

Review

Socioeconomic Constraints to Biomass Removal from Forest Lands for Fire Risk Reduction in the Western U.S.

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Abstract: Many socioeconomic constraints exist for biomass removals from federal lands in the western U.S. We examine several issues of importance, including biomass supply chains and harvesting costs, innovative new uses for bioenergy products, and the policy framework in place to provide incentives for biomass use. Western states vary greatly in the extent and utilization of forest resources, the proportion of land under federal ownership, and community and stakeholder structure and dynamics. Our research—which focused on the socioeconomic factors associated with biomass removal, production, and use—identified several important trends. Long-term stewardship projects could play a role in influencing project economics while being conducive to private investment. State policies are likely to help guide the growth of biomass utilization for energy products. New markets and technologies, such as biofuels, for use in the aviation industry, torrefied wood, mobile pyrolysis, and wood coal cofiring could greatly change the landscape of biomass use. Social needs of residents in wildland urban interfaces will play an important role, especially in an era of megafires. All of these trends—including significant unknowns, like the volatile prices of fossil energy—are likely to affect the economics of biomass removal and use in western forests.

Keywords: hazard fuels; fire risk; biomass; bioenergy; community; socioeconomic barriers; forest policy

1. Introduction

In the United States, the National Fire Plan of 2000 has led to federal agencies undergoing wide-ranging efforts to reduce wildfire risks while improving forest health in western forests. The 12 western states encompass close to 34 million hectare (ha) of timberland, with about 31.5 million ha (93%) being managed by federal agencies [1]. Despite several decades of mitigation efforts, wildfires have persisted, with 2.78 million acres being burned in western forests during 2017 [2]. An estimated 23.9 million ha of timberland in 12 western states have been identified as having high risks of stand-replacing fires [3]. Nearly 3800 communities near federal lands in western states are considered to be at high risk of wildfire [4]. At the same time, suppression costs between 2006 and 2009 ranged from \$1500 to \$4200 per ha [5].

Biomass utilization in western forests has been fairly limited, with the exception of California's use of biomass for electrical generation. Skog et al. [6] identified several classes of biomass resources available from western U.S. forests:

- thinnings related to hazard fuel treatments
- logging residues remaining after conventional logging operations
- pinyon-juniper treatments
- thinnings on private forestlands
- precommercial thinnings on national forestland (primarily in western Oregon and Washington)
- wood products manufacturing residues

In many parts of the west, biomass utilization has been largely related to wood products producers, with scant use of any of these other resources. Significant economic barriers continue to prevent widespread use of biomass in the western U.S. Unlike many eastern and southern locations, biomass is a more dispersed resource in the west. Primary factors influencing the economic feasibility of small-diameter harvests also depend on the different harvesting systems needed based on ecological and spatial parameters and on forest productivity [7]. There is also great regional variability in the volumes of harvest residues generated. Smith et al. [8] indicate that the volume of 2006 harvest residues for the Pacific coastal forests was about six times greater than that of the Rocky Mountain region.

It is also important to distinguish between thinnings as part of normal silvicultural treatments and hazard fuel thinnings which are designed to reduce fire risk, protect property, and increase the safety of community residents. However, for both types of treatments, a common denominator is the challenge of finding long-term economically viable markets. In Montana, it has been estimated that hazard reduction thinnings could yield upwards of four times more biomass than standard precommercial thinnings [9]. Other methods can also be used to improve the economic potential of fuel treatments. Prestemon et al. [10] used Monte Carlo simulation to assess economic benefits from mechanical treatments on western forestlands. They found that when product sales (including some larger trees greater than 21 inches diameter breast height (DBH)) were incorporated into prescriptions, more than 25% of treated areas would have net economic benefits. Their simulation allowed for three alternative prescriptions: (a) larger diameter tree removals favored, based on stand density index, (b) smaller diameter tree removals favored, also based on stand density index, and (c) thin-from-below prescription designed to achieve fuel hazard reductions.

Similarly, Bolding et al. [11] found that mechanical treatments of non-merchantable biomass could incur costs of up to \$2394 per ha, but when including merchantable stems (greater than 7-inch DBH) these net costs were reduced to about \$240 per acre. Ince et al. [12] found that the type of silvicultural prescription can significantly influence project economics. Here, even-aged thinning regimes (where 50% of original basal area was removed) were found to be less economical than uneven age regimes.

Wood energy development in western states is hindered by a lack of wood products infrastructure, which has been declining over much of the past 25 years [13]. Perhaps just as significant a driver of biomass utilization is the role of state policy, including renewable energy portfolio goals, especially in states that have abundant biomass resources. For example, California has set an ambitious goal of 33% renewable energy by 2020 [14], and Oregon a goal of 50% of electric use from renewables by 2040 [15]. Although these renewable goals also include wind, solar, and geothermal energy, wood is likely to play a key role in states where the wood products industry, and related supply chains, are well developed.

Several recent developments are helping make biomass use more economically viable. On Forest Service lands, several stewardship contracts have been completed [16]. Long-term stewardship contracts, lasting up to 20 years, are likely to play a key role in future biomass utilization. Long-term stewardship contracts are expected to allow time for wood products and biomass-related businesses to become established, often a problem with short-term contracts lasting only a few years. Other "game changers"—such as torrefied biomass, advanced gasification, cofiring wood and coal,

and new classes of bio-based products and mass timber products—are helping expand the reach of western forest products businesses. The combined effect of these factors is to augment existing value chains and develop critical infrastructure.

Several key themes related to biomass use and wildfire risk reduction in the western U.S. federal lands are examined in this synthesis. We first consider harvesting, transportation costs, and logistics, as well as the potential use of salvaged timber. Next, we look at both traditional and emerging wood products and innovative bioenergy products, as well as the economic factors that could enhance or limit their potential. Finally, we examine the role of forest policy—including federal and state policies—in stimulating biomass use and fire hazard reduction activities and reducing economic barriers.

2. Challenges and Strategies for Removing Biomass

2.1. *Harvesting Systems and Logistics That Are Commonly Used to Remove Biomass*

When considering biomass removals from western forests, the biomass component rarely “pays its way out of the woods”, and in some cases the true cost can be several times the market value of biomass. Steep terrain, road access, land ownership, and machine processing costs are leading barriers. Despite these barriers, there are a several types of commercial harvesting systems in use, and a number of strategies that can be used to overcome these challenges.

Mechanical removal of biomass from federal forestlands is often preferred, as this allows biomass to be removed without generating smoke and the risk of fire escape associated with prescribed burning or pile burn. This also has the potential added benefit of producing energy from a renewable source [17]. Three types of biomass harvesting operations are commonly used to remove biomass: slash recovery, whole-tree chipping, and integrated harvesting. Slash recovery operations focus on residues left at landings or along the roadside from timber sales, including commercial thinning, while whole-tree chipping systems are often used when small-diameter (less than 20 cm DBH) trees produced from fuel reduction thinning need to be removed. Slash recovery operations take place after harvesting sawlog materials, however, no sawlogs are harvested in whole-tree chipping operations. Integrated harvesting operations utilize forest machinery to harvest sawlog and biomass at the same time (i.e., with one-entry thinning).

