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Ascertaining the Trajectory of Wood-Based Bioenergy Development in the United States Based on Current Economic, Social, and Environmental Constructs

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Abstract

Wood-based bioenergy development could play a vital role in attaining energy independence, reducing carbon emissions, and ensuring rural prosperity in the United States. An understanding of policies supporting wood-based bioenergy development coupled with the current status of production of various wood-based bioenergy products would better the prospects of wood-based bioenergy development in the United States. An understanding of the economic feasibility, social acceptability, and environmental externalities would contribute to effective policy prescriptions for establishing the US bioeconomy. Based on a comprehensive review of existing studies, we show that the heat and electricity derived from woody feedstocks that would prevail in the future as a commercial-level conversion technology for wood-based ethanol production are still under development. Society in general is positive about the use of woody feedstocks for bioenergy development. The production cost of wood-based ethanol and electricity generation has not reduced over time, indicating a need for targeted policy support focusing on sharing the production cost of wood-based bioenergy products. Wood-based bioenergy development could meet the need for sustainable energy production without affecting existing roundwood markets with the advent of advanced silvicultural treatments and efficient biotechnologies.

INTRODUCTION

The total forestland in the United States is approximately 309 million hectares, out of which about 67% is classified as timberlands with productivity greater than or equal to 1.4 cubic meters per hectare per year (Oswalt et al. 2018). The total net biomass growth between 2012 and 2017 was 708 million cubic meters, whereas only about 52% of the net biomass growth was harvested in the same period (Oswalt et al. 2018). Additionally, the United States is a major producer, importer, and exporter of roundwood and finished wood products worldwide, with established supply chains for domestic and international markets. This implies that the United States could become a world leader in wood-based bioenergy development due to a large productive wood supply base, well-developed supply chains, technological know-how, and a skilled workforce. The development of wood-based bioenergy development would also help in decreasing the nation's reliance on foreign oil, enhancing rural prosperity, mitigating carbon emissions, and supporting ecosystem services essential for maintaining the quality of life for the population of the United States.

However, to the best of our understanding, no study has analyzed the existing literature for ascertaining any trends in the unit cost of production and environmental externalities of wood-based bioenergy products, in conjunction with issues related to policies and social acceptability. This information is vital for developing a platform to forecast the trajectory of sustainable wood-based bioenergy development in the United States. In this context, this review reflects on the social, economic, and environmental aspects of wood-based bioenergy development in the United States for ascertaining the trajectory of the same in the foreseeable future. For achieving the goal, we have divided this article into eight sections. The first section introduces the study, and the second one highlights the historical development of policies related to the wood-based bioenergy development in the United States. The third section details the current status of wood-based bioenergy products, focusing on ethanol, biopower, and wood pellets for heating and electricity generation. We have considered only three wood-based bioenergy products (ethanol, biopower, and wood pellets), reflecting on the emphasis of current policies on promoting ethanol derived from wood-based feedstocks and rising production of biopower and wood pellets in the United States. The fourth section covers the impact of projected demand for wood-based bioenergy products on markets and land use over time. This section also highlights the current status of supply of forestry feedstocks for US bioenergy development. The fifth section covers studies that focus on the economics of ethanol and electricity generation on a per-unit energy basis. The sixth section focuses on the social acceptability of wood-based bioenergy development in the United States, and the seventh section discusses externalities related to wood-based bioenergy development, with a special focus on carbon savings related to the use of wood-based bioenergy products in comparison to the equivalent fossil fuel-based energy products. Finally, the eighth section discusses the results and concludes the review.

POLICY DEVELOPMENT IN THE CONTEXT OF BIOENERGY DEVELOPMENT

Ethanol

The use of ethanol (blended with gasoline) in power engines started in 1908 with Henry Ford's Model T (Niphadkar et al. 2018). During the energy crisis of the 1970s, federal and state subsidies supported ethanol production in the United States (Solomon et al. 2007). The 2.5% ad valorem tariff and a $0.142/L duty on imported ethanol increased ethanol production in the early 1980s (Tyner 2008). In 1988, Congress passed the Alternative Motor Fuels Act, providing credits to automakers for meeting their corporate average fuel efficiency standards toward the manufacture of alternative-fueled vehicles, including flexible-fueled vehicles, which could use blended gasoline with up to 85% ethanol (Solomon et al. 2007). The enactment of the Clean Air Act Amendments in 1990 increased ethanol production in the United States, as it established the oxygenated fuels program and the reformulated gasoline program for controlling air pollution (Duffield et al. 2015). The Energy Policy Act of 1992 established alternative fuel vehicle purchase requirements for federal, state, and fuel provider fleets and established tax incentives for the private purchase of alternative fuel vehicles (Guo et al. 2007). In 2004, the American Jobs Creation Act created the Volumetric Ethanol Excise Tax Credit that changed the tax credit to a volumetric basis and increased blend level limit up to 10%, thereby increasing the production of ethanol nationwide (Tyner 2008). Furthermore, the enactment of the Energy Policy Act in 2005 (Pub. L. No. 109-58, 119 Stat. 594, 42 U.S.C. § 15801) increased ethanol production nationwide by establishing a renewable fuel standard (referred to as RFS1). The RFS1 mandated production of a minimum volume of renewable fuel each year, starting from 15.1 to 28.4 gigaliters between 2006 and 2012. The RFS1 also created a tracking system that generated the Renewable Identification Numbers (RINs) for renewable fuel use (EPA 2018) and provided a 30% tax credit for the cost of installing fueling facilities for alternative fuels (Duffield et al. 2015).

In 2007, Congress passed the Energy Independence and Security Act (EISA) that replaced the RFS1 with the more aggressive RFS2 (Pub. L. No. 110-140, 121 Stat. 1492, 42 U.S.C. § 17001), mandating production of 136 gigaliters of renewable fuels by 2022, including 60.5 gigaliters of cellulosic biofuel and a cap (56.7 gigaliters) on conventional ethanol (mostly corn ethanol). The Biomass Crop Assistance Program was created by the Food, Conservation, and Energy Act of 2008 for assisting the bioenergy industry in overcoming the hurdle of continuous biomass availability for renewable fuels, including cellulosic biofuels (McMinimy 2015). In addition to federal policies (Duffield et al. 2015), several states have also adopted policies for supporting ethanol production, such as the mandated E10 or E20 by Minnesota, Hawaii, Florida, Oregon, Pennsylvania, and Missouri; a ban on MTBE (methyl tertiary-butyl ether) by California, New York, and Connecticut as an oxygenate in gasoline for public safety; and the low-carbon fuel standard (LCFS) law enacted by California (Yeh et al. 2016).

Biopower

The US Congress passed the Public Utility Regulatory Policies Act as a part of the National Energy Act of 1978, which mandated that utility providers and distributors buy electricity from qualified facilities using renewable fuel. This act increased the number of biomass-based power plants in the United States and, therefore, the demand for woody biomass for electricity generation in the late 1980s (Aguilar et al. 2011). At the federal level, the Energy Policy Act of 1992 enacted two programs, namely, the Renewable Energy Production Incentive and Production Tax Credit (PTC). The first program provided financial incentives for renewable energy produced and sold by qualifying renewable generation facilities. The second program provided a tax credit to facilities generating electricity from closed-loop biomass, which refers to dedicated bioenergy crops (Aguilar et al. 2011). During the early 2000s, the American Jobs Creation Act of 2004 extended the PTC until 2013, thereby further increasing the demand for woody feedstocks for power generation. As an alternative to the PTC, the investment tax credit was extended to business by expanding the American Recovery and Reinvestment Act of 2009 for renewable electricity production. The Renewable Energy Grant program and loan guarantees were created in 2009 for investment in the renewable energy sector (Guo et al. 2012).

Other incentives in the form of government bonds (e.g., Clean Renewable Energy Bonds and Qualified Energy Conservation Bonds, in which borrowers paid back only the principal of the bonds, and the bondholders received federal tax credits) were also created to promote the use of woody feedstocks for electricity generation (Guo et al. 2007, Becker et al. 2011, DSIRE 2018). Additionally, there are other federal policies (e.g., the National Fire Plan of 2000, the Healthy Forests Restoration Act of 2003) that promote the use of woody biomass for bioenergy development (Balint 2009). Policies at the state level, such as the renewable portfolio standards (RPS) that require a minimum percentage of total electricity sourced from eligible renewables (Aguilar & Saunders 2010), have also increased the use of woody biomass to produce heat and electricity. From 1983 to 2017, the enactment of RPS increased from 1 to 29 states, applying to 55% of the total retail electricity sales, with more than half raising the target in recent years (Barbose 2018). A detailed list of federal and state policy initiatives for forest biomass utilization are presented in Becker et al. (2011) and DSIRE (2018).

