Fields of Fuel: Environmental and Economic Considerations of Transitioning Boardman to Biomass Using Corn and Wheat Residue in a Three State Area

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Executive Summary

As Portland General Electric's (PGE) Boardman Coal Plant (hereafter referred to as Boardman) considers a future in biomass combustion, it must carefully consider the immediate costs of converting and feeding its coal-fired infrastructure as well as the policy scenarios in which a new Boardman could exist. While PGE continues to consider the viability of torrefied *Arundo donax* as a biofuel feedstock, this report examines economic and environmental implications of an alternate transition: to torrefied agricultural residues from corn and wheat in Oregon, Washington, and Idaho. Biomass tax credits may result in substantial tax benefits with a switch to biofuels (section 2.3). However, the costs of transport ($28.5 million, section 3.4) and purchase ($34.5 million, section 3.5) of residue biomass total $63 million, without including the price of new torrefaction units and their staffing. Boardman would need to be able to accommodate 74,400 flatbed trucks coming in from the 27 surrounding counties annually to meet its baseload requirement running at an annual average 300 MW. Torrefaction capabilities would need to be scaled up two- to three-fold from the current capacity of 100 tons dry biomass per hour. Distributing these torrefaction facilities throughout the counties would enable a reduction in the transportation costs of $8.5 million (section 4.3) Combustion of this biomass results in 2.4 million tons of CO_2 emissions (section 2.4.4); Boardman currently emits 4.6 million tons of CO_2 burning coal. Omitting all power plant and torrefaction CO_2 emissions due to the biomass carbon being considered carbon neutral, the net annual CO_2 emissions associated with farming and transport to Boardman of the necessary amount of agricultural waste is 96,000 tons of CO_2 (section 5), substantially lower than current emissions. However, SO_2 emissions are projected to be substantially above legal limits based on the Regional Haze Rule (section 2.1.2 and 2.4.3). Both monetary and ecological costs will accrue in a policy landscape with more restrictive emissions standards than those in which Boardman developed. Conceivable future policies like cap-and-trade (state or federal), further greenhouse gas emissions regulation, and more Prevention of Significant Deterioration standards have the potential to adversely impact the Boardman facility in its transition to biomass. Tax credits and regulatory leeway for biomass, however, might support a successful transition. Whether or not Boardman becomes the first coal plant in the nation to switch to torrefied biofuels will likely be contingent on changes to the Western utilities structure or on exceptions for biofuel in state and federal legislation.

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1 Introduction

1.1 Boardman: Predicament and Possibility

Boardman is in a period of exciting opportunity and new frontiers for energy in the American West. Boardman may become the first coal-fired power plant in the nation to switch to torrefied biofuels – although not necessarily by choice. Caught between several state and federal policies for emissions regulations, Boardman became the defendant in cases between 2008 and 2010 brought by a coalition of environmental groups including the Sierra Club, Friends of the Columbia Gorge, Columbia Riverkeeper, Hells Canyon Preservation Council, and the Northwest Environmental Defense Center.[1] Identified as Oregon's single largest source of greenhouse gas emissions and harmful air pollution at the time (Figure 1), Boardman was required to follow two paths of action: first, to install interim pollution controls for mercury, sulfur dioxide and other emissions and second, to close as a coal plant by 2020. Boardman's slated closing presented, however, an opportunity: Boardman could switch from coal to biomass, biological material derived from living or recently living organisms, and remain open past 2020 as an energy-generating facility.

Boardman's transition would be notable for its scale, history, and legacy. While the first small biomass power plants were built in America in 1982, no plant has been converted at this scale and under so rigorous a set of political mandates. Most biomass power plants burn sawmill residues to turn the turbines to generate electricity, but older plants do so inefficiently because of the varying state (i.e. wetness, type) of residues. Other biomass power plants burn corn residues, rice husks, soy bean and sorghum residues, willow, switch grass, and organic waste from landfills as fuel.[2] Boardman would be able to source its biofuel from the ample agricultural biomass residue in the Pacific Northwest, the focus of our study. Locally-sourced residue from wheat and corn could conceivably fuel a portion of energy production in the region from which it came, a region that prioritizes environmental health.

[1] The Sierra Club's suit implicated multiple policies: federal and state Clean Air Act Regional Haze and Mercury Rules, the Resource Conservation and Recovery Act, the Title V Operating Permit, and the State's PUC Integrated Resource Plan.
[2] http://www.humanities360.com/index.php/biomass-energy-in-america-38323/