Depending on which biomass removal system is selected, operational logistics and machinery used are often different and highly variable, which directly effects the cost of biomass removal. Decisions to select one of the three biomass removal systems described are made based on the amount (e.g., tons/ha) and spatial location/distribution of biomass, material types (slash or whole trees), economics, and work requirements. For example, a fuel reduction thinning contract in Arizona used a whole-tree chipping method, as the thinning treatment required removal of trees less than 12 cm DBH [18]. However, a commercial thinning operation in northern California recommended an integrated harvesting system be used, as the contract required removal of both sawlogs and biomass within one entry and a limited time [17]. Both operations resulted in a cost that was higher than the market values of biomass feedstock (less than \$55/ oven dry ton (Odt)) in those regions at the time of operations. Compared to whole-tree and integrated harvesting operations, slash recovery operations often result in a lower cost (sometimes less than \$22/Odt excluding hauling cost). This is because biomass is already piled at landings or along roadsides and therefore does not require felling and extracting from stands [19].

2.2. *Challenges and Strategies for Biomass Harvesting and Transportation*

Besides the low market value of biomass, high costs associated with hauling biomass to energy markets have been identified as a major barrier making biomass utilization cost-prohibitive [20,21]. Chip vans carry a fixed amount of biomass (less than 23 metric tons in California and Arizona), and hauling cost increases with an increase of distance and travel time required to complete a round trip. Biomass hauling cost alone (excluding harvesting and comminution costs) often determine the

economic feasibility of mechanical removal of biomass for production of energy. Hauling distance on forest roads, in particular, directly determines travel time, as average travel speeds on forest roads are typically 16 km per hour (kph) for logging roads and less than 48 kph on graveled county roads [22]. Several strategies have been developed to reduce transportation cost, including blowing chips into a chip van container, resulting in an increase in bulk density of chips loaded [23] (Figure 1), lowering moisture content on site using natural air (i.e., transpiration) before comminution [24], and increasing hauling capacity using larger containers or double trailers [25].

Accessibility to harvest sites using a chip van is often limited due to its large turning radius on a horizontal curve and limited gradability on steep roads [26]. Forest roads have typically been used for hauling logs using a log truck as the design vehicle, and a chip van may not be able to travel through certain sections of roads that have less than an 18 m curve radius. A stinger-steered logging truck (typical design vehicle) can negotiate a horizontal curve that has a radius down to 15 m [27,28]. Thus, there are several challenges with navigating mountain roads with logging trucks and/or chip vans. Several recent innovations, however, are helping to enable these vehicles to navigate steeper grades on more primitive roads, resulting in more economical access to biomass harvesting sites. A rear-steerable-axle chip van was developed to reduce the issues associated with these tight curve radii, allowing the trailer to negotiate curves similar to those of stinger steer log trucks. In addition to turning radius issues, empty chip vans may not be able to climb steep roads (i.e., gradability) due to lighter weight on the drive axles or slippery road conditions due to snow or water.

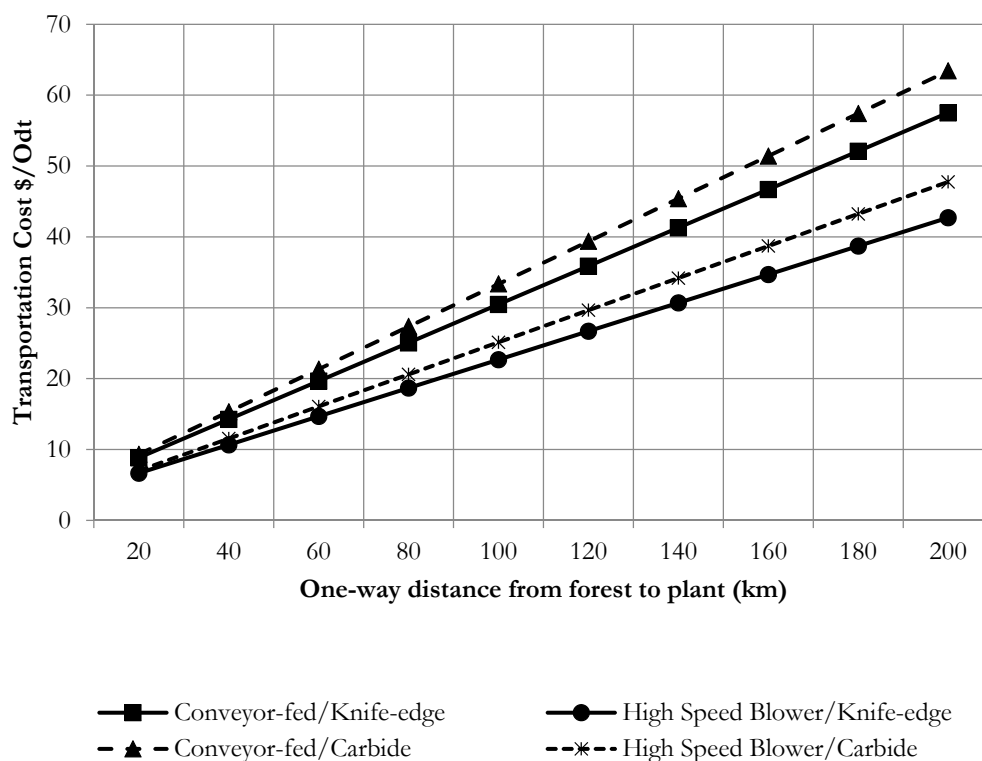


Figure 1. Transportation cost for each of the two loading methods (conveyer-fed by gravity and blowing chips into a container) on pulpwood size class residue. A combination of knife-edge bits and blower loading increased the bulk density of loads, resulting in \$14.70/Odt for hauling pulpwood type materials on a 200 km one-way trip. Source: Zamora et al. 2014 [23].

Gradability of a chip van on a horizontal curve is further limited because “either wheel loading is not equal or traction conditions are not uniform [26].” In addition to gradability, vertical curves often cause drop-center trailers to contact the road surface, either damaging the trailer or causing the vehicle to become stuck. To address this issue, an attempt was made to put a container on a stinger-steered truck in order to travel like logging truck, locking differential(s) allowing both sides of an axle to be powered, and reduced tire pressure was attempted to increase traction [29]. Results concluded that a single locking differential greatly assisted the gradability of pulling an unloaded chip trailer uphill on challenging road conditions.