Wood Pellets

Wood pellets were used as an alternative fuel in the 1970s for resolving issues related to the energy crisis (Peksa-Blanchard et al. 2007, Aguilar et al. 2011). Historically, most wood pellets consumed in the United States were for meeting domestic heating needs, especially in the New England states. These wood pellet stoves were not subsidized and mostly self-adopted by individuals or organizations. However, several states are currently providing subsidies for promoting the adoption of wood pellet stoves owing to their high efficiency and lower pollution levels. For example, New Hampshire provides 40% or up to $10,000 of equipment and installation cost of wood pellet central heating boilers and furnaces in residential buildings (DSIRE 2018). New York state provides cost incentives for both residential (45% or up to $16,000 for 35 kW units) and commercial (40% or up to $200,000 for 88 kW units) pellet boilers (NYSERDA 2018). Other states such as Massachusetts, Maine, and Connecticut have similar incentive programs. In addition to the support available at the state level, federal tax incentives are also available for pellet-based heating systems (DSIRE 2018). It is expected that existing policy support across state and federal levels will increase the demand for wood pellets for domestic heating needs in the coming years. At the same time, the export of wood pellets from the southern region of the United States to the European Union, including the United Kingdom, is increasing. European utility companies are increasingly using imported wood pellets from the southern United States as a feedstock for electricity generation instead of coal. This is mostly to satisfy the EU Renewable Energy Directive, which requires that 20% of consumed energy should come from approved renewable sources, including solid biomass, by 2020 (EU 2009).

Studies on Policy Modeling

Several studies have analyzed policies promoting the use of woody feedstocks for bioenergy development in the United States. Tharakan et al. (2005) evaluated the impact of three incentive programs (green premium price, a closed-loop biomass tax credit, and direct payments under the conservation reserve program) on the economics of cofiring willow (*Salix* spp.) biomass with coal in New York state. They found that the direct payments under the conservation reserve program reduced the delivered cost of biomass; however, other incentive programs were also needed for the economic viability of cofiring willow biomass with coal. Becker et al. (2011) classified and compared 370 state policies providing incentives for forest biomass utilization across the United States for developing a framework for connecting existing policies to specific components (harvesting, transportation, manufacturing, and consumer markets) of the biomass supply chain. They found that the types of policy instruments vary across regions in the United States, and they focus on different stages of the biomass supply chain. For example, the greatest percentage of policies enacted in the Great Lakes states targeted utilization through cost-share and granting programs followed by technical assistance and regulatory policies, most of which were geared toward manufacturing. Ebers et al. (2016) analyzed 494 state and federal policies in effect as of September 2013 related to the use of forest biomass for energy purposes, out of which 279 were incentive based, 115 were regulatory in scope, and 100 were information based. Cluster analysis suggested that neighboring states adopted a similar type of policy for promoting woody feedstocks for bioenergy development. Guo et al. (2012) created a woody biomass policy index through scoring and weighting different categories of state policies promoting the use of woody feedstocks for bioenergy development. They reported that Iowa, North Carolina, and Washington provided the strongest incentives, whereas Wyoming, Mississippi, and Virginia offered the weakest support to the wood-based bioenergy industry by the end of 2008. Pokharel et al. (2017) analyzed factors affecting the utilization of woody residues for bioenergy production in mills located in the southern United States, stating that an increase in the processing capacity of woody residues, equipment upgrades, and lower transportation costs were important determinants of utilization of woody residues. Abrams et al. (2017) found that the biomass policy system in the United States may not be well designed to support innovation, particularly due to conflicts between biomass promotion policies and existing forest, environmental, and energy policies. Young et al. (2018) reported that adoption of institutional woody biomass heating systems in the United States is driven by heating needs, fossil fuel prices, proximity to woody biomass resources, and fuel treatments under the National Fire Plan. G.C. & Mehmood (2010) reported that forest landowners in the southern United States typically prefer tax-based policies over direct subsidy support in the context of wood-based bioenergy development. A closer look into the studies suggests the existence of numerous policies at different administrative levels for promoting wood-based bioenergy development in the United States.

CURRENT STATUS OF WOOD-BASED BIOENERGY DEVELOPMENT

Ethanol

Since the implementation of RFS2 and other federal and state incentive programs, the annual requirement of noncellulosic conventional ethanol has been fulfilled without major delays. For example, a total of 15.9 billion liters of ethanol was produced in 2017, and almost all of it was derived from corn (*Zea mays*) in the midwestern states (EPA 2018). It has been increasingly difficult to satisfy the mandated volume of advanced biofuels as established in EISA 2007, especially the cellulosic ethanol, due to the lack of commercial-scale biorefineries. Progress in the production of cellulosic ethanol is still grim due to the lack of private investment, technology setbacks, uncertainties in future policies (Duffield et al. 2015), and irregular support from the federal government (Bracmort 2018). Thus, the RFS2 administering agency, the US Environmental Protection Agency (EPA), has lowered the applicable annual volume according to the projected volume of cellulosic biofuel (Bracmort 2018). The production of cellulosic ethanol grew from approximately 2.7 megaliters in 2014 to 21.7

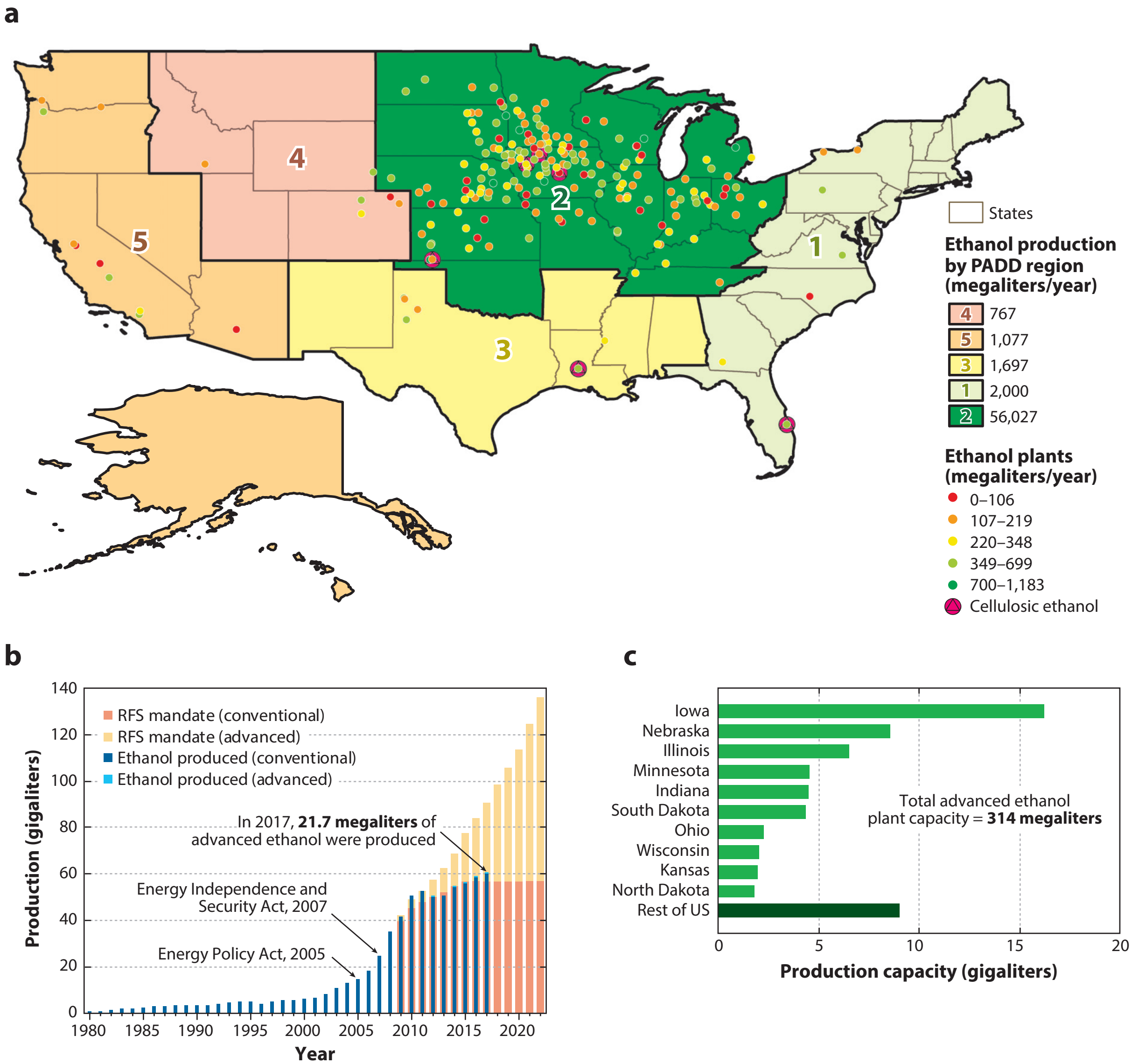

Figure 1

Regional ethanol plant capacities and temporal growth (1980–2017) of ethanol (conventional and advanced) production in the United States. (*a*) PADD regions and ethanol plant locations with ethanol production capacities. (*b*) Trends of ethanol production and RFS mandates. (*c*) Major ethanol-producing states in 2018. Abbreviations: PADD, Petroleum Administration for Defense District; RFS, renewable fuel standard. Panels *a* and *c* based on data from RFA (2018). Panel *b* based on data from EPA (2018).

