels, in some applications even favoring biomass. As a result of this tax, biomass became less expensive than coal by the late 1990s (Ericsson et al., 2004).

Second, the forest industries in Finland account for about 25 percent of the country's total energy consumption (Pingoud and Lehtila, 1997). Black liquor combustion is the most significant energy source within the forest industries. Pulp and paper complexes can serve as logical locations for integrated bioenergy facilities. These can include pellet manufacture, combined heat and power production, and biomass-based liquid fuel production. Finnish bioenergy use has been dominated by large users such as pulp and paper mills, which account for 80 percent of wood fuel use nationwide.

Third, backing by the central government in Finland via the Finnish Action Plan for Renewable Energy Sources aims to increase renewable energy use 50 percent above 1995 levels by 2010, and 100 percent by 2025 (Teppo et al., 2003). Government policies promoting biomass use have included investment subsidies, fossil fuel taxes, bioenergy research and development support, and dissemination activities. Innovations have led to commercial applications, including the use of fluidized bed combustors (FBC) in combined heat and power plants (Helynen, 2004). In FBC systems, biomass is mixed with a fluidized media such as sand during combustion. Advantages of FBC vs. conventional grate combustion include multi fuel capabilities (including use of low-grade fuels), lower maintenance costs, and reduced emissions, especially when substituting biomass for coal or when co-firing biomass with coal (Teppo et al., 2003).

Fourth, government backing of research has led to substantial improvements in bioenergy utilization. In 1993, the Finnish Ministry of Trade and Industry initiated eight new energy technology research and development programs such as the Bioenergy Research Programme (Korpilahti, 1998). Research areas of this program have included wood fuel delivery systems such as biomass forwarding, chipping, and transportation (Korpilahti, 1998) as well as evaluations of wood chip quality and chipper productivity (Asikainen and Pulkkinen, 1998).

Finland's approach to forest management has played an important role in bioenergy use and carbon cycling. Natural disturbances such as fire, insects, and disease have been largely suppressed over the years, and so timber harvesting has been the primary influence on the forest ecosystem carbon balance. Even with Finland's intensive forest industry, the total growing stock of forests has shown a net increase between the mid-1960s and mid-1990s (Pussinen et al., 1997). An important ecosystem service is the quantity of carbon sequestered in living forests, soils, and in durable wood products. In Finland it is estimated that about 66 percent of the carbon in harvested wood remains in durable products, while about 33 percent of the carbon is emitted relatively soon after harvest for energy generation (Pussinen et al., 1997).

Forest biomass processing and transportation can emit significant quantities of CO_2 from conventional fuels (Perez-Garcia et al., 2005). Therefore, a certain portion of the benefits from using forest biomass as fuel are lost when fossil fuels are consumed to recover or utilize the biomass. Wihersaari (2005) examined five wood-chip production scenarios in Finland for their contribution to direct and indirect greenhouse gases. The analysis suggested that non-renewable energy inputs (primarily diesel oil) were only 1.9-2.6 percent of biomass energy production. Thus, the ratio of output biomass energy to input fossil-fuel energy was about 50:1. Chipping scenarios evaluated included terrain chipping, roadside chipping, and chipping of loose residues at an energy generation facility (Wihersaari, 2005).

2.2. Sweden

In Sweden, high taxes on fossil fuels have been an important key to making biofuels more competitive (Roos et al., 1998). Sweden implemented a carbon tax in the early 1990s on fossil fuels used for