When considering operational logistics, centralized biomass recovery systems have been developed and have shown promise for both increased access to remote sites and facilitated transportation logistics. A modified dump truck having high ground clearance and short turn radius was cost-effectively used to deliver biomass from a biomass harvest site to a centralized grinding site; biomass was then ground to hog fuel and loaded onto a chip van [30,31]. Anderson et al. [32] compared two approaches using a dump truck to access harvest sites: (1) delivering loose slash materials to a central landing where they were stockpiled then ground directly into large chip vans and (2) grinding slash into dump trucks at the harvest site and delivering to a central landing where it was stockpiled and loaded into chip vans using a front-end loader. They found either approach had similar stump-to-truck costs of \$26–\$27 per green metric-ton; however, forwarding slash appeared to be more productive when slash was sparsely scattered. A roll-off container truck teamed up with a small front-end loader was cost-effectively used to remove chainsaw-felled and hand-piled biomass resulting from shade fuel break treatments from a site where chip van access was not possible [33]. In addition to the benefits of improved access to sites, a centralized biomass recovery system has increased potential for federal forestlands. This is because federal land management practices often favor less intensive harvests with biomass piles tending to be more sparsely scattered over larger landscapes. By contrast, a pile-to-pile operation (i.e., slash recovery) is often seen in industrial timber operations on private land where clear-cut operations generate large amounts of biomass highly concentrated within one timber harvest unit.

Recently, a group of researchers collaborated to convert biomass into pre-processed feedstock or products at or near the forest site [34]. Two major benefits were realized by integrating mobile biomass conversion technologies with in-woods biomass operations: (1) adding value to the converted products and (2) reduced transportation cost. Biomass materials were sorted and separated into stem wood and slash piles (including only limbs and branches) during timber harvesting operations, which allows lowering moisture content in biomass down to less than 20% while facilitating chipping operation to produce quality chips uniform in size with no contamination. Those wood chips were converted into biochar, torrefied wood chip, and briquettes at the conversion site located near the biomass harvest site. The concept examined in this study showed strong promise; however, further development of mobile biomass conversion technologies to reduce biomass conversion costs and finding markets that are willing to pay a higher price for those products are needed to advance this technology.

Catastrophic events such as droughts, insect outbreaks, and fires have occurred across many acres within federal forestlands. Although these can create large volumes of contiguous biomass, harvesting salvage material having a short “shelf-life” can be challenging and the value loss for some products almost immediate [35,36]. Prestemon et al. [37] estimated that 19.7 billion cubic feet of standing timber potentially could be salvaged across 8.2 million ha of western forestlands in the United States. While salvaged trees can be sources of biomass feedstock, biomass recovery rates from beetle-killed trees were lower than biomass harvesting from live forests, and a timely harvesting decision (i.e., soon after trees are dead) is key to reducing harvesting costs [38]. Safety is also of concern when working in stands of dead trees. Other species of trees—such as junipers (*Juniperus occidentalis* var. *occidentalis* and *Juniperus occidentalis* var. *australis*), saltcedar (*Tamarix* spp.), and Russian olive (*Elaeagnus angustifolia* L.)—removed from rangeland restoration treatments also provide potential bioenergy opportunity, but are often difficult to fell due to tree form and crown

characteristics. In addition, these trees are expensive to extract because they are typically of low volume and often scattered, resulting in low area volumes [39].

It is clear that “in-woods” considerations, including efficient harvesting, increased road access, and biomass pre-processing, all can have an impact on the future economics of the biomass supply chain. Ultimately, future economic innovations in biomass harvesting and transportation could be dictated by new products and markets.

3. Western Biomass Use and Products

3.1. Wood Products and Biofuels from Forest Harvesting Residues

Challenges finding profitable uses for woody biomass are not new. It is an issue that exists in all regions of the U.S. and can be traced back several decades. Changes in land management objectives that focus increasingly on ecosystem services, approaches to fighting wildfires, and shifts in demographics as people move into the wildland urban interface, have put a different face on the landscape. Lack of utilization opportunities has helped to increase the number of forested acres that are densely stocked with small-diameter trees. As a result, forest health has suffered and disturbance events such as wildfires and insect epidemics have increased in both size and occurrence. This is especially true in the western U.S., where catastrophic wildfires are in the news more frequently and tree mortality from insects and disease is rampant.

Biomass utilization has been seen as a way to offset the cost of restoration treatments, thus freeing up dollars that would allow more acres to be treated [40]. However, it is not just about utilization opportunities. Just because biomass is available does not necessarily mean the infrastructure exists to process it. Moreover, if the infrastructure is present to process the biomass or small logs, that does not mean they can, or are, producing a product for which there is increased market demand. Even if there is a market, competition or demand may not make it profitable to produce. Economics, specifically profitability for biomass industries, plays a major role, as does securing the capital to invest in new enterprises. There are many aspects to consider and think about when it comes to biomass utilization.

As noted earlier, woody biomass can take several forms. It may be small logs, tops and branches left in slash piles, chunkwood (unmerchantable or decayed pieces), or residues such as sawdust and bark from processing [41]. Several pathways to biomass utilization and different breakdown methods of woody material are available. Some require a simple mechanical breakdown process (e.g., lumber or veneer) while others require a series of breakdown processes to reach a final product (e.g., alcohols for biofuels). Research on some these pathways and products is ongoing. Processes and products may have demonstrated success at the pilot scale but have not yet been proven at the commercial level. This is primarily due to lack of capital to bring to commercialization [42]. Capital investment amounts vary—depending on which pathway you choose and whether you are starting from scratch or adding to existing infrastructure. Some take little capital investment, while others take millions of dollars to construct. In order to build biomass utilization capacity, there needs to be certainty that the business will be able to operate for more than 1 or 2 years, not just handle the biomass from a current project in the area. The scale and type of infrastructure must be a good match for material being removed [43].

What can you make from small-diameter trees and biomass removed in restoration treatments? Figure 2, while not exhaustive, provides an overall picture of raw material input, breakdown method, and the types of products that can be manufactured. It is not likely that one single wood product will solve all the challenges of biomass utilization.