megaliters by 2017, which is far below the mandated volume of about 21 gigaliters (EPA 2018). In 2017, only 21.7 megaliters of cellulosic ethanol were produced (**Figure 1*b***) compared with 1.28 and 20.8 gigaliters of revised mandated and statute volume required, respectively, as per the EPA guidelines (2018). There are four cellulosic ethanol plants in the United States with an annual ethanol production capacity of 314 megaliters (**Figure 1*c***) (RFA 2018); however, only one is

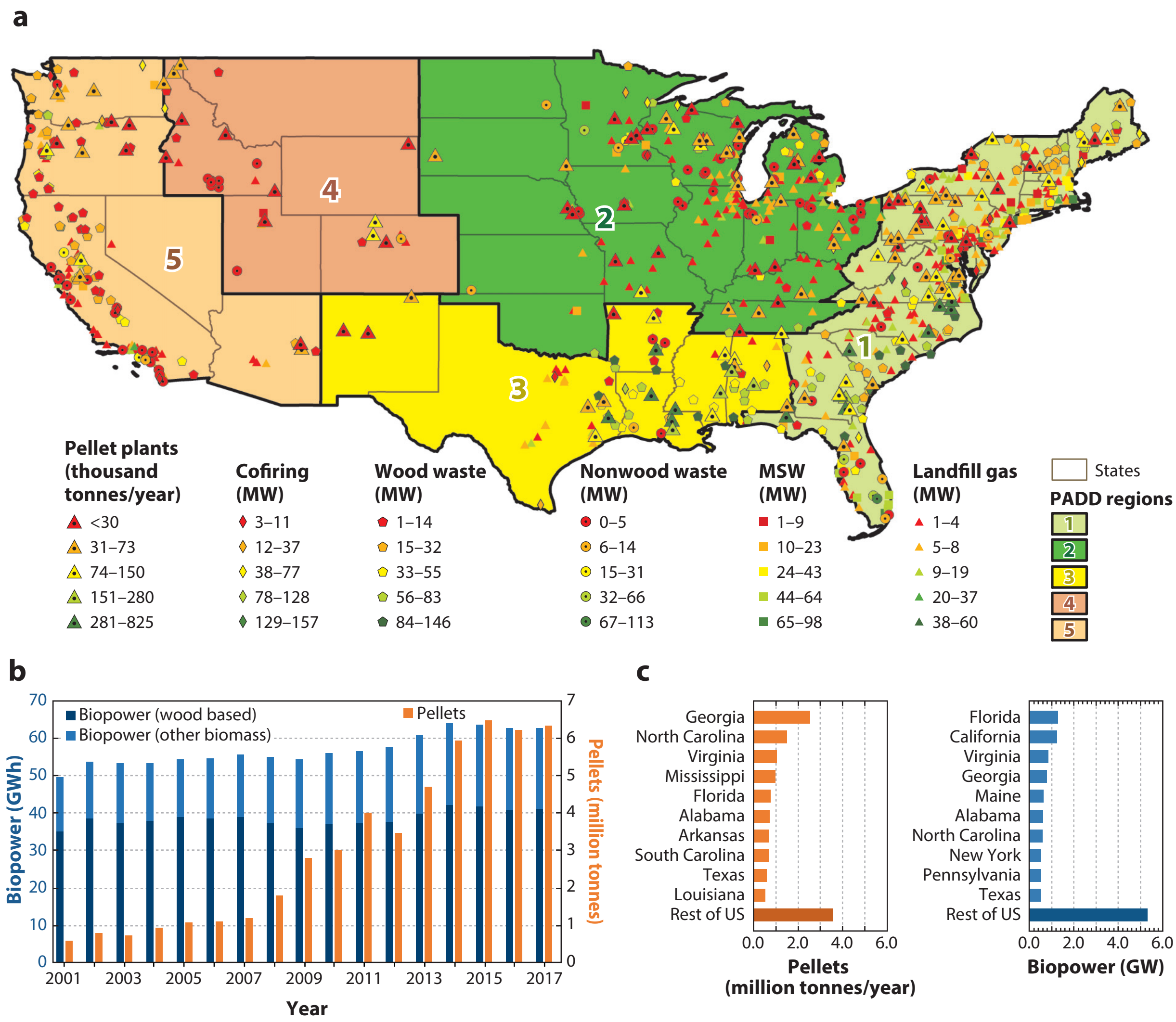

Figure 2

Regional biopower and wood pellet production and their growth over time (2001–2017) in the United States. (*a*) PADD regions showing power plants using biomass and pellet plants locations with production capacities. (*b*) Biopower and pellet production trends. (*c*) Major states producing pellets and biopower in 2018. Abbreviations: MSW, municipal solid waste; PADD, Petroleum Administration for Defense District. Figure based on data from EIA (2018a).

operational—the Project Liberty—with an annual production capacity of 76 megaliters of ethanol made from corn stover (RFA 2018).

Biopower

Approximately 17% of all electricity in the United States was produced by renewable sources in 2017, out of which 1.6% came from biomass-based resources (EIA 2018a). Woody feedstocks account for nearly 63% of the total electricity generated from biomass and waste, or 1% of the total generated electricity in the country (EIA 2018a). There are 193 wood-based power plants (**Figure 2*a***) producing heat and electricity, which contribute about 70% of the total power produced from biomass in the United States (**Figure 2*b***). The combined capacity of all biomass-based power plants in 2017 was approximately 12.8 GW or 1.1% of the nation's power production capacity. **Figure 2*c*** shows the leading states that produce power from biomass.

Wood Pellets

Historically, the domestic demand for wood pellets was low in the United States (Abt et al. 2014). The domestic use of wood pellets has increased from past few decades due to various incentives and enactment of favorable policies promoting the use of biomass for heat and power generation. In 2017, the total consumption of domestic wood pellets reached 1.72 million metric tons. The eastern, southern, and western regions shared about 50%, 30%, and 20% of the total pellets sold in the domestic market (EIA 2018b), respectively. However, the domestic wood pellet market in the United States is only a small portion (about 27%) of total wood pellet production. In 2017, most wood pellets (73% of the total wood pellets produced) were exported to the European Union, including the United Kingdom. Pellet production has grown from a negligible amount in the early 2000s to approximately 6.4 million metric tons in 2017 (**Figure 2*b***). The global wood pellet market is projected to increase from approximately 13 million metric tons in 2017 to 27.5 million metric tons by 2027 (Forisk Consult. 2018), which provides a robust growth opportunity for the wood pellet industry in the United States.

DEMAND AND SUPPLY OF WOOD-BASED BIOENERGY DEVELOPMENT

Demand

Based on current projections, the total demand for forest biomass to produce pellets, combined heat and power, power only, and liquid fuel would increase to more than 100 million metric tons per year by 2027 from ~75 million metric tons in 2017 (Forisk Consult. 2018). Several studies have analyzed the impacts of an increase in the demand for woody feedstocks due to expanding bioenergy markets on prices of roundwood products and associated land-use changes. Galik et al. (2009) mentioned that meeting the demand for bioenergy development will increase the demand for forest residues, which would vary regionally in both supply and price. In addition, exceeding the supply of forest residues could be accompanied by a dramatic spike in resource pricing in Virginia, South Carolina, and North Carolina, with implications for timberland owners and users of the forest resource base. Wang et al. (2015) developed an integrated dynamic, price-endogenous, partial equilibrium model of the forestry, agricultural, and transportation sectors in the United States to investigate land-use effects induced by changes in prices of forest and agricultural products due to the increased export of wood pellets between 2007 and 2032. It was reported that approximately 1.4 million hectares of land would move into forestry by 2032 due to the additional demand for wood pellets under the high-demand scenario where wood pellets are manufactured using feedstocks obtained exclusively from forestlands.