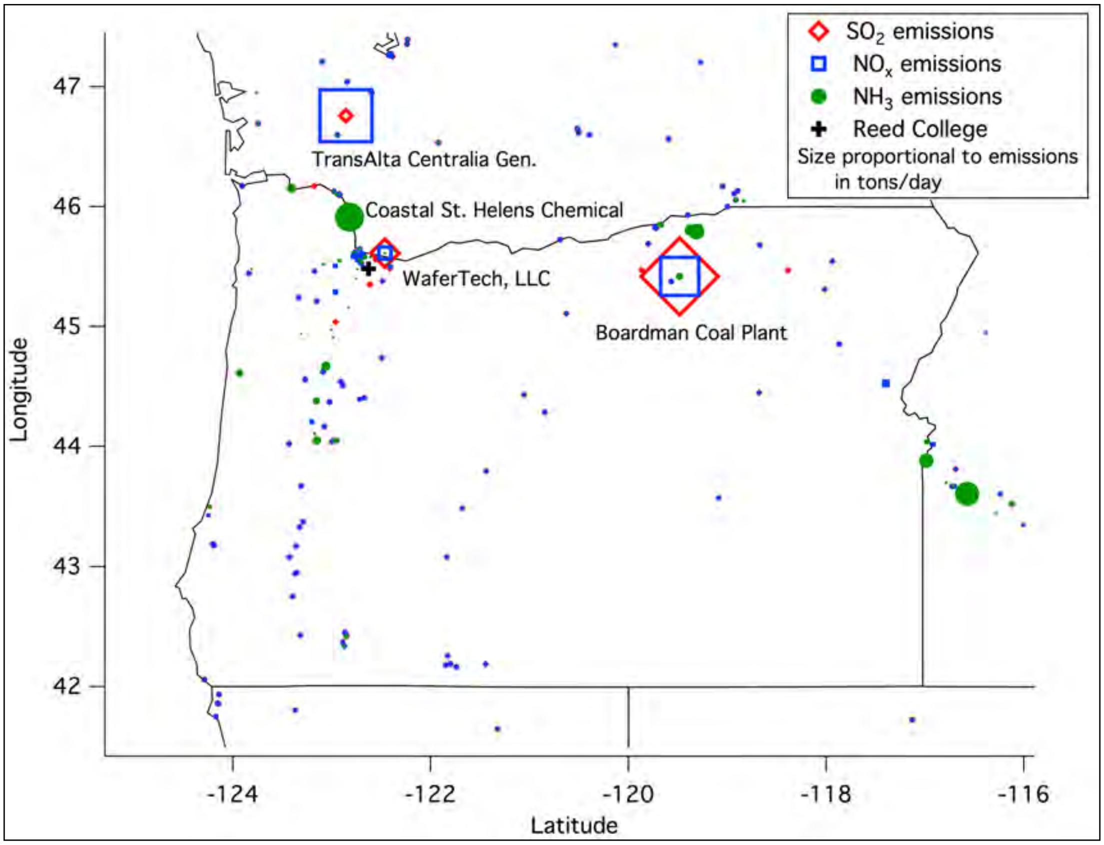

Figure 1. Pollution point sources in the Pacific Northwest. Data from EPA NEI 2008, courtesy of Greg Frost (NOAA), map by Hannah Allen (Reed Chemistry, '14)

A transition to other fuel sources aids both PGE and the state of Oregon in the long run. Closing 20 years early brings point-source emissions from the plant to zero in 2020 to comply with a recent agreement between PGE, Oregon Department of Environmental Quality, and environmental groups. Replacing Boardman's current power generation plants is crucial, however, as need for more resources is already causing upward pressure on PGE prices.[3] Boardman's shift to renewables aids in Oregon's efforts to meet its Renewable Portfolio Standard (RPS) by 2025. By that time, Oregon's three largest utilities (PGE, PacifiCorp and the Eugene Water and Electric Board) will have met a staggered increase in the percent of their portfolio that is powered by renewable energy sources. Boardman's transition to biomass serves both the conditions of the multiparty agreement as well as the state agreement to meet the new RPS.

How feasible is Boardman's transition from coal, technically and financially? What are the physical and political contexts to which Boardman will have to respond in the next 20 years? This report presents a network analysis of Boardman's potential biomass sources within the current and future political landscape of the Pacific Northwest.

[3] http://www.blueoregon.com/2010/07/closing-boardman-power-plant/#sthash.N5eG1uOq.dpuf

1.2 Brief History of Boardman and its relationship to Utilities

The history of the Boardman Power Plant depicts a microcosm of the Pacific Northwest's struggles and triumphs with the Western utility structure in the 1970s. Portland General Electric planned to build a plant that would provide a reliable base load of power to the Northwest, which suffered from outages due to inconsistent power supply from hydroelectric dams.[4] The plant, unspecified as to whether it would run on nuclear or coal fuel, was slated for completion by 1979. In the planning stages of 1972, PGE's nearby nuclear plant under construction was agitating local resistance against nuclear power.[5] The controversial choice between fuels would not be announced for several years.