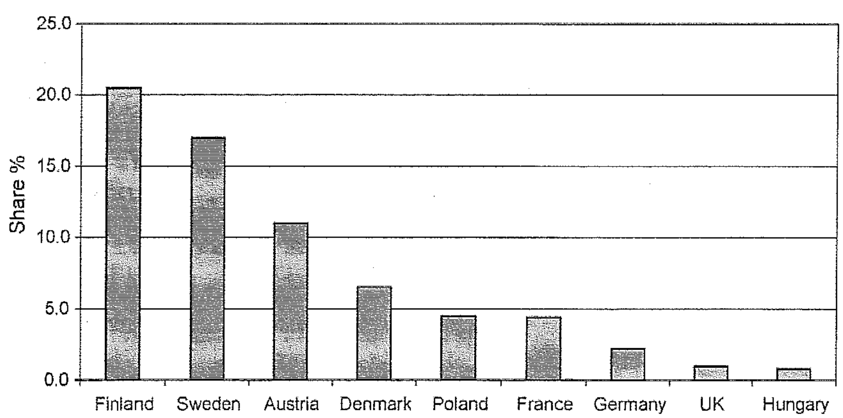

Fig. 2. Share of bioenergy produced as a percentage of total primary energy production in several European Countries in 2000. Source: Fagernäs et al. (2006).

thermal heating applications. This tax originally did not include electricity generation but this feature was added in 2003. The tax was sufficient to induce energy producers to switch from oil and coal to wood fuel for numerous applications, including district heating. As a result, wood became the fuel of choice for about 100 large district heating plants during the 1990s (Hillring, 2002; McCormick and Kaberger, 2005). Sweden's carbon tax has not been static in either its rate or its scope. Since its origin in the early 1990s the rate has more than doubled. In 2003, Sweden adopted a quota-based renewable portfolio standard that is expected to increase biomass-based electricity production (Ericsson et al., 2004).

One of the keys to successful wood fuel utilization in Sweden has been an effort to diversify broadly among several types of fuels, including briquettes, pellets, powder, and shavings (Hillring, 2002). In 2003, approximately 20 percent of the primary energy in Sweden was bioenergy (McCormick and Kaberger, 2005). Over the years, Sweden has maintained a role as one of the leading producers of pellets, with more than 95 percent of pellet production in Sweden during the mid-1990s being used to supply district heating systems (Aruna et al., 1997; Hillring and Vinterback, 1998). In some cases, entire communities are heated with wood pellets through district heating facilities. This helps to minimize transportation cost of pellets, and in some cases pellet mills have been co-located with district heating plants (Thek and Obernberger, 2004).

Innovation has played an important role in Sweden's bioenergy industry. An example is an integrated gasification power plant at Varnamo, Sweden. This plant has a total capacity of about 18 MW and has used wood combustion gases rather than steam to generate electricity, with thermal energy simultaneously being generated for the district heating system in the town ofVarnamo (Stahl and Neergaard, 1998). The facility is significant because of its potential to determine which biofuels and operating conditions are best suited for scaling to larger scale gasification systems. Although the demonstration program at Varnamo ended in 2000 and the plant has been shut down, several major projects are planned for this facility, including gasification of refuse-derived fuels, production of synthesis gas, and production of alternative transportation fuels (Stahl et al., 2004).

Wahlund et al. (2004) found that, for Swedish bioenergy systems, wood energy can maximize CO_2 reductions when it is pelletized and then substituted for or co-fired with coal. The study found that converting biomass into liquid transportation fuels provided only about half the CO_2 reduction when compared to traditional bioenergy combustion systems, and at a greater processing cost. Wood pellets and powder have been used in a combined heat and power (CHP) system in Enköping, Sweden, established in 1994. The generating capacity of the Enköping plant is 45 MW (thermal) and 24 MW (electrical), and it supplies close to 85 percent of the heating demand for the town, in which nearly all of the buildings are connected within the district heating system (McCormick and Kaberger, 2005).

2.3. Austria

As of 2001, Austria had approximately 26 percent renewable energy generation, including hydropower and bioenergy, ranking third among ED countries behind Iceland and Norway (Wörgetter et al., 2002). About 50 percent of renewable energy used in Austria is bioenergy, and the most substantial use is for domestic heating (Weiss, 2002). Currently more than 350 bioenergy plants consisting of a central biomass boiler and a distribution grid have been built in Austria (Weiss, 2002), ranging in size from 500 kW (thermal) to 30 MW (thermal). An important key to development of these district heating plants has been Austrian investment subsidies ranging up to 50 percent of construction costs for farmers' cooperatives, and between 10 and 30 percent of construction costs for most other operators (Roos et al., 1998).