Duden et al. (2017) combined a market-clearing model with a land-use change model for projecting change in land use because of increasing production of wood pellets in the southern United States. Projections show that in the absence of additional demand for wood pellets, natural timberland area is projected to decline by 450–15,000 km^2 by 2030, mainly through urbanization and pine plantation establishment. In contrast, under the high wood pellet demand scenario, more (2,000–7,500 km^2) natural timberland area is retained and more (8,000–20,000 km^2) pine plantation is established. Costanza et al. (2017) quantified landscape change from 2010 to 2050 under five scenarios of woody biomass production for wood pellets and liquid biofuels in North Carolina for ascertaining biodiversity trade-offs among selected scenarios. They concluded that bioenergy scenarios would have complex landscape effects, and the regions most likely to be affected by bioenergy production are critical for biodiversity. Therefore, we need to develop a better understanding of bioenergy production systems on local biodiversity. Other studies have also analyzed the impact of an increased demand for wood-based bioenergy development on land-use changes (McDonald et al. 2009, Kim et al. 2018), supply chains (Becker et al. 2011), and ecosystem services (Khanal et al. 2013, Duden et al. 2017, Tarr et al. 2017) in the United States.

Supply

The 2005 Billion Ton Study estimated that the forestry sector in the United States could provide annually more than 333 million dry metric tons of woody biomass (USDOE 2005). However, this number was revised to about 118 million dry metric tons by 2030 for a price less than US$88.2/dry metric ton at the roadside in the second Billion Ton Study after considering economic feasibility of biomass harvesting and collection (USDOE 2011). It was found that the southern region will be the major supplier of woody feedstocks for bioenergy development nationwide. Most recent estimates of the woody biomass availability in the United States by 2040 (**Figure 3**) are reported in the 2016 Billion Ton Study (DOE 2016). This suggested that at prices of up to $66.1/dry metric ton, 93.4 and 87.9 million dry metric tons/year of biomass resources will be potentially available from forestlands in 2017 and 2040, respectively, in the base-case scenario (all timberland, including federal lands). It was also reported that a large variation exists while estimating the availability of woody feedstocks for bioenergy development contingent on demand from the housing sector and other wood consuming industries (DOE 2016). He et al. (2014) developed a nationwide optimization model for assessing the feasibility of harvesting roundwood for bioenergy development and found that not all regions have the capacity to develop wood-based bioenergy facilities without consuming merchantable wood traditionally utilized for other wood-based industries.

Several regional-level studies have also focused on the availability of woody feedstocks for bioenergy development in the United States. Abt et al. (2012) simulated traditional and bioenergy wood use in Alabama, Georgia, and Florida under differing levels of market supply responses and estimated it to be approximately 12.5 million metric tons by 2037. According to Galik et al. (2009), North Carolina, South Carolina, and Virginia combined may produce about 5.3 million metric tons of forest biomass for bioenergy development. Goerndt et al. (2013) estimated the physical availability, within ecological and public policy constraints, of woody biomass for cofiring in selected power plants in the northern United States. They found that in the absence of any competition for feedstocks, 30% of the coal requirement could be replaced by wood-based feedstocks in selected states. Springer et al. (2017) analyzed the potential of short-rotation woody crops in midwestern states and found that estimates vary widely due to key parameter choices and assumptions ranging from the current annual potential of between 19.9 and 47.6 million dry metric tons to 8.1 and 210.5 million dry metric tons by 2030.

ECONOMICS OF WOOD-BASED BIOENERGY PRODUCTS

Cellulosic Ethanol from Woody Feedstocks

Existing studies ascertaining the cost of a megajoule (MJ) of ethanol produced report a range of ¢1.45 to ¢10.3 in 2015 dollars (**Table 1**). Some earlier studies have found lower ethanol production costs below ¢2/MJ (Phillips 2007; Frederick et al. 2008a,b). So & Brown (1999) analyzed three different conversion technologies, e.g., fast pyrolysis, simultaneous saccharification and fermentation

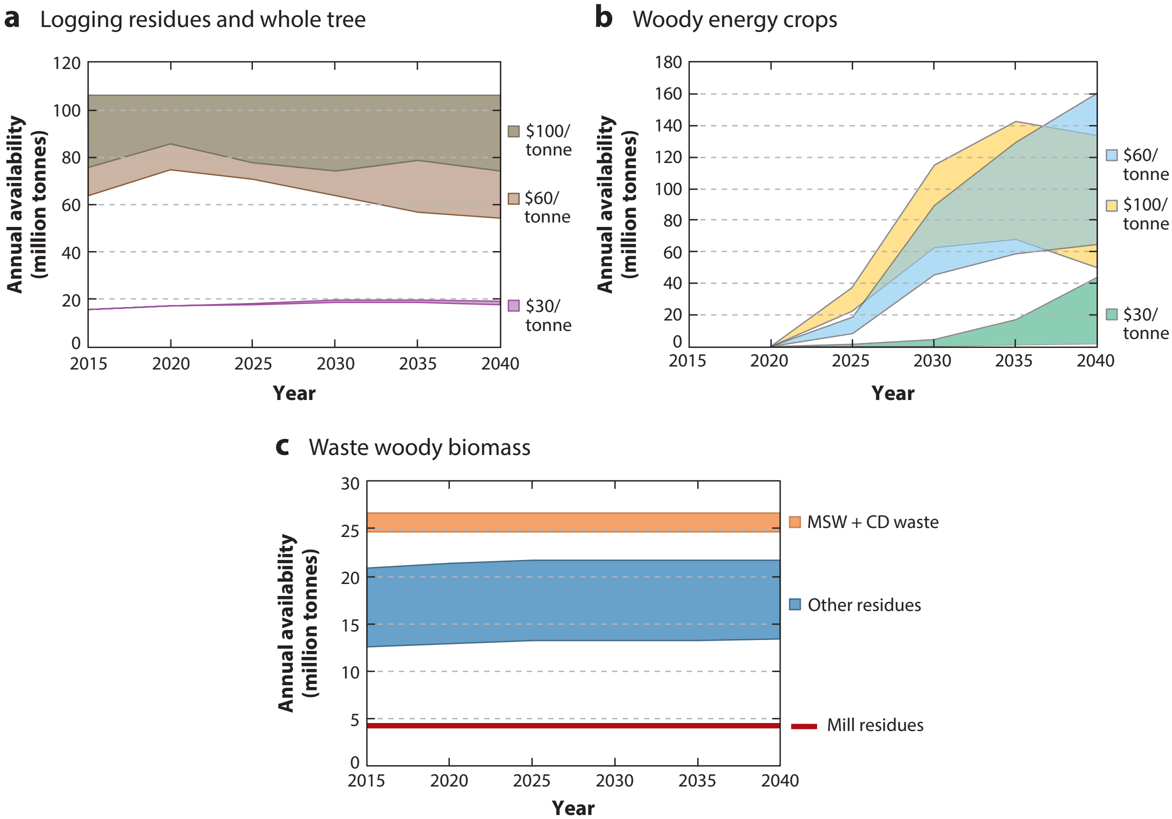

Figure 3

Availability of woody feedstocks over time at different prices for bioenergy development in the United States (2015–2040). (*a*) Availability of logging residues and whole tree. (*b*) Availability of woody energy crops. (*c*) Availability of waste woody biomass. The lower and upper bounds of the orange and blue areas show the availability at $40/tonne and $100/tonne, respectively (in 2015 US dollars). Mill residues (primary and secondary) can be available at $30/tonne. MSW (municipal solid waste) indicates woody materials that can be extracted from MSW and includes yard trimmings. CD indicates woody materials from construction and demolition debris. Other residues include thinning from other forest land, urban land, etc. [detailed description in DOE (2016)]. Figure based on data from DOE (2016).

(SSF), and acid hydrolysis and fermentation for converting wood into ethanol. They concluded that SSF was the cheapest conversion technology for producing ethanol, and fast pyrolysis was the most expensive option due to the initial higher capital cost. They summarized that SSF and acid hydrolysis were practically similar in production cost, and these options were more efficient in recovering lignin than the fast pyrolysis process. Phillips (2007) used Aspen Plus simulation software for modeling the production cost of ethanol for a conversion facility plant capable of processing 2,000 dry metric tons of biomass per day. Using gasification and catalytic synthesis, they found low production cost (¢1.54/MJ) for ethanol from poplar (*Populus* spp.) biomass and suggested that the cost of producing ethanol from poplar can be competitive with corn ethanol over time.