Nuclear power plants did not give everyone nightmares; A 1973 Chicago Tribune article sings technophilic praises of the nuclear plants proposed for eastern Oregon. Columnist Bob Wiedrich gushes about Boardman's near future of "a unique modular city," the ecological benefits of man-made reservoir systems, and the blessing of unprecedented productivity in the "little-known Eastern Oregon desert." But PGE would steer the development of the "last frontier" a little differently than proponents of nuclear power hoped.[6]

Wiedrich mused again about the plant nearly eight years later, responding to PGE's decision to burn coal at Boardman. His rosy sights had turned towards the bright future of Powder River Basin coal extraction, a huge operation conveniently located relatively close to Boardman. Wiedrich's columns exemplify national concerns about energy security in the 1970s: nuclear power promised energy independence, but did so in the growing shadow of meltdown fears. Coal provided energy independence along with complex industrial growth, much-needed jobs, and none of the Cold War-era nuclear anxieties.[7]

PGE chose coal by 1975, when they filed and received approval for their "Thermal Power Plant," now coal-specific, and by November of 1977 they had locked down the loan that would finance a new coal-fired power plant.[8] Boardman was approved two years before the amendments to the Clean Air Act in 1977.

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4 Bob Wiedrich, "Coal Will Fire This Hungry Plant," *Chicago Tribune*, July 25, 1980.
5 "Portland GE Plans New Plant in Oregon," *Wall Street Journal*, February 18, 1972
6 Bob Wiedrich, "A Last Frontier Bows to Science," *Chicago Tribune*, November 6, 1973.
7 Bob Wiedrich, "Coal Will Fire This Hungry Plant," *Chicago Tribune*, July 25, 1980.)
8 Oregon Department of Energy: Energy Facility Siting 1975, "Final Order;" Oregon Department of Energy: Energy Facility Siting 1975, "Thermal Power Plant Cite Certification;" Staff Reporter, "13 Banks Set Accord For $200 Million Loan," *Wall Street Journal*, November 16, 1977.
8 Staff Reporter, "13 Banks Set Accord For $200 Million Loan," *Wall Street Journal*, November 16, 1977.

1.3 Utilities in the Pacific Northwest

There has been an unusually strong federal role in energy policy within the Columbia Basin. The Northwest's power industry has engaged federal assistance on the creation of the Bonneville Power Administration (BPA), the negotiation of the original Columbia River Treaty between the US and Canada, the development of the Pacific Northwest-Pacific Southwest Transmission Interties, the passage of the Northwest Power and Conservation Act of 1980, the role of the Northwest Power and Conservation Council, the restructuring of the electric utility industry, and a series of other interventions. When considering the future of what is now the PGE Boardman coal plant, both structural needs and policy requirements present crucial issues and opportunities that might arise. Any transition to biomass could be a catalyst to innovate technologically and politically by taking an active role in restructuring Pacific Northwest utilities.

The Western Interconnection, the utility grid fed by plants like Boardman, is subject to the contextual nuances of the energy needs in the Pacific Northwest. When considering the biofuel conversion option for the Boardman plant, seasonal shifts in regional energy demands might have as much of an impact on load as seasonal availability of crops. Every electric grid system attempts to supply all electricity as soon as demand arises, such that generation equals load, but this ideal remains a challenge. The Northwest must consider its future obligations as much as its cyclical demands.

When considering a biomass future for Boardman, PGE must examine the potential futures of the overarching electric grid. The Western Grid 2050 Report suggests that the western grid (its transmission system, generation system and distribution system) might be restructured by future legislation.[9] Reportedly, the nation's electrical distribution system would face a lower risk of severe outages if it were divided into scores of 'gridlets' rather than the three major grids that exist today for the East, the West and a large chunk of Texas. Researchers report that having a larger number of smaller grids would reduce the risk of cascading, catastrophic failures.[10] To that end, any attempts Boardman makes to localize its energy sourcing (whether in wind from the Columbia Gorge or in locally harvested biomass crops) will reinforce the value of a reliable energy source that does not have to compete with other smaller grids for their own fuels. It might be to Boardman's benefit that a diversified set of fuel can localize fuel sources for Oregon's smaller grid; the ability to burn biomass may offer Boardman a crucial edge if competition for resources between grids occurs.

[9] http://www.cleanenergyvision.org/clean-energy-vision-technical-report/western-grid-2050-key-findings/
[10] http://www.nbcnews.com/science/science-news/researchers-suggest-its-time-downsize-power-grid-n75206

1.4 Oregon's Renewable Energy Structure

Oregon is one of the few states in the union that possesses an abundant and diverse mix of renewable energy resources that can be converted to electricity (Figure 2); this is convenient for the 25% RPS set for the state. Oregon has large rivers for hydroelectric production, gorges and ridges for wind electricity production, abundant sunshine for solar electricity production, a coastline that can provide wave-powered electricity, multiple biomass resources that can be combusted in turbine electricity production, and volcanic activity that can be captured to produce geothermal electricity.