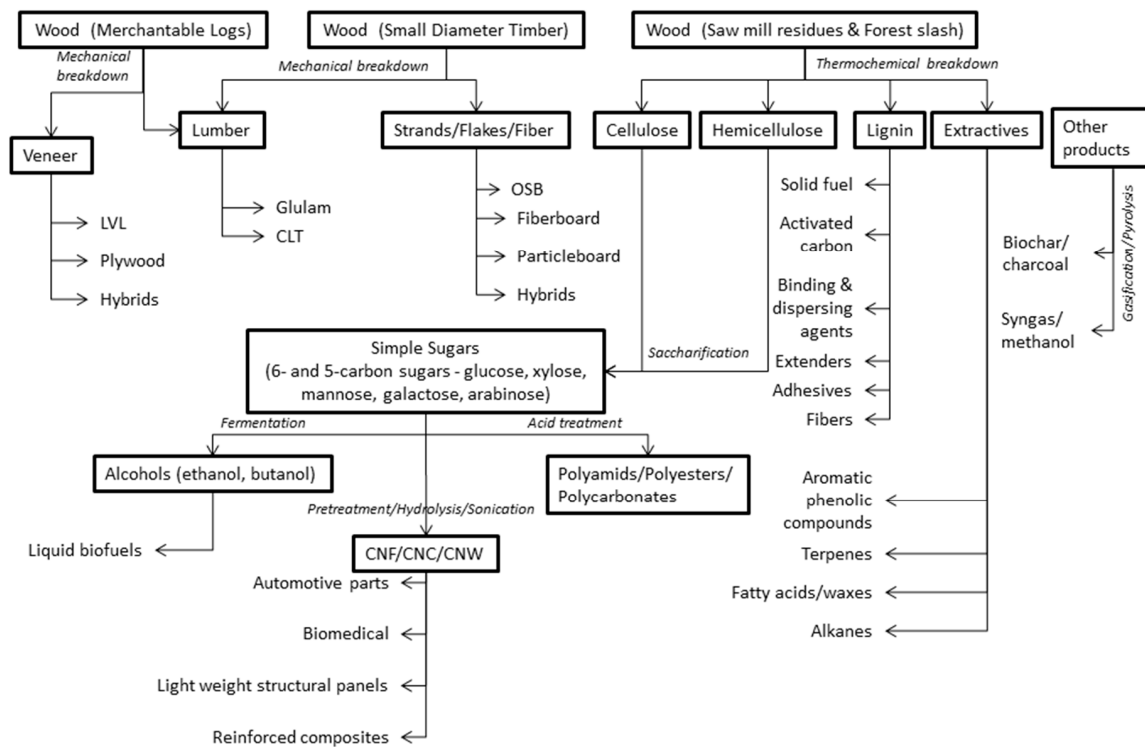


Figure 2. Raw material form, breakdown processes, and products that can be manufactured from small-diameter trees and woody biomass. Figure caption abbreviations to insert: (LVL=laminated veneer lumber, CLT=cross laminated timber, OSB=oriented strand board, CNF=cellulosic nanofibrils, CNC= cellulosic nanocrystals, CNW=cellulosic nanowhiskers) Source: Lowell et al. [44].

One of the key considerations is ensuring that raw material characteristics match the product that is planned for manufacturing and that the supply is sufficient and consistently available. Scale of operation is critical. Many failed attempts at biomass utilization can be attributed to supply issues. When dealing with small-diameter trees from forest restoration treatments, there must be a realistic knowledge of the size, quality, and quantity of material that will be removed. For example, Table 1 illustrates the raw material requirements for different size sawmills. What scale of production will a specific feedstock supply support?

Table 1 also points out that manufacturing does not produce just lumber. Byproducts (or residues) of some processes, as in the case of sawmilling, will need to be handled—utilized, sold, or hauled away—at your expense. Integration of processes and products offers one solution, but balance of materials can be an obstacle. In some cases, especially at the rural community level, it may be best to start small, with a proven process, and grow an industry as supply becomes stable. Lowell et al. [44] provide a Biomass Enterprise Economic Model that allows a user to explore a phased approach to growing an integrated biomass enterprise based on the mechanical breakdown pathway. While many equate biomass utilization with wood energy (heat and electricity), it often is only part of the picture.

Table 1. Raw material requirements for different lumber production scenarios, ranging in size from micro to large sawmills.

	Units of Measure	Micro Sawmill	Small Sawmill	Medium Sawmill	Large Sawmill
Production/shift	Thousand board feet, lumber scale	5.0	50.0	150.0	400.0
Annual production	Million board feet, lumber scale	1.25	12.5	37.5	100.0
Chip, sawdust production	Million cubic feet	0.07	0.70	2.10	5.6

Table 1. Cont.

	Units of Measure	Micro Sawmill	Small Sawmill	Medium Sawmill	Large Sawmill
Annual log requirement	Million board feet, log scale	0.625	6.250	18.75	50.0
Log truckloads per year		130	1302	3906	10,417
Chip vans per year		55	549	1648	4394

Source: Nechodom et al. (2008) [45].

The biorefinery concept (thermochemical breakdown) relies on producing a suite of products, including things like chemicals, specialty products, and fuels. Many new technologies are still in development or at the pilot stage and have not moved to commercialization because they still cannot be produced economically. Through thermochemical breakdown, wood is broken down into its macromolecular cell wall components of cellulose, hemicellulose, and lignin plus other components such as extractives. As with mechanical breakdown, you not only get the fraction of wood that you plan on using to manufacture a product [46]. Byproducts must be handled as well.

Capital for developing new projects using existing technology can be scarce. It gets harder when looking to bring a new product to market. Some products are still not at the point where they are economically competitive (e.g., aviation jet fuel from woody biomass) [47].

Probably the easiest thing to do with some woody biomass is to burn it to generate heat and electricity. In its raw form (hog fuel), this is the lowest value product. However, there are numerous other pathways for wood energy that increase value, from firewood and pellets to aviation jet fuel.

3.2. Current Wood Energy Use in Western States

A total of 32 biomass electrical facilities operate in western states, with installed capacity of 847 MW (Table 2) [48]. Bioenergy use is well developed in California, where more than 18 solid-fuel biomass electrical facilities are present, consuming more than 7 million tons of biomass and agricultural wastes per year [49]. Many of these sites were established over 30 years ago and have contributed up to 15% of California's total renewable energy generation. In Oregon, wood energy use is also vibrant, often related to the wood products industry and the residues they generate. Here, close to 14 combined heat and power plants utilize between 2.7 and 3.6 million metric-tons of wood per year [48].

Table 2. Electric generating facilities in western states using woody biomass feedstocks.

State	Number of Facilities	Total Installed Capacity (MW)
Arizona	1	27
California	18	457
Colorado	1	11.5
Montana	1	3
Oregon	5	156
Washington	6	193

Source: compiled from Gibson 2011 [48].

Despite many economic barriers, there have been notable wood energy successes in western states. Notable success stories for wood energy include the Fuels for Schools program, started in 2003 in Darby, Montana. Within 7 years, more than 19 wood energy systems had been established, including schools, a university, a landfill, and 2 prisons [50]. This represents a diverse group of energy users and also demonstrates how quickly new wood energy applications can come online. Wood energy use is more limited within the four corner states (Colorado, Utah, Arizona, and New Mexico), however, these states typically have greater numbers of coal plants, potentially resulting in increased opportunities for cofiring.

Wood pellets, although more expensive than chips, are nonetheless an important wood energy product. In western states, there are 29 commercial-scale pellet mills with a total capacity of one million

metric tons per year (Table 3) [51]. The wood pellet industry in the western U.S. could benefit from several possible trends, including cofiring biomass at coal facilities and potential export markets to Asia. There are opportunities to use processes such as hot water extraction of wood chips in biorefining, where the woody biomass is then a byproduct that can then be used in the pellet and pulp and paper industries. Amidon et al. [46] found that this process imparted beneficial properties to the residual woody biomass, including lower ash content and higher lignin and cellulose content.