Austria has shown a willingness to invest in innovative bioenergy systems, in part due to investment subsidies supported by the central government. Small-scale combined heat and power systems have seen significant developments in Austria, including the installation of a pilot plant using Stirling engine technology (35 kW electric and 220 kW thermal output). A Stirling engine is an external combustion reciprocating engine having an enclosed working fluid that is alternately compressed and expanded to operate a piston. Stirling engines can use any type of fuel to convert heat into mechanical energy. Several additional Stirling engines were scheduled to be installed in Austria during, 2004, although challenges include increasing the overall electrical efficiency and reducing ash deposition (Biedermann et al., 2004).

Austria has also been innovative in reducing emissions from thermal waste systems. One of the largest and most sophisticated of these is Fernwärme Wien, a network of ten interconnected plants that includes the Spittelau Thermal Waste Treatment Plant in Vienna, Austria (Fig. 3). Fernwärme Wien processes city waste, distributing heat and hot water to more than 200,000 dwellings and 4400 industrial customers in Vienna (Hewlett-Packard Development Company, 2004). This system has been described as being so efficient that its daily emissions equal that of only two city buses (Grtibler, 2007). Most of what appears to be "smoke" from the facility is almost pure water vapor.

Small-scale heating systems such as wood pellet furnaces have also become widely used in Austria, increasing from about 425 furnaces in 1997 to about 3466 furnaces in 2001 (Wörgetter et al., 2002). Growth in the small-pellet furnace market has been

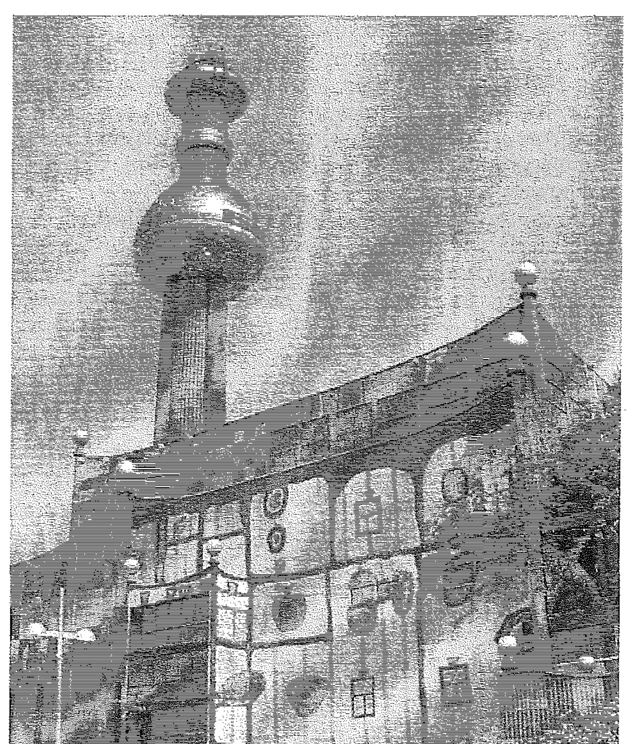

Fig. 3. Spittelau thermal waste treatment plant, a unit of the Fernwärme Wien system, in Vienna, Austria. Photo: Robert Monserud.

strongly supported by the central government, which offers investment subsidies for new pellet furnaces that average 25 percent of investment cost (Obernberger, 2002). This growth has spurred development of at least 30 manufacturers of small-scale pellet furnaces.

Plant ownership of bioenergy district heating systems in Austria has been concentrated in agricultural cooperatives (58 percent of total) but has also included private ownership, mostly sawmills (30 percent). Utilities own only 2 percent of district heating systems (Stockinger and Obernberger, 1998). As with small pellet furnaces, biomass district heating plants in Austria have been highly supported by central government funding, with subsidies ranging from 30 to 50 percent of investment costs (Stockinger and Obernberger, 1998). Other new innovations and trends under development include small-scale wood dust or powder burners, combination pellet-solar systems, and new types of combined heat and power systems (Obernberger, 2002).