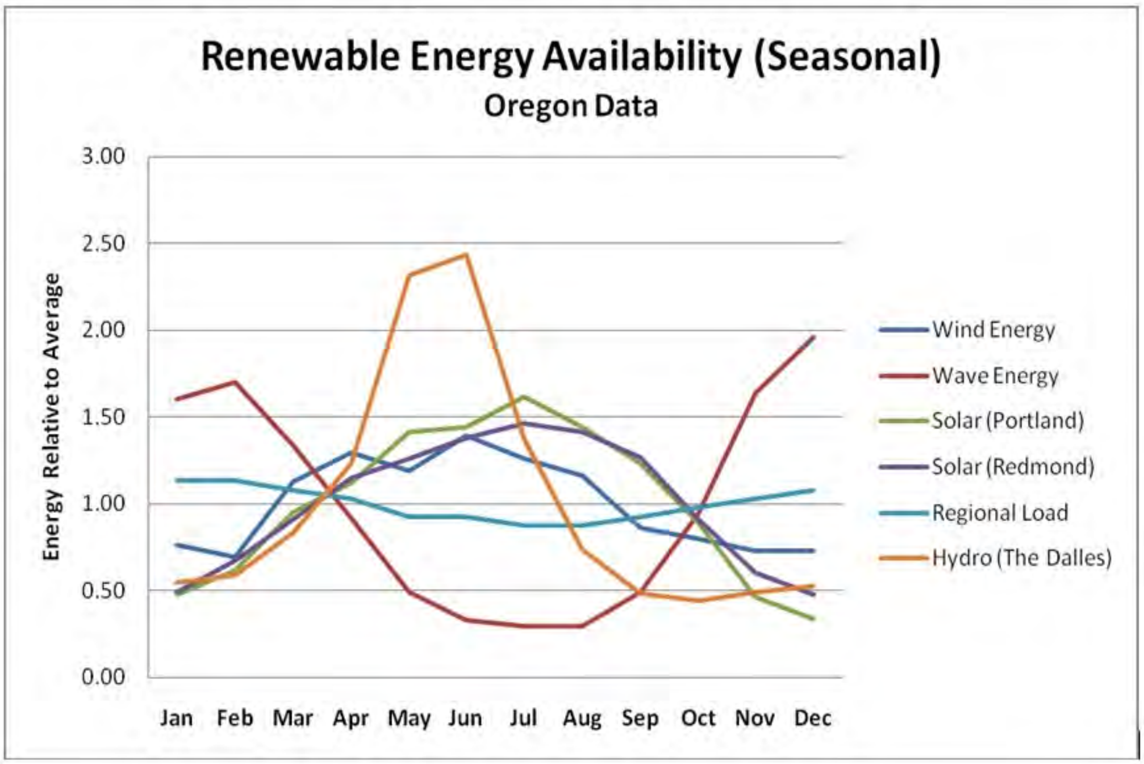

Figure 2. Seasonal availability of Renewable energy sources for Oregon.[11]

Early in its history, Oregon had used a combination of hydroelectricity and biomass (known as "hog fuel") to produce electricity. The TW Sullivan hydroelectric plant at Willamette Falls produced the first electricity for consumption in Oregon in the 1880s, and until the mid 1960s, renewable sources such as hydroelectric power from the mighty Columbia River power system provided much of Oregon's baseload electric power.[12] This system was manufactured into what Richard White deems an "Organic Machine," an energy system that, although modified by human interventions, maintains its natural, its 'unmade' qualities.[13] Biomass might have a similar future in that same Gorge. But by the mid-1960s, the large

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[11] http://solaroregon.org/news/a-100-renewable-electricity-vision-for-oregon-we-can-do-it
[12] Kolde 1954.
[13] White 1995, page ix.

hydroelectric sites had been fully developed, and the use of electricity was growing. The 1970s brought both nuclear and coal-fired electricity to the Northwest to supplement any and all energy demand. The 1980s brought natural gas to power plants, the new darling of the American fossil fuel industry.[14] More than anything else, price has determined which fuels are in vogue.

Different energy use patterns are best supported by hydroelectricity, wind, solar, geothermal, biomass, and wave power resources. Some only produce intermittently and vary seasonally, daily, and hourly, and others can provide a consistent baseload of energy to customers and are easily stored. Coal provides a reliable baseload when the variable renewables fail, but so could biomass. As illustrated in Figure 2, a mix of renewable energy is currently patched together to support baseload needs as those sources are seasonally available. Hydroelectric power remains available and plentiful, but can vary inconveniently in the early summer, as can large-scale wind generation in the winter. Both of these sources have been used in the Northwest long enough that their seasonal, diurnal, and location-specific energy production characteristics can be reasonably predicted. Biomass can be dried, stored, and managed in anticipation of load needs. Biomass is an attractive alternative baseload to coal that, once torrefied, remains safe from the seasonality of harvest.

[14] Kolde 1954.

2 Policy Brief: Emissions policy relevant to Boardman's transition to biomass

Boardman Power Plant's switch from burning coal to burning biomass for a more sustainable source of energy will involve in-depth reconsideration of federal and state emissions laws. This section is designed to be an overview of the policies at play in this transition to biomass combustion, and how they will change from current emissions policy with regards to coal combustion. It is our hope that this policy brief will inform Boardman's ability to transition to biomass legally, and that it will enable the plant to avoid further investment in emissions control systems to comply with relevant policies. We also seek to predict future policy changes that the plant may want to take into account. This brief includes overviews of the following relevant federal and state policies: Clean Air Act Regional Haze Rule (RHR), Prevention of Significant Deterioration (PSD) permitting, Best Available Retrofit Technology requirements (BART), Oregon Biomass Tax Credit, and Oregon Emissions Performance Standards for Base load Generation (S.B. 101).