Table 3. Pellet mills and capacity, by state, for the western U.S.

State	Number of Pellet Mills	State-Wide Pellet Capacity (tons per year)
Alaska	1	31,751
Arizona	2	72,574
California	2	154,221
Colorado	3	206,837
Idaho	7	227,400
New Mexico	3	47,173
Oregon	7	268,523
Utah	2	77,109
Washington	1	34,472
Wyoming	1	4535

Source: compiled from Anon 2017 [51].

3.3. Cofiring Coal and Woody Biomass

In the western U.S. states, there are 128 operating coal-powered electrical facilities [52]. In cofiring, coal and biomass are mixed together before being combusted. However, in the U.S., cofiring is currently done very little on an ongoing basis, and very few plants in the west have even conducted test-burning trials. Economic factors influencing cofiring were evaluated by Aguilar et al. [53] and Goerndt et al. [54]. Their econometric models evaluated plant location, the number of coal-fired power plants in a county, and availability of wood mill residues. A key finding of this research was the need for flexible design in power plants to accommodate fuel feeding, fuel handling, and transportation systems suitable for both biomass and coal feedstocks at various ratios. Although their research focused on the northern U.S., some of these findings could also be relevant for western states. For example, given the distributed nature of both the forest resources and the location of power plants in western states, flexibility will be needed for power plants to economically utilize biomass.

Many western coal plants are located near national forests, offering an opportunity for co-combusting these materials. However, due to the large size of coal-burning plants (many consume more than 1 million tons of coal per year), cofiring even at relatively low ratios can still require large volumes of woody biomass. A current challenge is finding grinding equipment capable of processing both wood and coal down to the small sizes needed for pulverized fuel injection systems. Other economic barriers can be the capital investment needed for new fuel handling equipment. This is often the case when cofiring at rates greater than about 5% of energy value.

Although forest biomass removals represent a viable feedstock for cofiring, they must also be consistent and reliable over the long term, especially if capital investments in plant equipment are required. For example, Nicholls et al. [55] considered the use of woody biomass from fire hazard reduction thinnings near Fairbanks, Alaska, as a cofiring feedstock. It was found that long-term cofiring operations would require a range of woody materials, including forest harvesting residues, sawmill residues, and municipal wastes. In Arizona, the Four Forest Restoration Initiative (4FRI) project could provide cofiring feedstocks to one or more coal facilities over the next 20 years. Use of salvaged timber also represents a cofiring opportunity. Beagle and Belmont [56] evaluated five coal power plants in Colorado and Wyoming, finding sufficient beetle-killed biomass within 160 km of each facility to cofire at a 20% level.

Future economic trends could favor the use of torrefied biomass as a cofiring feedstock. Torrefied wood is simply biomass that has been heat treated at temperatures of about 300 °C, driving off volatile compounds. Due to its high energy density, torrefied wood can be transported more economically than traditional wood chips or harvesting residues. Torrefied wood is closer to the fuel density of coal and handles much like coal, both operational advantages. Due to its water repellent properties, it can also be stored outside longer than wood chips, eliminating the expense of building covered storage systems. Finally, agricultural residues can also be torrefied, giving flexibility to the feedstocks used.

Perhaps the biggest “game changer” for torrefied wood utilization would be if one or more western coal plants either cofired or converted entirely to torrefied wood. This possibility is being explored for the conversion of the Boardman, Oregon power plant away from coal (starting in 2020). However, since the state of the art capacity for torrefied biomass in the U.S. is only about 45,000 metric tons per year, numerous distributed facilities would be needed to supply a even single coal plant, even at relatively low cofiring rates [57]. Acharya et al. [58] reviewed six different torrefaction technologies, including proven methods as well as those under development. Economies of scale in production could lead to lower cost torrefied fuels, making them more competitive with coal.

3.4. Economic Barriers for Biomass Use on Western Forests

The economic feasibility of mechanical treatments is directly related to the value of products removed. For example, Hartsough et al. [59] collected data from seven sites in the western U.S., finding that the upfront costs of mechanical treatments were greater than for prescribed fire, but the net costs (after accounting for timber value removed) were often less than those for fire. Of the seven regional sites evaluated, project economics were most favorable for the southern Cascades and central Sierra (with net profits averaging about \$7165 per ha).

Fried et al. [60] modeled an 11 million ha study area in Oregon and northern California, finding that, if mechanical treatments were applied to 2 million ha, the sustained biomass yields would be enough to fuel four 50 MW power plants. Merchantable timber products would result in net revenues of \$2.6 billion. Thus, careful site selection is critical when considering long-term planning needed for investment in wood products and power plant infrastructure. In similar work (but over a wider multistate area), Skog et al. [3] found that delivered values of biomass from western forests could range from \$3953 to \$6424 per ha if stems greater than 18 cm DBH were utilized primarily for higher value products. If all biomass were to be chipped, delivered values ranged from \$1062 to \$1581 per ha.

Skog et al. [6] also found that the potential amounts of forest biomass supplied is very sensitive to price. In a 16-state western region, biomass supplies were relatively unaffected when prices ranged from \$30 to \$50 per Odt. However, between \$50 and \$75/Odt, prices increased by about 64% (Table 4). Further, terrain can greatly influence economics [61]. In this analysis of 12 western states, net revenues from mechanical treatments were positive in all 8 types of treatments considered for slopes of less than 40% (but only 4 of 8 treatments when slopes were greater than 40%).

Table 4. Base case cumulative forest biomass supply by state and roadside cost.

Biomass Supply (oven dry tons/year) at Various Roadside Costs (\$ per oven dry ton)			
	\$30	\$50	\$75
Arizona	222,599	228,874	2,092,106
California	3,966,745	4,104,845	4,263,956
Colorado	279,369	341,516	1,542,596
Idaho	1,478,387	1,669,077	1,803,476
Montana	1,554,616	1,768,144	1,850,486
Nevada	7122	7195	1,370,524
New Mexico	299,745	352,722	1,675,499

Table 4. *Cont.*

Biomass Supply (oven dry tons/year) at Various Roadside Costs (\$ per oven dry ton)			
Oregon	1,712,498	1,824,752	1,850,106
Utah	101,966	128,534	1,776,062
Washington	1,657,948	1,803,262	1,820,173
Wyoming	185,505	211,075	298,320
Total	11,466,500	12,439,996	20,343,304

Source: compiled from Skog et al. (2008) [6].