2.4. The Netherlands

The central government of the Netherlands has provided substantial support for renewable energy since 1996. This includes three fiscal instruments: green funds, tax credits, and an energy tax. In 2001, a system oftradable green certificates was introduced (Kwant, 2003). Despite these instruments and incentives, Dutch renewable energy goals are somewhat more modest than other EU countries, owing to the relatively small land area and high population density (Kwant, 2001).

Co-firing biomass with coal has been explored extensively in the Netherlands. In co-firing, coal and biomass are burned together, usually in a combustion system designed for coal, and usually with the bulk of the heat output coming from coal. Co-firing often represents a promising near-term means of substantially increasing biomass use for electrical generation in regions where coal burning is common. Much of the power plant infrastructure is already in place, and typically only modifications for wood fuel processing and handling are required. Pellet fuels or bulk fuels such as chips can be easily substituted for coal on grate-fired systems by virtue of the similarity of their particle sizes with that of coal.

Key advantages to co-firing wood and coal include an existing infrastructure for coal already in place, reduced sulfur and nitrogen emissions, and relatively little additional capital investment in fuel storage and handling. An important aspect of co-firing biomass with coal is that, owing to the large facility size of many coal plants, even a small percentage substitution can utilize substantial amounts of biomass. For example, test burns in the Chariton Valley region of Iowa (U.S.) with switchgrass and coal have averaged 12.5 Mg of switchgrass per hour (Chariton Valley Biomass Project, 2007), representing about 3 percent heat input to the 725 MW power plant (Amos, 2002). A similar test project in Denmark at a 150-MW facility involved co-firing with straw at up to 20 percent substitution on an energy basis (Wieck-Hansen et al., 2000). Drawbacks included the potential for corrosion from chlorine and potassium compounds in the biofuel component. Both facilities utilize pulverized fuel and thus require extensive biomass preparation.

Both waste incineration and co-firing of biomass with coal are two of the leading options for increasing bioenergy use in the Netherlands, as indicated in an action plan from 2005 to 2010 (Kwant et al., 2004). High population densities in small land areas may favor certain types ofbioenergy use such as co-firing and use of urban wood wastes, while low population densities might favor considerably different uses such as wood pellet burning in the Scandinavian countries (Kwant et al., 2004).

2.5. Gennany

Within the European Union, Germany is both the largest producer and the largest consumer of biodiesel. A target has been set in Germany for biofuels to provide 5.75 percent of the total transportation energy supply by 2010 (Bomb et al., 2007). There are currently 25 biodiesel facilities in Germany, and construction plans for an additional 10 facilities were announced in 2006. Close to 80 percent of the EU bio-diesel production is derived from rapeseed (canola) oil, with soybean oil and a marginal quantity of palm oil making up the rest (Eikeland, 2006). Germany accounted for close to 50 percent of the EU aggregate production ofbiodiesel in 2004 (EurObserver, 2005).

A strategic aspect of Germany's biodiesel production has been whether to produce pure biodiesel B 100 vs. a low-level biodiesel blend known as B 5. Low-level blending of biodiesel is relatively easy, inexpensive, and does not require special pumping infrastructure. However, it will be harder to meet renewable energy targets due to the much smaller amounts used as compared with B 100 formulations (Bomb et al., 2007). A key to success with biodiesel use in Germany has been strong collaboration to formulate a national transport fuels strategy. The primary participants have included the German Federal Government, oil companies, automobile manufacturers, and German research institutes.

2.6. Brazil

One of the top examples of long-term economic success in renewable energy is Brazil's national ethanol program. Brazil's National Alcohol Program (NAP) has been modified over the past three decades to reflect changes in Brazil's political, economic, and energy priorities. The NAP (also known as PROALCOOL) also provided credit guarantees and low fixed-interest rate subsidies for construction of distilleries (Schmitz et al., 2003). Initially developed in the 1970s, the program is largely based on sugar cane, an easily fermented sugar. This program receives substantial government subsidies, has had relatively long periods to realize a payback, and is now becoming profitable.

Economies of scale and technological advances over the past few decades have narrowed the gap between ethanol and fossil fuels in Brazil (Goldemberg et al., 2004). Ethanol now supplies 40 percent of automobile fuel in Brazil, and the success of the ethanol program is evidenced by participation of foreign investors in 20-35 percent of Brazil's new ethanol projects, including up to 43 sugar mills currently under construction (Regalado, 2007).