2.1 Clean Air Act compliance regulations

2.1.1 Prevention of Significant Deterioration (PSD) permitting

At the conclusion of discussions between the Department of Environmental Quality and PGE concerning Boardman Power Plant's plan to be in compliance with Clean Air Act (CAA) emissions regulations in 2010, it was negotiated that Boardman would adopt stringent BART standards for all SO_2, NO_x, and Particulate Matter (PM) emissions.[15] This largely involved the addition of new low NO_x burners, a dry sorbent injection system for controlling SO_2 and a carbon injection system for controlling mercury emissions, all of which have been installed as of 2014.[16]

Because Boardman was authorized before the CAA amendments of 1977 requiring PSD permits, the plant was able to negotiate for slightly less strict BART emissions standards. The RHR states that any "major stationary source of pollution" that undergoes "major modification" will be subject to a revision of PSD permitted emissions.[17] Thus, the application of current BART standards will last until 2020 when Boardman shuts down in

[15] Corson 2010.
[16] PGE 2014.
[17] The EPA defines "major stationary source" as a facility that emits 10 tons/year of a hazardous air pollutant or a 25 tons/year combined total of all hazardous air pollutants. EPA 1999.
The EPA defines "major change" as a physical change or change in the method of operation of a major stationary source that would result in a significant net emissions increase of any pollutant subject to the CAA. *Ibid.*

the expected transition to biomass energy production, at which time its emissions standards will be subject to revised regulations under the PSD permitting system.

PSD standards are widely perceived to be more stringent than BART standards because of the increased considerations of the effects of air pollution, specifically in Class I Wilderness areas.[18] Where BART standards address only the visibility of Class I Wilderness Areas, PSD permit requirements address visibility, National Ambient Air Quality Standards (NAAQS), and increment composition.[19]

This new permitting will be carried out through the New Source Review (NSR) program, which is intended to ensure that modifications to the facility do not worsen air quality and that emissions remain as clean as possible for the surrounding communities. NSR permitting may involve NAAQS emissions beyond those regulated in the RHR such as carbon monoxide, lead and ozone.[20] Additionally, this review will include new standards for greenhouse gas emissions subject to the Title V Greenhouse Gas Tailoring Rule, one of the main rules violated that the Sierra Club lawsuit cited against Boardman.[21] This will likely require that PGE Boardman make significant changes to the plant to cap carbon emissions; corresponding CO_2 emissions calculations follow in section 2.4below.

2.1.2 Regional Haze Rule: Current BART specifications and considerations for future PSD regulations

Current emissions standards under the RHR's current BART standards for Boardman's coal emissions are:

- 0.12 lbs/mmBTU SO_2 emissions over a 30-day rolling average.
- 0.28 lbs/mmBTU NO_x emissions over a 30 day rolling average
- 0.23 lbs/mmBTU NO_x emissions over a 12 month rolling average
- 0.012 lbs/mmBTU PM emissions measured through source testing.

Any compliance extensions of the emissions limits will end on July 1, 2014. All emissions must be in compliance with these standards by that time, and will be measured every 180

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18 A federally designated Class I Wilderness Area, defined under the CAA, includes national parks greater than 6,000 acres, wilderness areas and national memorial parks greater than 5,000 acres and international parks that existed in 1977. WDEQ 2014.

19 Finneran 2007. Also see USEPA 1990: "A PSD increment…is the maximum allowable increase in concentration that is allowed to occur above a baseline concentration for a pollutant. The baseline concentration is defined for each pollutant (and relevant averaging time) and, in general, is the ambient concentration existing at the time that the first complete PSD permit application affecting the area is submitted."

20 EPA 2011. Boardman has not had any issues controlling these pollutants in the past, and new PSD standards are likely to require no new regulations and controls for the plant with regards to them.

21 Finneran and Fisher 2010, see n. 2 on page 1.

days through a Continuous Emissions Monitoring System (CEMS). In 2017 NO_x emissions must be reduced to 0.070 lbs/mmBTU with a CEMS compliance report issued by January 1, 2018 detailing current emissions and the efficiency of low NO_x emissions technology.[22]

As of 2014, Boardman does not plan to install any new emissions control systems, as it would be economically impractical if PGE wishes to turn a profit burning biomass.[23] In order for the transition to biomass to be legally feasible, Boardman and PGE must prepare for expected decreases in allowable emissions under new PSD regulations. This can be aided by ensuring that all potential biomass crops must have SO_2, NO_x, and PM emissions (subtracting percentages removed through emissions control technology) lower than the range of emissions currently accepted through burning coal.

Given the current standards and emissions control systems and sulfur content of crop residues, we have also calculated speculative SO_2 emissions from biomass. See the Calculations Appendix for specific calculations for Boardman's current SO_2 emissions for coal (both with and without new emissions control technology). Even with a 75% emissions reduction with the dry sorbent injection system and lower SO_2 levels from biomass combustion, Boardman may find it challenging to meet more stringent PSD regulations. Projected emissions levels for biomass range from 0.134-0.255 lbs SO_2/mmBTU, compared with the current standard of 0.12 lbs/mmBTU (See Figures 3 and 4 in section 2.4).