Thus, many variables can influence project economics for biomass removals, including type of treatment (fire versus mechanical), slope, current prices of biomass and of higher valued lumber products, transportation costs, and the proportion of larger, higher value stems removed. One variable that could receive future attention is accounting for fire suppression costs. Larson [62] found that small-diameter biomass utilization led to negative financial returns in the context of the first 10 years of the 4FRI stewardship contract. However, when considering the avoided wildfire suppression costs in the analysis, net gains were realized. Huang et al. [5] found that average suppression costs for 2006–2009 in western forests were high, ranging from \$1563/ha (fiscal year 2007) to \$4234/ha (fiscal year 2009).

3.5. Partnership Models

To address biomass utilization more holistically, partnerships that cross land ownerships have developed at the federal level (e.g., Collaborative Landscape Forest Restoration Program), the regional level (e.g., Four Corners Sustainable Partnership), and the local level (e.g., Applegate Adaptive Management Area). New authorities that allow for a more stable supply over a longer period of time have also been implemented (e.g., stewardship contracting, Good Neighbor Authority).

Stewardship projects on federal lands are a means of exchanging “goods for services”. For example, a contractor will remove forest biomass, and in doing so reduce fire risk and improve forest health. Several notable stewardship contracts have been completed successfully in western states, including Oregon, Idaho, Montana, Colorado, and Arizona [16]. Kerkvliet [63] found that the Clearwater Stewardship Project in western Montana provided a \$23 million increase in sales for eight Montana counties in addition to the creation of 148 jobs. In Arizona, the White Mountain Stewardship Project, started in 2004, became the first 10-year stewardship project, with close to 20,000 ha treated [64]. During the first 5 years, government funding of \$30 million had generated \$40 million in local investments, expenditures, and tax revenue. Currently underway is the 4FRI stewardship contract in Arizona. The 4FRI Stakeholder Group consists of more than 30 organizations—conservationists, scientists, local governments, and industry leaders. A goal of 4FRI is to implement restoration treatments across almost 1 million ha over 20 years. As the 4FRI stewardship contract progresses, it will serve as an opportunity for more empirical research regarding the role of forest policies and also the degree to which local (i.e., decentralized) policies can be effective.

3.6. Innovation in Biomass Utilization

Innovation will also play a key role in biomass utilization; for example, new ways of using biomaterials. Growing demand for bio-based materials will require its efficient use and could include a technique call “cascading”. Here, materials are prioritized for use at certain life cycle stages. For example, wood could be used for lumber in home construction, and at the end of its useful life, chipped for energy. Nybakk et al. (2011) [65] found that innovation within the bioenergy sector is often motivated by either new market conditions (for example, rising prices of fossil fuels), newly available biomass sources, or were driven by changes in company strategies (including visionary leaders). In the western U.S., this is evident in the nascent liquid fuels industry. Here, innovative new products (i.e., jet fuels from woody biomass) will require innovations in transforming supply

chains [66]. Other innovative uses of biomass include use in construction materials (i.e., plaster, insulation, and/or concrete) [67].

Firm size and the trajectory of new business growth can also be closely related to innovation. Wagner and Hansen [68] found that small wood products firms tend to perform well across three types of innovation (process, product, and business systems). Larger firms, primarily due to greater access to capital, excelled in process innovation. Innovation could also play a key role in developing new bioenergy applications for western forests. For example, pyrolysis has been explored with woody biomass to create liquid fuels and torrefied wood. Recent research has explored mobile pyrolysis systems, an in-woods innovation, creating transportation cost benefits. Brown et al. [69] found transportation advantages when distances greater than 300 km were required (versus wood chip delivery). Current work is underway to assess different wood fuel types, including clean wood chips versus softwood (limbs and tops) and hardwood (limbs and tops) [70].

Bioenergy products and technologies are becoming more flexible and diverse. This could bode well for the future of biomass utilization on western forestlands because of the distributed nature of the resource, which often leads to economic barriers. Although delivered costs of biomass are still often higher than their market values, innovations in supply chain management could help narrow this gap. Further, one or more “game changers” (for example, expanded use of torrefied wood or aviation fuel) could alter the bioenergy landscape. Alternative and innovative uses of biomass and biomass coproducts are likely to remain as national priorities—for example, energy security and climate change remain on the forefront. Social barriers can also limit biomass use and acceptance. The importance of community involvement in fuel reduction treatments has been suggested as a key way to mitigate social barriers [71]. Further research on innovation with the forest products industry, including biomaterials and new energy products, should help to increase diffusion and reduce barriers across social, political, technical, and economic arenas.

4. Forest Policies and Biomass Utilization

4.1. Background

Research has identified nearly 500 state and federal policies influencing forest-based bioenergy development [72]. These policies are organized into three approaches: incentives, regulations, and information. Incentive policies aim to reduce the capital cost and operating expense of projects. Regulations mandate production and consumption standards and information policies include feasibility studies and the dissemination of information. The growth of these policies can be attributed to a variety of policy and forest management motivations, including the use of locally available feedstocks to reduce dependence on foreign energy sources, reduce greenhouse gas emissions [73], and stimulate economic opportunities [74]. Utilizing low-value wood products, such as forest residues, for energy purposes also presents an opportunity to reduce costs of fuel reduction treatments and enhance forest restoration, offset carbon emissions [75], engage local communities, and create permanent jobs [72,76–78]. Resulting state and federal policies affect each step in the supply chain, regional public and private investments, and use a wide range of incentives, regulations, and other types of mechanisms to affect wood energy development [79].

In the short run, the heightened demand for forest biomass as an energy source will depend on age class structure of forest biomass, and the impact of price and availability of wood for traditional wood products such as pulp and paper [80,81]. However, research conducted in Europe suggests that multiple uses of forest residues are possible, depending on the profitability of the residues for bioenergy and the competition between end uses [82].

4.2. Supply Chain

Becker et al. [79] introduced a supply chain policy framework to evaluate effects of state and federal policies on bioenergy development, applied across all 50 states. The number of policies affecting behaviors is important, but also the types of policies. Some states enact a higher total number of policies for a given supply chain step, such as manufacturing, while other states are partial to certain types of policy instruments, such as tax incentives applied to the manufacturing sector. Every state has at least one biomass utilization policy, however, nine of these states had just three or fewer policies. Tax incentives were the most common policy instruments across all states, followed by technical assistance programs and procurement policies. Despite concerns about the cost of raw material transportation, only two states were identified as having policies for offsetting transportation cost [76,79,83,84]. In fact, high transportation cost was rated as the biggest challenge (73%) amongst U.S. Forest Service managers; yet, policies aimed to mitigate transportation costs are essentially nonexistent [78].

Research aids policy development, identifies synergies along the supply chain, and allows policymakers to consider the range of approaches taken to enhance forest biomass utilization. Revealing such policy gaps in the supply chain encourages policymakers to consider the effectiveness and interaction of individual policies, both at the state and federal level, and in context of intersectorial linkages. Failure to coordinate policies across supply chains risks stranding investments, while failing to leverage activities and relationships among businesses, public and private forest landowners, and consumer [85].