In many countries, gasohol blends (i.e., ethanol-gasoline blends) typically contain only about 10 percent ethanol. However, in Brazil, these ratios are often 20 percent or higher and Brazil also uses large quantities of ethanol that are not blended with gasoline. Since 1976 the blend ratio has varied between 11 and 25 percent, and since 1994 it has remained above 20 percent. A market for ethanol is assured through government policy by an annual Presidential Decree that specifies the blending ratio of ethanol in gasoline nationwide. The actual percentage to be used in transportation fuels nationwide is then set by a national committee of various ministers. An important aspect of Brazil's domestic alcohol industry is that the government sets no production limits (Bolling and Suarez, 2001).

As of the late 1990s, several direct benefits from Brazil's ethanol program have been identified that include employment of up to 1 million people, high production levels of ethanol and sugar, and urban air improvements (Rosillo-Calle and Cortez, 1998). A potential future benefit in Brazil is the ability to generate large amounts of electricity directly from sugarcane bagasse, estimated to be as much as 3000 MW nationwide (Coelho et al., 1999).

Development of a bagasse-based electrical power industry would likely require government support in setting electrical rates.

3. Discussion

3.1. National energy policies

National energy policies play an essential role in determining adoption rates of new bioenergy technologies as well as total use of biofuels, Several EU policies that have proven effective include:

- Incentives and subsidies for pellet stove purchase and for construction of district heating systems (Austria).
- Incentives for bio-diesel production (Germany).
- Carbon tax on fossil fuels (Sweden).
- Incentives for bioenergy research and development (Sweden and Finland).
- Incentives for ethanol production and mandated ethanol blends in transportation fuels (Brazil).

Certain policy measures have taken decades to become effective, such as Sweden's carbon tax (early 1990s) and Brazil's ethanol program (mid-1970s). Weiss (2002) suggests that driving forces for successful bioenergy development on a national level include a strong political commitment combined with the active participation of industry, innovators, and funding institutions.

3.2. Regional specialization

Bioenergy case studies in Sweden, Austria, and the U.S. have identified several important factors for successful market growth, including integrating bioenergy with other businesses, competition within bioenergy markets and other businesses, and national and local policies (Roos et al., 1998).

It is clear that part of Europe's success in bioenergy over the past two decades has been due, at least in part, to regional specialization where different countries have different comparative advantages. Notable examples of regional specialization include Germany's biodiesel production, Austria's wood pellets, Sweden and Finland's district heating systems, and co-firing of biomass with coal in the Netherlands and Denmark.

Population density, land area, and forest type play an important role in regional specialization. For example, Finland has a relatively low population density, large forested area, and a large primary forest products industry. This has favored the use of primary wood residues such as wood pellets and chips for large district heating plants. The Netherlands and Denmark have relatively high population densities, small forest areas, and mostly agricultural residues. This has favored applications such as co-firing of straw with coal and combustion of urban wood waste.

Regional specialization in biofuel production could potentially become less important as international trade increases. Already biomass is being shipped from the Baltic countries to the Nordic countries. The most common biofuel traded internationally is refined solid products such as pellets and briquettes (Alakangas et al., 2002).

3.3. Advanced and emerging technologies

Future trends in bioenergy facilities could include improvements in combustion efficiency, the use of diverse biomass sources such as lower grade fuels, improvements in steam cycles, and more common use of fuel dryers (Bain and Overend, 2002). Small-scale combined heat and power systems have seen significant development in Austria, although challenges remain with improving their output efficiency.

Given the range of potential biofuels and the variation in particle size, moisture content, and levels of contamination, it will be important for new technologies to accommodate this variability, and to minimize its effects on combustion efficiency. Circulating fluidized-bed gasifiers can handle a wide range of fuel types. A Dutch firm has tested 10 different biomass residues, among them demolition wood, verge grass, railroad ties, and cacao shells (van der Drift et al., 2001). The circulating bed gasifier was very flexible in its ability to burn a variety of fuels, with fuel moisture content an important parameter. An important ecosystem service provided by bioenergy systems that combust urban wastes is the avoided cost of landfill disposal.