As a potential additional step in the process to further decrease emissions, the calculations include the potential to leach out sulfur before torrefaction takes place, which would reduce the sulfur content by 71.4% for *Arundo donax*.[24] This process for *Arundo donax* is assumed to translate to corn and wheat residues. If Boardman utilizes the leaching process, Boardman will likely not exceed sulfur dioxide emissions regulations (SO_2 emissions between 0.028-0.073 lbs/mmBTU); use of this method appears to be crucial for compliance with the RHR.

Calculations for NO_x and PM emissions will be largely determined by the development of new technology for the combustion of torrefied biomass. Though the PM emissions of biomass are not well known, we expect that the current baghouse emissions reduction efficiency of 99% for PM will eliminate potential PSD violations with regards to particulates from biomass.[25]

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[22] DEQ 2012.
[23] Lei 2014.
[24] Matyas, Johnson et al. 2012.
Matyas, Johnson et al. note that the leaching process can be done in two ways: 1) Torrify the biomass and then leach out the sulfur resulting in a 71.4% S reduction, 2) Leach sulfur out of dry biomass and then torrify it resulting in a 76.3% S reduction. Because our calculations involve torrefied biomass, we assume the first process in the appendix. Because this process is sufficient in bringing SO_2 content below RHR regulations then we can assume the second process would be desirable but not necessary.
[25] Booth 2014.

Similar NO_x calculations are not possible since the production of NO_x depends on combustion temperatures as well as fuel N content, and will need to be measured experimentally through a test of biomass combustion with the low NO_x burners once the plant has transitioned after 2020.[26] By way of comparison, PGE Boardman's current fuel, Powder River Basin (PRB) coal, typically contains between 0.9 and 1.64% nitrogen, while potential dry biomass crops contain between 0.26 and 1% nitrogen.[27] Low NO_x burners suggest a bright future: assuming Boardman succeeds in complying with NO_x BART regulations by 2017, new low NO_x burners with an emissions reduction potential of about 50% may demonstrate more than sufficient cleaning technology to make NO_x emissions negligible.

2.1.3 Greenhouse Gas Emissions (GHG) regulation under Title V of the CAA

As of 2011, all new Title V and PSD permits will include greenhouse gas emissions from all of the stationary sources that bear part of the responsibility for 70% of the nation's CO_2 emissions.[28] Title V permits will be required for plants with a GHG of 100,000 tons/year or more.[29] Boardman falls under this category. Though biomass can be considered "carbon neutral" in that its production sequesters an equivalent (if not larger) amount of carbon than it emits when burned, controversially, no exemptions exist for carbon emissions for biomass thermal plants.[30] Potential sequestration of carbon is ignored in Title V and PSD permitting for GHG emissions, and permitting will be related only to the direct GHG emissions from the plant.

The most recent permits for PSD biomass emissions involve the Energy Answers Arecibo waste burning biomass facility in Puerto Rico and the Sierra-Pacific Industries wood burning biomass facility in California, which can both act as models for what Boardman can expect in terms of regulation. Both facilities were created and/or modified specifically for biomass burning, and may experience a different permitting situation than Boardman if the EPA

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[26] Nordin and Merriam 1997. NO_x can be emitted as NO, NO_2, NO_3, N_2O, N_2O_4, or N_2O_5. Typically, the total process of combusting Powder River Basin coal produces NO, N_2O, and NO_2. *Ibid.*

[27] For coal, see Nordin and Merriam 1997; for biomass, see Lewis Garcia-Perez et al. 2012, Medic 2012. There is no significan loss of N between dry biomass and torrified biomass. Medic 2012.

[28] EPA 2013, "Clean Air Act Permitting for Greenhouse Gases."

[29] The Tailoring Rule used to include "the Deferral Rule", an exemption for biomass facility carbon dioxide emissions due to their consideration as a "carbon neutral" renewable fuel source. However, this exemption was revoked on July 12, 2013, and all biomass facilities will be liable for the PSD and Title V regulations. Bowman 2013.

[30] The EPA is currently still working on revisions to the GHG emissions policy for biofuel, as there is no clear distinction yet for these emissions. The Supreme Court seems unlikely to overturn the D. C. Circuit's July 12, 2013 decision not to exempt biofuels, but has yet to rule one way or the other. The EPA is waiting on Supreme Court decisions before moving forward. Childers 2014.

decides to tailor biomass emissions standards to specific facilities in the future. Regardless, the interaction with the EPA and these facilities will be a useful tool.[31]

Because the EPA is still considering the "net zero emissions" of biomass and awaits further Supreme Court action on this topic, there is a chance that this regulation of biomass emissions may change in the future.[32] However, this change will be coupled with stricter stationary source CO_2 emissions rules that the EPA will officially mandate in June 2014, rules which will require a highly significant reduction of Boardman's CO_2 emissions.