Frederick et al. (2008a) estimated that ethanol could be produced at a cost ranging from ¢1.84 to ¢4.04/MJ by acid hydrolysis and fermentation of loblolly pine (*Pinus taeda*) in the southern United States. In their study, they considered cellulose fiber as a coproduct. Frederick et al. (2008b) have found similar estimates with cogenerated electricity credits from the same feedstock. Wooley

Table 1 Cost of ethanol production from forestry feedstocks (2015 dollars)[a]

Reference	Technology	Feedstock	¢/MJ (min)	¢/MJ (max)
So & Brown (1999)	Fast pyrolysis	Wood	2.82	ND
	Saccharification and fermentation	Wood	2.29	ND
	Acid hydrolysis and fermentation	Wood	2.42	ND
Wooley et al. (1999)	Acid hydrolysis and enzymatic hydrolysis	Yellow poplar	2.58	ND
Phillips (2007)	Gasification and catalytic synthesis	Hybrid poplar	1.54	ND
Frederick et al. (2008a)	Hydrolysis, cellulose fiber as coproduct	Loblolly pine	1.84	4.04
Frederick et al. (2008b)	Hydrolysis, with electricity credits	Loblolly pine	1.78	2.11
Gnansounou & Dauriat (2011)	Hydrolysis, with electricity credits	Poplar	3.93	ND
	Hydrolysis, without electricity credits	Eucalyptus	2.90	ND
Gonzalez et al. (2012)	Gasification and catalytic synthesis	Loblolly pine	2.65	ND
		Natural hardwood	2.80	ND
		Eucalyptus	2.90	ND
Dwivedi & Khanna (2014a)	Hydrolysis, with electricity credits, intensive management	Slash pine	3.70	7.41
	Hydrolysis, without electricity credits, intensive management	Slash pine	4.51	8.11
	Hydrolysis, with electricity credits, intensive management	Slash pine	3.70	9.51
	Hydrolysis, without electricity credits, nonintensive management	Slash pine	4.51	10.31
Dwivedi & Khanna (2015)	Hydrolysis, intensive management (reforested)	Slash pine	4.30	4.50
	Hydrolysis, nonintensive management (reforested)	Slash pine	4.30	4.50
	Hydrolysis, intensive management (afforested)	Slash pine	4.30	4.50
	Hydrolysis, nonintensive management (afforested)	Slash pine	4.30	4.50

[a]We have used a conversion factor of 21 MJ per liter of ethanol (Thomas 2000) to compare results reported in different studies.
Abbreviation: ND, no data.

et al. (1999) considered simultaneous dilute acid prehydrolysis and enzymatic hydrolysis with yellow poplar (*Liriodendron tulipifera*) biomass and found a slightly higher production cost (¢2.58/MJ). For the similar conversion technology, Gnansounou & Dauriat (2011) compared eucalyptus (*Eucalyptus* spp.) and poplar (along with straw and switchgrass, *Panicum virgatum*) for ethanol production and found that the ethanol derived from eucalyptus costs less than that from poplar. Even though more ethanol can be produced from poplar per dry matter basis (349 L/dry metric ton) than eucalyptus (334 L/dry metric ton), the production cost of ethanol derived from eucalyptus was cheaper, as eucalyptus yield was higher than poplar, and feedstock cost was lower. A lower cost of ethanol production from loblolly pine compared to eucalyptus and natural hardwood was reported by Gonzalez et al. (2012). The difference was due to higher production of ethanol per dry metric ton from loblolly pine. Loblolly pine also provided higher net present value than other feedstocks in the study by Gonzalez et al. (2012).

Dwivedi & Khanna (2014a, 2015) provided detailed information on ethanol production using slash pine (*Pinus elliottii*) as a feedstock for various management choices, i.e., intensive versus

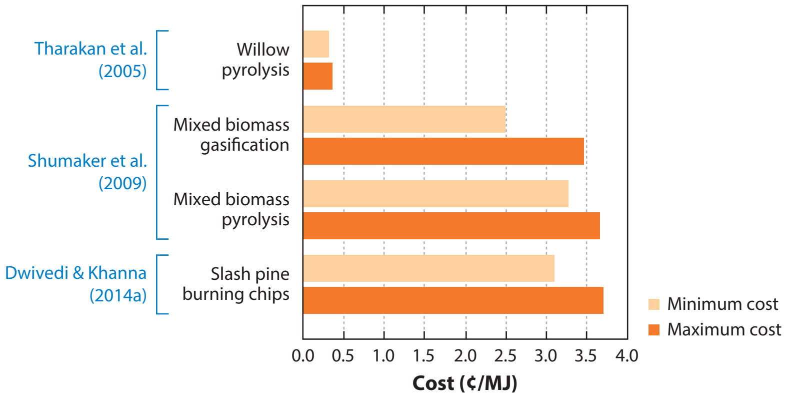

Figure 4

Unit electricity cost (2015 US dollars) of electricity from woody biomass (except wood pellets).

nonintensive. In general, nonintensive forest management with no fertilizer and herbicide yielded a lower unit cost for ethanol than did intensive forest management. Their land expectation value estimation suggested that the optimal rotation age plays a significant role in the production cost coupled with forest management choices. The presence of cogenerated electricity credits lowered the cost of ethanol by approximately ¢1/MJ, according to Gnansounou & Dauriat (2011) and Dwivedi & Khanna (2014a). Reforested and afforested slash pine did not seem to have any significant difference in terms of ethanol production cost according to Dwivedi & Khanna (2015). Because the cost of ethanol production from forestry feedstock is higher than the fossil fuel alternative, a need for subsidy and incentive programs is suggested by existing studies. A carbon tax of $25 and $30/metric ton of carbon dioxide emission was estimated by Dwivedi & Khanna (2015) and Dwivedi & Khanna (2014a), respectively, for ensuring production of ethanol from woody feedstocks in the United States in general and in the southern United States in particular.

Biopower

Existing studies ascertaining the megajoule of electricity produced from woody feedstocks (not including wood pellets) report a range from ¢0.3 to ¢3.7 in 2015 adjusted dollars (**Figure 4**). Tharakan et al. (2005) found that willow biomass can be supplied to the power plant for ¢0.36/MJ, and it can be as low as ¢0.3/MJ with an increased yield. Even at that price, it was not competitive with coal because the price of coal was 0.16/MJ at that time. They found that the Conservation Reserve Program payments reduce the delivered price only by 33% and, therefore, other incentive programs will be needed for the economic feasibility of cofiring willow biomass with coal. Using a different conversion technique, Shumaker et al. (2009) estimated the overall production cost of electricity derived from feedstocks in Georgia, such as pecan (*Carya illinoinensis*) hulls, poultry litter, wood chips, wood residues, corn and cotton (*Gossypium hirsutum*) residues, hay, and switchgrass. They reported lower prices for wood chips and wood residue than for most other feedstocks. They also compared electricity production cost from mixed biomass for different-sized power plants. It was found that the production cost declines by approximately ¢0.28/MJ when plant size increases from 160 to 533 wet metric tons/day of the incoming feedstock. They also evaluated two electricity production methods (gasification and pyrolysis) and concluded that gasification costs less than pyrolysis independent of plant sizes. Dwivedi & Khanna (2014a) reported that electricity

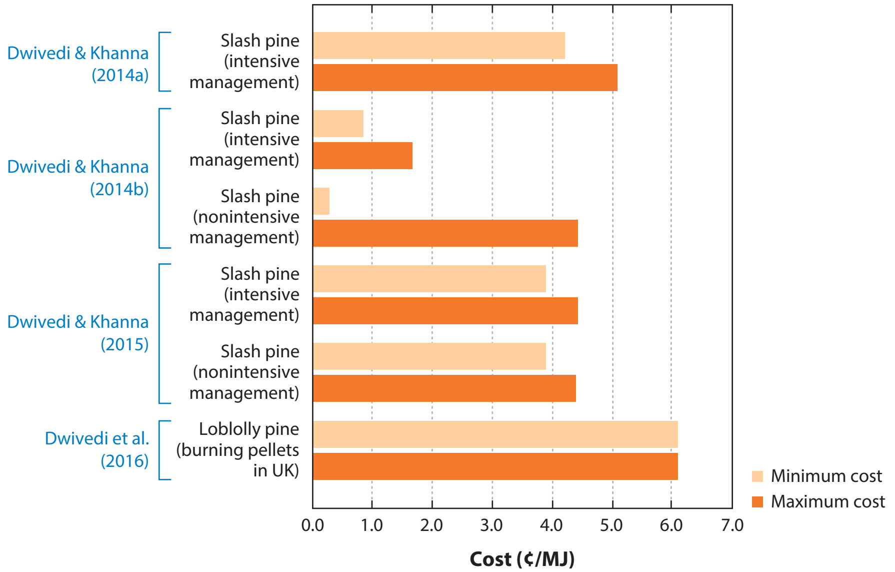

Figure 5

Unit electricity cost (2015 US dollars) of electricity from wood pellets.

generated from burning wood chips obtained from an intensively managed slash pine plantation would range from ¢3.1 to ¢3.7/MJ. Heller et al. (2004) discussed energy savings for electricity from willow biomass that makes the economic case of biopower stronger. They reported that cofiring could increase the net energy ratio to 0.34 (about a 9% increase) compared to the average grid energy ratio of 0.26 in the United States. The authors also reported that biomass gasification is a significantly better option, as the net energy ratio ranged from 9.9 to 13.3. Studies indicate that financial incentives are necessary to make wood-based electricity competitive. Robinson et al. (2003) concluded that cofiring biomass with coal for electricity is a cost-effective use of biomass, especially when costs related to emissions are taken into account.