Integrated systems containing both biomass and small-scale solar heating systems have been explored in Austria. As of 1998, 12 solar-assisted biomass systems were in place for district heating. In Austria, a typical solar installation for a detached single home can provide 20-40 percent of the energy for space heating and hot water needs (Faninger, 2000). Combined systems could play an important role in helping meet renewable energy targets when biomass is not widely available. Systems that integrate more than one form of renewable energy allow for more reliable energy delivery when one source is disrupted.

"Bioenergy combine" is a term used to describe plants that use woody biomass to produce thermal energy and electricity while also manufacturing pellets. An example is a facility in Skelleftea, Sweden that produces a mixture of fuel pellets (59 percent yield), electricity (12 percent yield) and thermal energy (20 percent yield) (Wahlund et al., 2004). Bioenergy combines, as well as other production arrangements where several bioenergy products are produced on a single site, are likely to become more common, and could offer significant economies of scale. Such facilities could include pulp and paper facilities modified for biofuel production.

New combustion technologies can help in utilizing the broad range of fuels for energy production. In Lahti, Finland, mixed fuels that include wood, paper, cardboard, and some plastics are burned in a circulating fluidized bed gasifier, which then supplies heat to a coal boiler. The gasifier capacity is about 45 MW, which is about 15 percent of the total capacity with coal.

New technologies have been developed in Austria for medium-scale combined heat and power production systems (Weiss, 2002). Several demonstration plants have been built, including a biomass gasification plant using steam in a fluidized bed system in Ctissing, a steam cycle CHP plant in Reutte, and an organic Rankine cycle plant in Admont. In an organic Rankine cycle system, energy is generated when a high molecular mass organic fluid (the working fluid) is pumped into a boiler where it is evaporated, passed through a turbine and then re-condensed.

Microturbines with generating capacities between 30 and 150 kW have become promising for small-scale power and heat generation. At least 300 microturbines are in place within the EU (janssen et al., 2004). Barriers to commercialization include conversion inefficiencies, high initial investment costs, and nitrogen emissions. In the U.S., a small modular biomass system has been developed for rural electrical markets (Scahill et al., 2002). This system uses a fixed bed, down-draft gasifier design. Units currently being used range from 5 to 15 kW, with 50-100 kW units under development (Zerbe, 2006).

3.4. Ecosystem services and bioenergy

Ecosystem service benefits can be broadly grouped into two categories: extractive and non-extractive goods and services. In Finland, several classes of ecosystem services have been identified including timber stumpage, tourism, air quality improvements, non-timber products, and climate change abatement (Matero and Saastamoinen, 2007). Specific definitions of ecosystem services have considered final ecosystem service units in relation to a nation's gross domestic product (GOP), to allow for a more accurate accounting (Boyd and Banzhaf, 2007).

One difficulty with ecosystem services is accurately accounting for them over time and space. Issues include inappropriate scaling up from small-scale studies to large areas or regions, and double-counting ecosystem services that are used to produce secondary goods (Matero and Saastamoinen, 2007). The value and extent of ecosystem services from forests will likely be influenced by climate change. Schröter et al. (2005) indicate that some trends, such as potential increases in forest area and productivity, may be positive at least in the near term. Changes in the area of surplus agricultural lands could also contribute to increased bioenergy production (Schröter et al., 2005). Counterbalancing these positive predictions are the potential for reduced soil fertility, reduced water availability, and increased risk of forest wildfires.

Estimates of the global contribution of biomass energy can vary by a factor of 4, based on a review of 17 studies (Berndes et al., 2003). Two key parameters are land availability and yields of energy crops. Estimates of the 2050 supply of plantation wood also vary by as much as a factor of 5. If biomass crops were to displace natural land cover such as forests and wetlands, some ecosystem services (e.g., biodiversity) would likely be diminished (Cook and Beyea, 2000).