Abrams et al. [85] surveyed biomass producers and users at various supply chain steps in six states (California, Oregon, Washington Minnesota, Wisconsin, and Michigan) to explore whether and how policy influences innovation and decision-making. The study design attempted to decipher the effects of individual policies as well as the interaction of policies vertically (evaluating the balance of state and federal policies) and horizontally (across the supply chain). Overall, only 12% of the responses mentioned policies as factors influencing innovation; the remaining 88% focused on nonpolicy impacts such as new technology or perceived market advantages. This suggests policies may be narrowly impacting forest biomass innovation [85]. Tax policies (37% of identified policies), disbursements and direct subsidies (34%), and rules and regulations (12%) were most frequently identified as influential. When compared across the supply chain, power and utility producers were the most likely to be influenced by state or federal policies.

4.3. Instruments

Policy instruments may be defined as “the set of techniques by which governmental authorities wield their power in attempting to ensure support and effect or prevent social change” [86]. The social change in this context means change in how we generate electricity and heat, and fuel for transportation and manufacturing. Social change can be achieved more readily through a complementary mix of policy instruments than using individual policies because firms and individuals face different constraints and opportunities; a single policy will not change the behavior of all relevant actors [87].

Gossum and colleagues advance a framework for analysis that identifies four key features of effective policies [88]. First, a broad range of policy instruments—such as tax incentives, regulations, or technical assistance programs—are needed to affect social change, and that policy’s performance will depend on the optimal pairing of these instruments with appropriate institutions at local, state, and federal levels [89]. Second, policy instruments that invoke motivational and informative structures are preferred to policy interventions that are highly coercive, especially when actors perceive that there could be self interest in adopting new approaches [90]. This is the case with bioenergy development, renewable energy generation, forest restoration, and economic development, which collectively offers opportunities for mutual benefit. Third, instruments may effectively influence behavior of some firms but not all of them and not all the time, and therefore must be responsive and flexible to change. This is important in the context of bioenergy development because of the

rapid escalation in policies, both state and federal, and the evolving context of forest management and climate change [86,91]. Fourth, approaches that create win-win scenarios encourage actors to exceed policy requirements. This too is relevant to providing adequate incentive for private forest landowners to participate and is beneficial where requirements on energy producers result in more efficient or diversified production.

In context of forest bioenergy, previous research highlights the importance of financial incentives, which generally afford flexibility in design and intention and have the ability to generate information regarding market conditions which is relevant to policymakers [78,92,93]. For example, if a financial incentive is too excessive or inadequate, policymakers can adjust the monetary value. Compared to mandatory policy instruments, financial incentives have the ability to adapt to market conditions [93].

Aside from financial policies, USDA Forest Service managers identified developing use of infrastructure, building partnerships, and formal agreements to develop federal biomass supply as important strategies for increasing forest biomass use [78]. Business owners, however, rarely mentioned government support of research, infrastructure, and procurement policies as influencing innovation, but instead cited taxes, direct payments, and regulations as the most influential. This inconsistency could be because policies affect businesses indirectly, which make the policies difficult to recognize [85,94].

Procurement policies focusing on energy procurement, such as net-metering on the utility grid, may be ineffective at targeting small biomass facilities. Net-metering requires utilities to purchase excess electricity, but small biomass facilities only produce heat for space heating needs thus causing procurement policies to inadvertently favor larger biomass facilities [95]. This suggests that high financial startup costs continue to be significant barriers to implementing new, small biomass facilities [78,95].

While the proliferation of biomass policies suggests growth of the biomass industry, or at least interest in seeing it grow, it also contributes a layer of complexity and possible challenges [80]. For example, incentive policies such as energy portfolios, subsidies, or tax credits could alter the market value of the wood [76,85]. The effectiveness of a policy seems to be a result of how the policy is designed and integrates with existing policies, rather than solely relying on the individual policy type. Rivera et al. [92] recommends further research on the integration of new policies with existing policies to better understand policy goals and interaction of multiple policy types.

4.4. Policy by State/Region

Policymakers should be aware of state- and region-specific challenges of biomass use to design effective policies and foster competition among renewable energy platforms [76,79,92]. Regional differences exist in terms of forest products and energy sectors, social and environmental concerns, and land ownership and use [78]. In regions like the southwest, where the risk of wildfire is significant, more targeted and diverse policy instruments focusing on incentivizing biomass harvesting with fuel reduction or forest restoration practices may be necessary to overcome barriers.

Aside from regional variations, neighboring states tend to influence one another in terms of the number and types of policies implemented [72,79]. States actively seeking to provide incentives appropriate for the types of forest resources present not only serve as examples for neighboring states but will be essential in crafting legislation appropriate for the specific resources available and the scope of the challenges.

Overall, regulatory approaches were found to be common in all states except four southern states and Idaho. Every state has at least one incentive policy that allowed forest biomass to receive government support, but only a limited number of states had legislation promoting forest bioenergy specifically. Financial incentive amounts vary from state to state. For example, the maximum deduction for wood-burning installation varies from \$500 in Arizona to \$20,000 in Idaho, and tax credits for residential customers range from \$500 in Montana, to \$7000 or 35% of project cost in Oregon [72].

4.5. Location

High costs of transportation result in a limited radius for feedstock, making the location and scale of operation a critical factor [76,83]. The arrangement of the supply chain relies heavily on the choice between centralized and decentralized bioenergy production [77,96]. Decision makers consider the availability of the resource, potential price changes due to new interactions, technical restrictions, and the material already used by the forest products industry when considering the location for a biomass facility [76,95].

Installing biomass facilities near a sustainable supply of forest biomass is a critical component for facility success. Areas with high proportions of federal land or fuel reduction activities on forestland near populated areas are thought to be a significant source of energy because these lands typically occur near existing roads, thus enhancing transportation feasibility. There is a fine line between whether roads will increase or impede biomass facility success. Though roads are clearly required to transport biomass, high road density may indicate urban areas that are less likely to support the adoption of biomass facilities [95].

Some research supports the development of decentralized, small-scale biomass facilities. The development of decentralized, small-scale biomass facilities alleviates pressure on forest resources, decreases transportation costs, and may be resilient to supply disruptions, such as invasive species and wildfire. This is supported in the western U.S., given the distributed nature of forest biomass and the long transportation distances often required. Becker et al. [83] found that colocation of processing facilities and shorter travel distances resulted in the largest cost reductions in the supply chain. The depot concept, as it relates to integrated biorefineries and proposed by the Northwest Advanced Renewable Alliance Project, models solids depots (which receive and mechanically process biomass from forest treatments) and liquid depots that can receive raw material from the forest or a solids depot [97].