Biopower from Wood Pellets

Pelletization of biomass is a critical variable in estimating electricity production cost (**Figure 5**). Although pelletization seems to be more feasible for long transportation, it adds cost for shorter transportation distance of biomass. Electricity from pellets can be approximately ¢1/MJ more expensive than from chips (Dwivedi & Khanna 2014a). Dwivedi et al. (2016) analyzed the pathway for pellets produced from loblolly pine and reported a unit production cost of about ¢6/MJ. This estimate was higher than other estimates of unit production cost, as it included the transatlantic shipment of pellets from the southern United States to the United Kingdom. Dwivedi & Khanna (2015) reported that forest management choices (intensive and nonintensive) did not make any significant difference in the unit production cost. Using logging residues instead of pulpwood or a combination of logging residues and pulpwood reduced the production cost by approximately ¢0.28/MJ under both intensive and nonintensive forest management choices. Electricity generated using wood chips had lower carbon abatement cost ($7/metric ton of carbon dioxide) than did electricity derived from wood pellets ($38/metric ton of carbon dioxide) according to Dwivedi & Khanna (2014a, 2015).

SOCIAL DIMENSIONS OF WOOD-BASED BIOENERGY DEVELOPMENT

Several studies have focused on the social dimensions of wood-based bioenergy development in the United States. For example, Susaeta et al. (2011) surveyed the public in Florida, Virginia, and Arkansas to assess their willingness to pay for wood-based electricity generation and found that the respondents were willing to pay $0.41/unit of electricity generated from woody feedstocks. Susaeta et al. (2010) surveyed the public in three southern states to estimate their willingness to pay for ethanol blends of 10% (E10) and 85% (E85) where ethanol was derived from woody feedstocks. The willingness to pay for E10 was ¢14.8/L, ¢15.3/L, and ¢12.7/L in Arkansas, Florida, and Virginia, respectively. The willingness to pay for E85 was ¢21.7/L, ¢30.9/L, and ¢28.0/L in Arkansas, Florida, and Virginia, respectively. Additionally, several studies using the input-output modeling approach have reported that the use of woody feedstocks for bioenergy development will lead to better employment opportunities and economic growth (Gan & Smith 2007, Perez-Verdin et al. 2008, Joshi et al. 2012, Henderson et al. 2017).

Joshi & Mehmood (2011) surveyed nonindustrial forest landowners in the United States and demonstrated that landowners' willingness to harvest woody biomass for bioenergy development was influenced by their ownership objectives, size and structure of the forest, composition of tree species, and demographic characteristics. Aguilar et al. (2014) conducted a survey of nonindustrial forest landowners to ascertain their willingness to harvest for timber and woody biomass, timber only, woody biomass only, and nothing. They found that timber revenues had a greater marginal effect on the willingness to harvest timber and woody biomass, compared with harvesting timber. This highlights the importance of strong traditional timber markets for increasing the availability of woody feedstocks for bioenergy development. Dwivedi & Alavalapati (2009) used a multicriteria decision-making approach for ascertaining perceptions of four stakeholder groups about the use of wood-based bioenergy development in the southern United States. Becker et al. (2013) surveyed 1,109 family forest landowners in Minnesota and Wisconsin and found that payment offered to a landowner to harvest biomass coupled with landowner attitudes and opinions regarding soil impacts, aesthetics, and energy independence were important indicators of stated willingness to harvest biomass for bioenergy development. Stidham & Simon-Brown (2011) interviewed 40 individuals in Oregon to explore the social context of converting forest biomass to energy. They found that stakeholder groups are concerned about access to a consistent long-term supply of biomass and envision bioenergy development as a medium of forest restoration in the region. Hitchner et al. (2016) and Schelhas et al. (2018) have used ethnographic methods to ascertain the relationship between cultural norms related to wood-based bioenergy development across scales in the southern United States. Several other studies have also explored the social dimensions of wood-based bioenergy development in the United States (Buchholz et al. 2007, Mayfield et al. 2007, Susaeta et al. 2009, Plate et al. 2010, Aguilar & Saunders 2011, Joshi & Mehmood 2011, Gruchy et al. 2012, G.C. & Mehmood 2012, Joshi et al. 2013, Leitch et al. 2013). An analysis of studies focusing on social dimensions suggests a positive outlook on wood-based bioenergy development. Incentives will be needed for biomass harvesting at the landowner level, coupled with a thoughtful communication strategy at the societal level, to characterize the benefits of wood-based bioenergy development in a subtle manner.

EXTERNALITIES OF WOOD-BASED BIOENERGY DEVELOPMENT

Some studies have also investigated policy frameworks and developed case studies measuring the sustainability of wood-based bioenergy development in the United States. For example, Cook & Beyea (2000) expressed concern that the development of wood-based bioenergy development could lead to intensive management of forests, thereby adversely affecting vital ecosystem functions, including biodiversity conservation. Several studies have analyzed the role of bioenergy development on water quality and quantity (Shepard 2006, Griffiths et al. 2017, Caldwell et al. 2018, Griffiths et al. 2018), soil carbon (Schlamadinger et al. 1995, Coleman et al. 2004), and local biodiversity (Grodsky et al. 2016, 2017; Fritts et al. 2017). Dale et al. (2017b) developed case studies for assessing the impact of the development of wood pellets on forest conditions in the southeastern United States and found that the production of wood-based pellets there could enhance greenhouse gas sequestration in forestlands over space and time. Dale et al. (2017a) have emphasized the systematic monitoring and evaluation coupled with rigorous scientific research of managed forests for ensuring sustainable development of transatlantic wood pellet development in the southern United States. Parish et al. (2017) have proposed reference scenarios for evaluating the sustainability of wood pellet production in the same region to avoid conflicting estimates and large uncertainties across studies, which focus on the environmental impacts of wood-based bioenergy development. There exists a policy debate about the merits of carbon-related benefits of the use of woody feedstocks for bioenergy development relative to equivalent fossil fuel–based substitutes (Cornwall 2017, Schlesinger 2018). However, Khanna et al. (2017) and Dwivedi et al. (2019) have clearly articulated assumptions behind such a wide range of claims about the carbon intensity of electricity derived from woody feedstocks in general and wood pellets in particular. In this regard, we report on studies that reflect on the carbon intensity of wood-based bioenergy products to ascertain a trend in published studies.

Carbon Intensity of Wood-Based Ethanol

Higher estimates of the carbon intensity of wood-based ethanol from the literature (**Table 2**) range from 20 to 25 gCO_2eq/MJ (Dwivedi & Khanna 2014a,b; Daystar et al. 2015) and lower estimates are about 10 gCO_2eq/MJ (Dwivedi & Khanna 2015). Even higher estimates are considerably lower than its fossil fuel alternative gasoline, at approximately 93 gCO_2eq/MJ (EPA 2018). Budsberg et al. (2012) found net negative emissions (−17 gCO_2eq/MJ) of ethanol derived from willow. However, when electricity coproduct allocation was assumed, net emission was 20 gCO_2eq/MJ, which was 77% less than from gasoline.