Employment can be regarded as an important ecosystem service derived from forestry operations. The value of direct employment in Sweden for pellet production was more than double that of briquette production (Hillring, 2002). Labor inputs estimated in Sweden for utilizing various types of biofuels under scenarios of increased bioenergy use include 1.5 employees per petajoule (PJ) for wood manufacturing residues, 32 employees per PJ for logging residues, 113 employees per PJ for short-rotation forestry with a low level of mechanization, and 25 employees per PJ with a high level of mechanization.

Bioenergy systems can also provide a reduction in CO_2 emissions as compared with fossil fuel systems. In Sweden, the energy strategy recommended to create the largest and most sustainable CO_2 reduction is the use of wood pellets as a substitute for coal (Wahlund et al., 2004). Other options, such as creating ethanol and other liquid fuels, are estimated to reduce CO_2 emissions only half as much as wood pellets (Wahlund et al., 2004).

Many of the ecosystem services provided by woody biomass in European forests are also relevant in the U.S. Skog and Rosen (1997) outline four classes of environmental needs that would be enhanced by increased use of biomass for electrical power or ethanol: reduced carbon emissions, improved forest health, diversion of urban wood waste from landfills, and production of liquid fuels. However, loss of ecosystem services such as biodiversity, and soil and water resources would need to be weighed against expanded use of woody biomass.

3.5. The future direction of bioenergy production in western U.S. forests

Western states have substantial biomass resources, including material from forest thinnings, wood products mill residues, agricultural residues, and urban wood waste (Rummer et al., 2003; Perlack et al., 2005). In the western U.S., strong incentives exist to remove biomass fuels to reduce wildfire hazards. Numerous utilization options are being explored, including wood pellets, co-generation, composite products, and thermal energy for schools (Nicholls et al., 2008). However, to date most bioenergy project development is based either on economic merits or the need to reduce fire risks within wildland-urban interface areas, without fully considering effects on ecosystem services. For example, in the western U.S. bioenergy projects are often established at or near sawmills because low-cost residues are available. More recently, bioenergy projects are also being sited at schools and other public buildings within areas of high wildfire risk. Barriers to economic use of biomass in western states can include long transportation distances, steep terrain, lack of roads, inefficient harvesting of small stems, and low availability of labor.

A major problem associated with utilizing biomass from western forests is that there are relatively few cases where small-diameter biomass will "pay its way" out of the woods (Wagner et al., 1998; Skog et al., 2006; Rummer et al., 2003; LeVan-Green and Livingston, 2001; Fight et al., 2004). In some cases, harvesting and transportation cost deficits can be minimized by producing higher value products (e.g., lumber) from larger stems included with biomass removals. Skog et al. (2006) found that uneven-aged silvicultural treatments on gentle slopes were the only scenario (out of four evaluated) that provided positive net revenues while reducing fire hazards in western forests (the average net revenue was $1694 per hectare). In a related study, restoration thinnings for ponderosa pine forests in the western U.S. were evaluated by Fiedler et al. (1999). This research found that on slopes less than 35 percent, net revenues of $2300 per hectare were possible when a sawlog-pulpwood market was present. However, steeper slopes requiring cable-yarding systems could require subsidies of $1400 per hectare or more.

Polagye et al. (2007) used a single integrated pathway to evaluate the economic potential of biomass from wildfire reduction to generate energy from overstocked stands in the western U.S. Their analysis considered scale of thinning, duration of thinning, and distance to end markets, and they found that for shorter transportation distances, co-firing biomass with coal was most viable option. For longer transportation distances production of pellets and/or bio-oil became more viable. Although mobile, small-scale bioenergy facilities could be considered, stationary production of biofuels at a fixed plant location was recommended when thinning durations were expected to be more than 5-7 years (Polagye et al., 2007).

An important aspect of hazardous fuel removals in the western U.S. has been more than 189 stewardship contracts established by federal land management agencies to treat forests having high wildfire risk (Office of the President, 2005). These contracts are becoming longer in duration and frequently cover larger forested areas. The White Mountain Stewardship contract on the Apache-Sitgreaves National Forest in Arizona, U.S.A. (Zieroth, 2006; Neary and Zieroth, 2007) is noted as a successful example of hazardous fuel reduction on a large scale. After 1.5 years of this 10-year stewardship contract significant biomass removals have occurred, and more than 8000 ha are under contract for future treatments. The stewardship contract is helping to ensure steady biomass supplies for a nearby bioenergy facility (3 MW capacity) and a wood-pellet manufacturing facility.