Despite these perceived benefits, several small-scale plants can create negative consequences such as heavy competition for inputs, high labor costs, and increased road congestion [98]. Regardless of the scale, it is important to implement a replanting management plan once forest biomass harvesting takes place, to prevent overutilization of the resource [77]. However, sustainable replanting programs would depend on many factors including species type, land ownership, site ecology, and forest management objectives, among other factors. In the western U.S., when thinning is done to reduce wildfire risk, replanting would not be required. Ultimately, the scale of the facility depends on the conditions in the area, technology platform, financial conditions, and interactions with the existing wood products industry. Research suggests establishing plants that can take numerous types of energy feedstocks (grass, wood, agricultural residues, and more) provides one approach to mitigate this challenge [76].

Thus, several elements can shape forest policy in western states lands, including how supply chains are structured, policies by state or region, and how policy instruments are implemented. State policies have become especially effective, with several western states setting ambitious goals for renewable energy use, for which woody biomass can be a key component. A key advantage of financial incentives (for example, Oregon's biomass tax credit), is that the incentive amounts can be fine-tuned to achieve desired results.

5. Discussion

After several decades of mechanical fuel treatments and wildfire, there are still large areas of hazard fuels remaining in western forests. This includes not only healthy forests, but large areas of unhealthy overstocked forests as well. There are also many hectares of dead and dying trees as a result of disturbances such as droughts, insect outbreaks, and fires. Large-scale stewardship projects (primarily in Arizona) are making significant progress at removing biomass as well as fine-tuning administrative aspects. However, harvesting and transportation of biomass is still very expensive, unless at least some larger merchantable stems are harvested as well. Innovative harvesting systems can reduce costs—for example, integrated systems that remove both sawlogs and biomass within

one entry and over a limited time [17]. Other innovations have included additional biomass processing at the forest site. Han et al. [34] sorted and separated biomass during timber harvest operations, then converted chips to biochar, torrefied wood, and briquettes.

Numerous studies have evaluated costs of mechanical thinnings, demonstrating the lack of profitability when harvesting for wood chips, and the strong potential profitability when including a portion of larger merchantable stems. Other work has demonstrated that selected regions of the west (for example, southwestern Oregon) contain enough timber and biomass for a sustainable wood products industry and wood energy development [60]. However, many western forest types (notably, pinyon-juniper) would have only a small fraction of this potential. When considering viable bioenergy products, critical aspects must be considered such as the scale of operation, production pathways, and infrastructure required. Nonetheless, more than 30 electrical wood energy facilities are present in western states, about 30 pellet production facilities exist, and numerous wood chips thermal systems (primarily in schools) are in place.

The use of renewable fuels, in general, continues to rise as states pursue ambitious renewable portfolio standards. Tax incentives are commonly used to promote biomass, as are technical assistance programs and procurement policies. However, only two states are known to have policies for offsetting transportation cost. Since many states have multiple policies related to biomass utilization [79], the effectiveness of a given policy often depends on how the policy integrates with other existing policies. In western states, where biomass transportation is a major concern, carefully crafted policies that consider the full scope of related incentives could help shape future bioenergy development.

The future use of biomass from western forests, in an era of climate change and megafires, will depend on many factors. Insect and disease epidemics, drought, and other large-scale events could impact millions of acres, including those in sensitive wildland–urban interfaces. However, “game changing” technologies, such as wood–coal cofiring, large-scale torrefaction, and biorefineries could greatly alter the biomass landscape. In this scenario, biomass supply and value chains would need to be carefully constructed to avoid over-allocating available resources. Sustainability is key. Several changes to the manner in which biomass projects are valued—including accounting for fire suppression costs, carbon costs, and other externalities not currently considered—could also greatly alter the economics for restoration projects.

There are also broad economic factors influencing wood fiber supplies, including biomass. For example, during the 1960s–1990s, extensive forest plantations were established to ensure a steady supply of wood. This was then followed by a period of decreased demand for newsprint, packaging, and other fiber products, leading to lower prices. Thus, on many Forest Service lands, biomass and commercial timber is not economically viable, especially on western forests, where steep slopes and long transportation distances can increase costs. Biomass use has also met resistance from two key national entities—environmental groups and the pulp and paper industry. In the case of environmental groups, resistance has occurred in efforts to block biomass use for fear that energy generation may supplant environmental considerations. In the case of the paper industry, wood fiber from biomass could be seen as a competing raw material to traditional pulp wood. This ongoing resistance is one reason why U.S. renewable energy policies have lagged behind those of the European Union (although other factors are undoubtedly relevant also).

Developments in the fossil fuel industry have also played a role in limiting the use of biomass for energy. First, low natural gas prices have made it difficult for bioenergy to be economical without substantial subsidies. Second, although biomass cofiring with coal has been identified as a way to incrementally reduce fossil fuel use, innovative uses of wood and coal have not yet resonated among power plant managers, except for limited test burns. Perhaps the biggest wildcard, then, will be the future course of fossil fuel prices and their interaction with biomass derived fuels. The past has indicated a sharp interest in wood fuels when oil prices are at high levels, and vice versa when oil prices are low. Economic measures that help to stabilize these price swings should bode well for future

biomass use in the western U.S., while also continuing to improve forest health and reduce fire risk for impacted communities.

6. Conclusions

Large areas of hazard fuels, overstocked forests, and dead and dying trees remain in western forests. However, harvesting and transportation of biomass is often cost prohibitive, particularly in remote locations having steep topography. Mechanical thinnings for biomass removals are economically feasible only when including a portion of larger merchantable stems. There are enough timber and biomass materials present in selected regions of the U.S. for both wood products industry and wood energy development. However key factors such as the scale of operations, various pathways of forest products, and infrastructure requirements must be considered. Evidence of successful biomass utilization in the western U.S. is clear, with more than 30 electrical wood energy facilities, 30 pellet production facilities exist, and numerous wood chips thermal systems are in place. The use of renewable fuels, in general, continues to rise as states pursue ambitious renewable portfolio standards. In western states, where high cost of biomass transportation is a major concern, carefully crafted policies that consider the full scope of the biomass value chain is needed.

The future use of biomass from western forests, in an era of climate change and megafires, will depend on many factors, including insect and disease epidemics, drought, and other large-scale events. However, “game changing” technologies, such as wood–coal cofiring, large-scale torrefaction, and biorefineries could greatly alter the biomass landscape in the future. Given that western U.S. forest landscapes are often more dispersed than other regions of the country, biomass supply and value chains would need to be carefully constructed to optimize the allocation of resources for various scales of operation and types of wood products and biomaterials.

Competing fuels for conventional energy use will also play a key role in biomass utilization. Recent low natural gas prices have made it difficult for bioenergy to be economical without substantial subsidies. Perhaps the biggest unknown, then will be the future course of fossil fuel prices with respect to biofuels. Policies that help to stabilize these price swings should encourage future biomass use in the western U.S., while continuing to improve forest health and reduce fire risk for impacted communities. Policies that emulate the successful use of biomass and biofuels in Europe, if adopted in the U.S. could also play a role in stimulating the bioeconomy.

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