Excluding the CO_2 sequestration from plant growth, the emissions from Boardman will likely vary between crops. Our calculations demonstrate that Boardman's biomass crops will create less CO_2 emissions even without counting the sequestration largely because the plant will be running at 300 MW rather than 615 MW. For example, the Lewis et al. report on *Arundo donax* states that burning the plant will emit 4.05 million tons per year of CO_2, while current coal emissions are approximated to be 4.6 million tons per year.[33] Additionally, our calculated CO_2 emissions for combined corn and wheat biomass fuel equal approximately 2.35 million tons per year of CO_2, not including the additional emissions from torrefaction, transportation, or that which is during crop growth. Under current CAA standards that do not take biomass sequestration into account, Boardman should expect to implement new GHG emissions reduction technology such as a carbon capture system in order to comply with Title V and PSD regulations in the near future.

2.2 Oregon GHG emissions regulations S.B. 101

Currently, Oregon's state GHG emissions standards are some of the most stringent in the nation. At this time, the state standards present a more direct concern to Boardman than the more relaxed federal legislation on greenhouse gases. Current standards set by Senate Bill 101 (S.B. 101) state that any new Oregon utility may not release more than 1,100 lbs CO_2/MWh.[34] Burning coal, Boardman currently emits 2,128 lbs CO_2/MWh, above the state limit. However, current statutes in section 4(2) of S.B. 101 and ORS 469A.25 consider biomass a renewable energy source whose GHG emissions will not be subjected to Oregon GHG emission regulation. Though Boardman's transition to biomass will not be regulated under current circumstances, close attention should be paid to the potential for the changes

[31] For reference, The Energy Answers Arecibo waste-energy site regularly emits 466,619 tons CO_2e/year and will be subject to PSD standards of 75,000 tons CO_2e/year. This plant runs at 77 MW, about 25% that of Boardman's projected biomass MW production. The Sierra-Pacific Industries wood chip biomass plant creates about 10% of the energy that Boardman currently does, and the PSD permit is still in the development stage. This plant is located in EPA region 9, where the regulation process may be more similar to Region 10 where Boardman is located than that of Region 2 where the Energy Answers Arecibo plant is located. EPA 2013, Fact Sheet for CAA. See also EPA 2014.
[32] Childers 2014.
[33] Lewis, Garcia-Perez et al. 2012.
[34] Marten 2009.

in the implementation of this section of S.B. 101 when the impending CAA GHG emissions regulation are put into place, as federal law will have preemption over state regulation.

Additionally, in case S.B. 101 undergoes changes similar to those of Title V, which eliminated the consideration of biomass as a carbon neutral renewable energy source, we have calculated Boardman's potential emissions using the legislature's unit of measurement in lbs CO_2e/MWh. We found that the emissions will be 3115 lbs/MWh and 1808 lbs/MWh respectively for *Arundo* and corn/wheat biomass (see Figures 3 and 4 in the section 2.4).[35]

Another consideration is potential future legislation for a cap and trade system in Oregon or at the federal level. In 2007, S.B. 80 proposing an Oregon cap and trade system failed to pass. On top of a lack of bipartisan support, this bill did not pass because of the anticipation that a federal cap and trade system would soon be implemented with the passage of the American Clean Energy and Security Act.[36] Though both bills failed, there is growing public and international support for cap and trade systems, and the success of California's cap and trade system constitutes a feasible model for new Oregon law. PGE should expect more stringent GHG emissions regulations in the future, and can plan to avoid future lawsuits under new federal carbon emissions laws.

2.3 Biomass Energy Tax Credit

To be eligible for the tax credit under ORS 315.141, biomass must be produced or collected *in Oregon state* as a feedstock for bioenergy or biofuel production *in Oregon state*. No similar subsidies exist for biomass produced, collected or used for energy in Washington and Idaho. HB 4079 and ORS 496b.403 state the credit rates for biomass in Oregon:

- For woody biomass collected from nursery, orchard, agricultural, forest or rangeland property in Oregon, including but not limited to prunings, thinning, plantation rotations, log landing or slash resulting from harvest or forest health stewardship, $10.00 per bone dry ton.
- For grass, wheat, straw or other vegetative biomass from agricultural crops, $10.00 per bone dry ton.[37]

Our calculations suggest that 500,773 tons of Oregon crop residues that will be eligible for this subsidy.[38] This amount is a combined total of 30,161 tons of corn residue and 470,311 tons of wheat residue. With the price of corn stover at $20/bone dry ton and the price of

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[35] See appendix for calculations. These numbers take into account solely the emissions from Boardman's smoke stack and not emissions from transportation, torrefaction or sequestration.
[36] Marten 2009.
[37] ODOE 2013.
[38] This amount is derived from the "residueCalculations.csv" spreadsheet in column Q "TotalResEst".

wheat straw at $18.8/bone dry ton before the tax credit (see "Purchasing Cost" calculations in section 3.5), this much residue will cost approximately $9,445,093.44.