Management choice is an important criterion for carbon emissions. In general, intensive forest management of slash pine emitted higher carbon emissions than the choice of nonintensive forest management (Dwivedi & Khanna 2014a,b; 2015). The nonintensive forest management choice could lower carbon emissions by 2 gCO_2eq/MJ. However, intensive forest management was a better option for carbon savings in certain scenarios based on per-unit land basis (Dwivedi & Khanna 2014b). Under both forest management choices, Dwivedi & Khanna (2014a) reported that carbon emission from ethanol production from slash pine was approximately 18 gCO_2eq/MJ lower in the presence of cogenerated electricity credits. The difference in carbon emissions can also be made with the choice of biomass from forestry feedstock such as logging residues only, pulpwood only, or a mixture of both. The ethanol derived from logging residues of slash pine had the least carbon emissions under all forest management choices on a per-unit energy basis. However, it is important to consider the amount of biomass available as a feedstock for bioenergy development while estimating the carbon emissions related to the wood-based bioenergy products. While using logging residues and pulpwood obtained from a slash pine plantation together for ethanol production, the carbon emissions were found to be different between calculations based on per-unit energy basis versus calculations based on per-unit land basis (Dwivedi & Khanna 2014b). Using a mix of logging residues and pulpwood as a potential feedstock for ethanol production was the least carbon intensive on a per-unit energy basis, but most carbon intensive on a per-unit land

Table 2 Carbon intensity of ethanol production from woody feedstocks

Reference	Technology	Feedstock	gCO_2e/MJ (min)	gCO_2e/MJ (max)
Budsberg et al. (2012)	Saccharification and fermentation	Willow	−17	20
Dwivedi & Khanna (2014a)	Hydrolysis, with electricity credits, intensive management	Slash pine	3.5	9.7
	Hydrolysis, without electricity credits, intensive management	Slash pine	21.9	28.1
	Hydrolysis, with electricity credits, nonintensive management	Slash pine	1.8	14.6
	Hydrolysis, without electricity credits, nonintensive management	Slash pine	20.2	33
Dwivedi & Khanna (2014b)	Hydrolysis, intensive management	Slash pine	21.9	22.86
	Hydrolysis, nonintensive management	Slash pine	20.24	20.48
Daystar et al. (2015)	Gasification and alcohol synthesis	Loblolly pine	26.1	ND
		Eucalyptus	21.7	ND
		Unmanaged hardwood	24.9	ND
		Forest residues	25	ND
		Forest residues with burdens	25.1	ND
Dwivedi & Khanna (2015)	Reforested, intensive management	Slash pine	11.80	12.85
	Reforested, nonintensive management	Slash pine	9.76	10.47
	Afforested, intensive management	Slash pine	11.90	13.33
	Afforested, nonintensive management	Slash pine	9.52	10.47

basis. This highlights the importance of evaluating efficiency from the perspective of both land and energy before making bioenergy-related decisions, especially in the context of sustainability.

Dwivedi & Khanna (2015) showed the impact of another important variable in deriving ethanol from slash pine—afforestation versus reforestation. It is logical to think that sequestered carbon in the land will be higher in afforested land compared to reforested land. However, on a per-unit energy basis, that did not make any noticeable difference in the carbon emissions. Daystar et al. (2015) estimated the carbon intensity of ethanol derived from loblolly pine, eucalyptus, unmanaged hardwoods, and forest residues (along with switchgrass, which we do not report) and found that ethanol derived from eucalyptus had the lowest carbon intensity. They evaluated forest residue under two scenarios with and without various feedstock production burdens. These burdens resulted from the establishment, maintenance, and harvest of primary biomass activities. However, these two options were not significantly different from each other. Emission from unmanaged hardwood (24.9 gCO_2e/MJ) did not differ from forest residue (25 gCO_2e/MJ). Loblolly pine was the most intensive option (26.1 gCO_2e/MJ) among these feedstocks, but the authors made a case that this difference was inconsequential.

The Carbon Intensity of Biopower

Based on various forest management choices and biomass processing methods, the carbon intensity of wood-based electricity can range from 12 to 47 gCO_2e/MJ (**Figure 6**). These estimates are considerably lower than the carbon intensity (324 gCO_2e/MJ) of coal-based electricity in the United States (EIA 2018a). Huang & Bagdon (2018) reported lower greenhouse gases

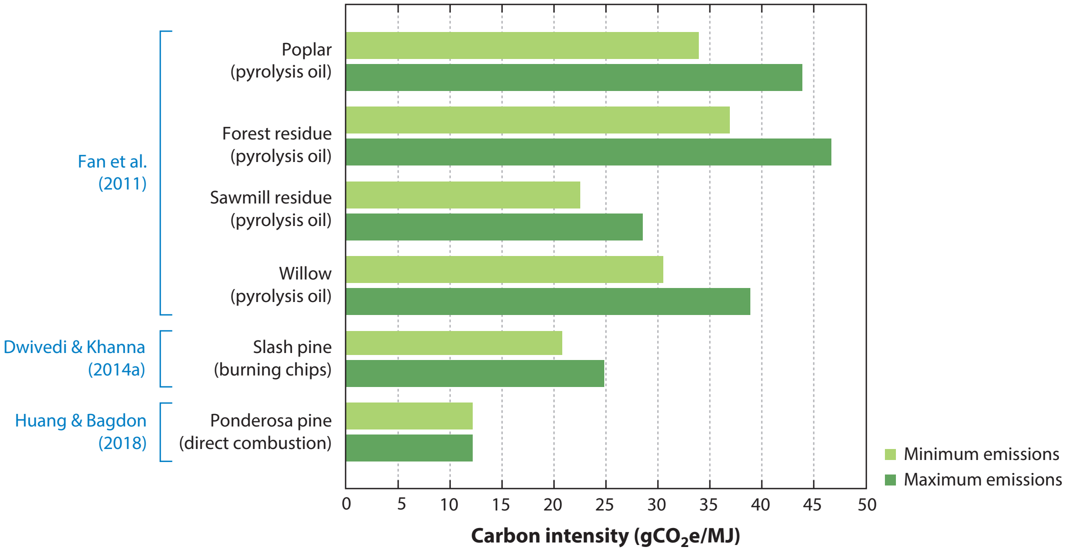

Figure 6

Carbon intensity of electricity from woody biomass (except wood pellets).

(12.2 gCO_2e/MJ) because they have considered the direct combustion of mixed biomass from ponderosa pine to produce electricity. They compared coal-fired and biomass-based power production for several air pollutants and found that wood-based electricity saves about 95% of carbon emissions. Fan et al. (2011) compared pyrolysis oil from poplar, forest residue, sawmill residue, and willow biomass under three scenarios of replacing coal, natural gas, and oil for electricity production. They reported a 77% to 99% carbon savings for power generation compared to its fossil fuel alternative. Among them, carbon savings were highest when pyrolysis oil replaces coal and lowest when it replaces natural gas. The carbon intensity of electricity derived from sawmill residue was lowest (23–29 gCO_2e/MJ), whereas the electricity derived from forest residues was most carbon intense (37–47 gCO_2e/MJ). Burning chips from intensively managed slash pine emitted 21–25 gCO_2e/MJ of electricity (Dwivedi & Khanna 2014a) based on the choice of biomass—logging residue, pulpwood, or combined. These estimates suggest high carbon savings in the biopower sector compared to fossil fuel. Other studies also reported significantly lower carbon emissions for electricity generation from cofiring biomass compared to coal (Mann & Spath 2001, Robinson et al. 2003, Heller et al. 2004, McKechnie et al. 2011, Loeffler & Anderson 2014, Sebastián et al. 2011).

Carbon Intensity of Biopower from Wood Pellets

Pelletization increases the carbon intensity of electricity derived from wood pellets. Estimates of carbon intensity electricity derived from wood pellets range from 37 and 82 gCO_2e/MJ based on forest management systems and transportation distances (**Figure 7**). Even after adding carbon emission (155 kg CO_2e/metric ton of wood) from pelletization (Dwivedi et al. 2011), the carbon intensity of electricity derived from the wood pellets relative to coal-based electricity is lower by at least 75% in the United States. Dwivedi et al. (2011) estimated and compared the global warming impact of electricity production from slash pine produced and used in Florida and the Netherlands. They concluded that electricity from wood pellets has a lower global warming impact than their fossil fuel counterparts in both places and, obviously, it is significantly lower in