In the longer term, hazardous fuel removals in western states may be supplemented with other biomass sources, including forest products manufacturing residues, harvesting residues from forest management activities, and urban wastes. For example, McCarl et al. (2000) identify five biofuels that could be substituted for coal when producing electricity: milling residues, whole trees, logging residues, switchgrass, and short-rotation woody crops. However, in many regions there are already well-developed markets for biomass residuals, and future biofuel applications could be limited.

Although the policy to reduce forest fuels has become a national priority, enhanced carbon storage is also an important goal in the context of climate change. These potentially conflicting priorities need to be considered in terms of the mix of ecosystem services provided under each scenario. For example, Harmon et al. (1996) estimated that only 23 percent of carbon from harvests in Washington and Oregon went into long-term storage, with wooden structures and landfills being the most important carbon pools for this harvested material. One way to determine the optimal mix of ecosystem services is to consider not only economic benefits but also environmental and social benefits. This so-called "triple bottom line approach" has been used successfully in Europe (Sims, 2003).

Bioenergy projects and other forms of clean or renewable energy have been promoted through a range of renewable energy portfolios developed by various U.S. states. These instruments identify specific renewable energy goals. Although the portfolios are carried out on a state-by-state basis, a regional Western Governors Association (WGA) has also been formed to promote many of the goals. Serving 19 western U.S. states, the WGA has adopted a resolution to examine the feasibility of developing 30 GW of "clean and diverse energy" by 2015. Half of this energy would be obtained from biomass (Western Governors' Association, 2006). The WGA goal is perhaps the strongest parallel to date between European and western U.S. bioenergy efforts.

One of the greatest challenges for bioenergy projects in the West will be to find an appropriate niche among other types of renewable energy. Within the near future, electrical generating costs for nonbiomass renewable energy (including solar, wind, and geothermal) are all projected to remain lower than those for biomass energy systems (NREL, 2002). This will likely have an important influence on the portfolio of renewable energy projects that will use biomass from western U.S. forests, as well as the range of ecosystem services provided.

4. Conclusion

Examples from the EU, Brazil, and other nations point to encouraging possibilities for bioenergy use in the western U.S. In many cases biofuel resources, technologies, employment, and ecosystem services have already been evaluated at working facilities in these nations.

During the 1990s, heat production from biomass in the EU increased at an average annual rate of 2 percent and electrical production from biomass increased 9 percent annually (Faaij, 2006). As more bioenergy facilities come on-line in the western U.S., the choice of conversion technology and energy product will have a bearing on the total primary energy that biomass resources can provide.

Often these choices can have an important impact on ecosystem services. For example, it is estimated that using biomass for ethanol production and other liquid fuels will only reduce CO_2 emissions by about half as much as if the same biomass were used to produce wood pellets (Wahlund et al., 2004). Further, the type of biomass used for energy production, whether from harvesting residues, wood products manufacturing residues, or short rotation forestry, can have an important influence on employment (Hillring, 2002). Employment rates are greater for bioenergy than when fossil fuels provide the same energy service (Sims, 2003).

In conclusion, we have identified several elements of bioenergy development in the EU and in Brazil that could be adopted in the western U.S. as a means of increasing biomass utilization for energy. Most of these elements are directly related to a strong, cohesive, and forward-looking central government policy.

1. An innovative and well-funded bioenergy research and development program.
2. A willingness to invest in pre-commercial technology, establish bioenergy demonstration, and support innovative pilot projects.
3. Direct investment subsidies for selected bioenergy projects.
4. Use of bioenergy in conjunction with other types of renewable energy to provide a complete renewable energy package.
5. Development of integrated facilities capable of simultaneously providing a range ofbioenergy products and ecosystem services.
6. Determination of economic values of key ecosystem services provided by bioenergy.

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