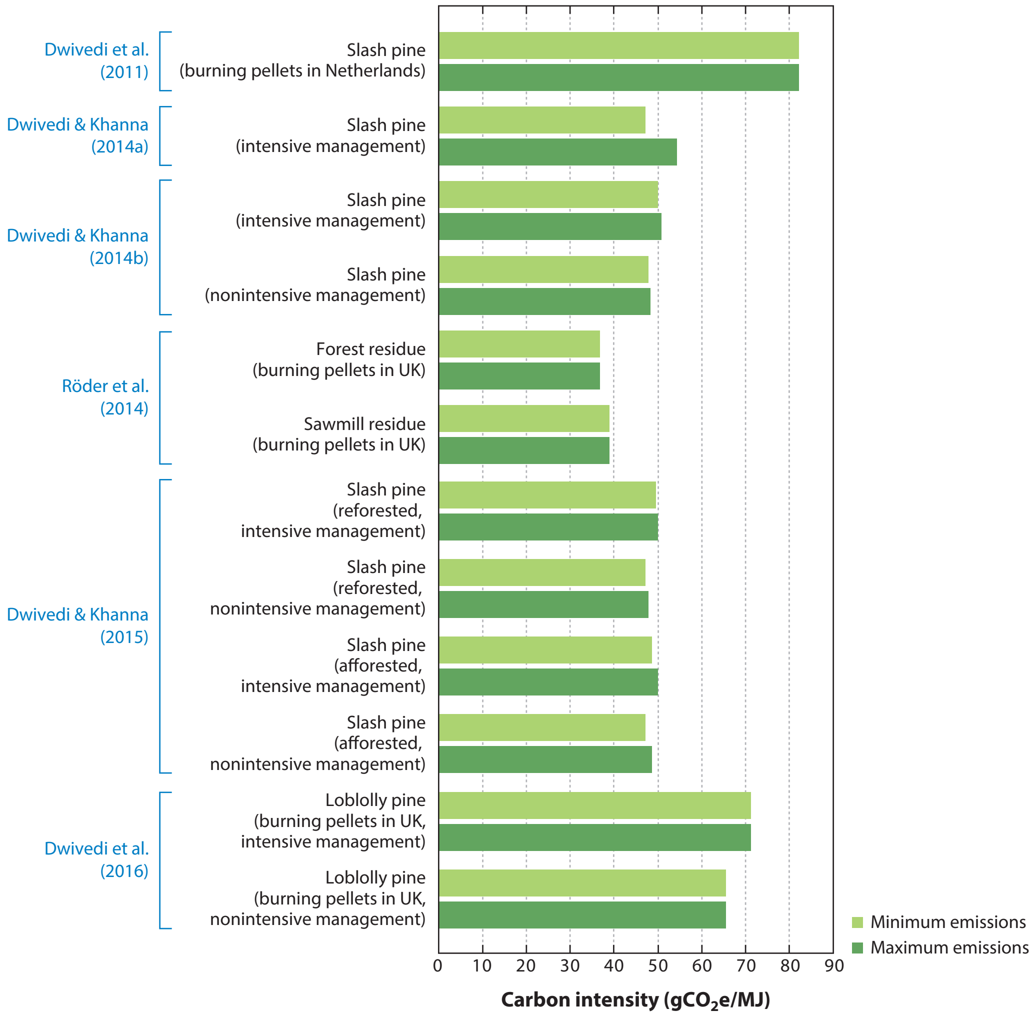

Figure 7

Carbon intensity of electricity from wood pellets.

Florida. This study reports a net savings of between 49% and 72% for every unit of electricity produced using imported wood pellets instead of fossil fuel in the Netherlands. These savings are even higher in Florida, between 74% and 84%. The authors recommended that tightening the energy efficiency standards in the supply chain could further reduce the carbon intensity of electricity generated from wood pellets.

Röder et al. (2014) also compared forest residue and sawmill residue for electricity production. For pellets produced in the southeastern United States and used in the United Kingdom, they found that forest residue is less carbon intensive (37 gCO_2e/MJ) than sawmill residue (39 gCO_2e/MJ). Dwivedi et al. (2016) also analyzed a similar pathway, burning southeastern US pellets in the United Kingdom, for pulpwood derived from loblolly pine and reported higher estimates for carbon emissions (65–71 gCO_2e/MJ). This is understandable, as this study considered harvesting pulpwood for electricity instead of residue, which accrues fewer carbon emissions.

Wang et al. (2015) studied a similar pathway comparing pellets from forest biomass only and together with agricultural biomass to account for carbon emissions related to direct and indirect land-use changes induced by the demand for wood pellets for export purposes. They estimate carbon intensity between 44 and 78 gCO_2e/MJ, which is comparable to other studies analyzing a similar pathway (Dwivedi et al. 2011, 2016).

DISCUSSION AND CONCLUSION

Policies supporting biofuel development in the United States have not been successful in promoting the use of wood-based ethanol development. This is mostly because a commercially viable conversion technology is still not available that could compete with existing prices of various competitive fuels derived from crude oil. In the meantime, the demand for woody biomass for generating heat and electricity is increasing in the United States. Most demand for biomass-based heat is concentrated in the midwestern and northeastern states, as wood pellet stoves are increasingly gaining popularity in these two regions fueled by state support. On the other hand, most demand for the biomass-based electricity originates from the European Union, as European power utilities are increasingly importing wood pellets from the southern United States to replace coal-based electricity. Therefore, it is very likely that in the foreseeable future a large amount of potentially available woody biomass (97 million tons by 2040) for bioenergy development will be diverted for manufacturing wood pellets to meet either the domestic demand for heating or the international demand for electricity generation.

It is important to keep in mind that forest productivity has increased over time in the United States (Fox 2000). In the 1950s, only 0.81 million hectares were under planted pines in the southern United States relative to 12.9 million hectares at the end of twentieth century (Fox et al. 2007a). Silvicultural improvements have considerably enhanced the productivity of pine plantations, leading to a situation where plantations established in the 2000s could produce in excess of 28 cubic meters per hectare per year relative to plantations established in the 1950s and 1960s with the productivity of only 6.3 cubic meters per hectare per year or less (Fox et al. 2007a). This incredible increase in productivity led to a decrease in harvest age of pine plantations in the southern United States (Fox et al. 2007b). Adams et al. (2005) also found that silvicultural treatments (fertilizers) increased the productivity of Douglas fir [*Pseudotsuga menziesii* (Mirb.) Franco] in western Washington by an average of 20% compared to unfertilized stands. It is expected that new emerging technologies like CRISPR would further help to increase the productivity of the forest plantations in the United States (Tsai & Xue 2015), thereby sufficing the need for additional biomass, if any, for the emerging wood-based bioenergy industry. However, caution is warranted to ensure that new biotechnologies and silvicultural technologies are compatible with changing climate (Hanson & Weltzin 2000) and to reduce the risk to bioenergy stakeholder groups starting from a family land landowner to an investor in the bioenergy sector.

The projected cost of ethanol production across existing conversion technologies has not shown any decreasing trend. This can be again attributed to the absence of any commercially viable conversion technology. The average maximum and minimum costs of producing a megajoule of ethanol across conversion technologies were ¢5.9 and ¢2.9, respectively, depending on the price, yield, and sugar content of the selected feedstock. The projected cost of electricity production has not changed much over the years. The average maximum and minimum costs of producing a megajoule of electricity were found to be ¢3.34 and ¢2.4, respectively, depending on the price and yield of selected feedstock. This further implies that wood-based electricity generation is relatively cheaper on an equivalent energy basis than ethanol derived from woody feedstocks in the United States. The production cost of electricity derived from wood pellets was higher due to the higher pelletizing cost and transatlantic shipment of wood pellets. Altogether, the production costs of bioenergy products (ethanol, biopower) were higher than equivalent products obtained from fossilized fuel resources.

The average maximum and minimum carbon intensities related to a megajoule of ethanol across conversion technologies were 17.8 and 14.8 gCO_2, respectively, depending on the selected conversion technology, feedstock type, and emissions allocation methods. The average maximum and minimum carbon intensities related to a megajoule of electricity were 46.03 and 42.66 gCO_2, respectively, without accounting for biogenic carbon emissions, mostly depending on the selected feedstock type and forest management. This further implies that the carbon intensity of wood-based electricity generation could be higher on an equivalent basis than the ethanol derived from woody feedstocks. Our study shows that the carbon intensity of electricity derived from imported wood pellets in the European Union is even higher due to carbon emissions related to the pelletizing and transatlantic shipment. Altogether, the carbon intensity of bioenergy services (ethanol, biopower) obtained from woody feedstocks was much lower than equivalent services obtained from fossilized fuel resources.

Our study indicates that strong policy support is needed for promoting wood-based cellulosic ethanol in the United States. Additionally, investments in research are needed to reduce the production cost of wood-based ethanol. In the meantime, the focus should also be placed on generating electricity from woody feedstocks, as it is cheaper overall and saves a significant amount of carbon emissions relative to electricity derived from coal or natural gas. We hope that our study will suitably guide future policy deliberations on the utilization of woody feedstocks for accomplish the objectives of attaining energy independence, reducing carbon emissions, and ensuring rural prosperity in the United States in a sustainable manner.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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