After the tax credit the cost of these crops will be $10/bone dry ton and $8.8/bone dry ton respectively. This much residue will then cost approximately $4,400,360.44, saving Boardman around $5,044,733 in biomass costs if all crop residue available within Oregon is purchased. According to the Energy Information Administration (EIA), PRB coal costs $13.02 per short ton. Given this price, we calculate that Boardman currently spends around $32,550,000 on coal, excluding private negotiations with the mine. The resulting overall savings in fuel costs only of switching from coal to biomass is $28,149,640.[39]

2.4 Emissions Calculations for different fuel sources

2.4.1 Units

- M_x = Mass fuel source used (x-fuel source)= T/ (BTU/$lb_{biomass\ crop}$)*2000lb/ton
- T= BTU/year
- E = Energy (MWh/year)
- Em_x = emissions (x fuel source)
- P_s= Percent composition sulfur
- P_c= Percent composition carbon
- η = Efficiency (3.4BTU/MWh)

2.4.2 Calculation Notes

- Boardman's energy generation per year is assumed to be 615 MW for coal and 300 MW for biomass.[40]
- Use of a dry sorbent injection system yields an assumed 75% reduction in SO_2 (sulfur) emissions from burning biomass.[41]
- Use of leaching technique results in a 71.6% reduction of sulfur content.[42]
- Total SO_2 emissions from burning biomass are multiplied by 0.95 due to the 4.6% sulfur lost during the torrefaction process.[43]
- Torrefied biomass has only 70% of the original mass of non-torrefied dry biomass.[44]

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39 EIA 2014.
40 Lewis, M. et al 2012.
41 PGE 2014.
42 J. Matyas et al 2012.
43 J. Matyas et al 2012.
44 See Torrefaction section of this report.

2.4.3 Sulfur Dioxide Emissions[45]

$$Em_{SO2} = \frac{(P_S * M_x * 2000lb/ton * 64\ g\ SO_2/32g\ S) * 0.95)}{(E * (\eta))}$$

Coal: M_c- 2.5 million tons/year

BTU for 615 MW at 80% capacity- 4.3 million MWh/year

P_s PRB low sulfur Coal- 0.9%S or 0.3% S

$$Em_{SO2} = \frac{(0.009 * 2.5 * 10^6 tons * 2000lb/ton\ * 64\ g\ SO_2/32g\ S)}{(4.3 * 10^6 MWh\ * (3.4BTU/MWh))}$$

$$Em_{SO2} = 6.155\ lbs\ SO_2/mmBTU$$

$$Em_{SO2} = 2.051\ lbs\ SO_2/mmBTU\ (under\ 0.3\%\ S\ calculation)$$

Arundo: M_a- 1.56 million tons/year torrefied

BTU for 300 MW- 2.6 million MWh/year

P_s - 0.19%

$$Em_{SO2} = \frac{(0.0019 * 1.56 * 10^6 tons * 2000lb/ton\ * 64\ g\ SO_2/32g\ S) * 0.954}{(2.6 *\ 10^6 MWh * (3.4BTU/MWh))}$$

$$Em_{SO2} = 1.02\ lbs\ SO_2/mmBTU$$

$$Em_{SO2}\ with\ 75\%\ reduction\ = 0.2552\ lbs\ SO_2/mmBTU$$

$$Em_{SO2}\ with\ 71.6\%\ reduction\ and\ leaching = 0.072\ lbs\ SO_2/mmBTU$$

Corn Straw: M_{cs}- 1.79 million tons/year dry= 1.253 million tons/year torrefied

BTU for 300 MW- 2.6 million MWh/year

P_s- 0.1%

$$Em_{SO2} = \frac{(0.001 * 1.253 * 10^6 tons * 2000lb/ton\ * 64\ g\ SO_2/32g\ S) *\ 0.954}{(2.6 *\ 10^6 MWh * (3.4BTU/MWh))}$$

$$Em_{SO2} = 0.5863\ lbs\ SO_2/mmBTU$$

$$Em_{SO2}\ with\ 75\%\ reduction\ = 0.1346\ lbs\ SO_2/mmBTU$$

$$Em_{SO2}\ with\ 71.6\%\ reduction\ and\ leaching\ = 0.03851\ lbs\ SO_2/mmBTU$$

[45] Numbers for these calculations can be found in Lewis et. al 2012, Matyas et al. 2012, and Clarke et al. 2011.

Wheat Straw: M_w- 1.85 million tons/year dry = 1.295 million tons/year torrefied
BTU for 300 MW- 2.6 million MWh/year
P_s - 0.1%

$$Em_{SO2} = \frac{(0.001 * 1.295 * 10^6 tons * 2000 lb/ton\ * 64\ g\ SO_2/32g\ S) *\ 0.954}{(2.6 *\ 10^6 MWh * (3.4 BTU/MWh))}$$

$$Em_{SO2} = 0.559\ lbs\ SO_2/MWh$$
$$Em_{SO2}\ with\ 75\%\ reduction\ \ = 0.14\ lbs\ SO_2/mmBTU$$
$$Em_{SO2}\ with\ 71.6\%\ reduction\ and\ leaching\ \ = 0.0399\ lbs\ SO_2/mmBTU$$

Wood: M_s- 1.512 million tons/year dry = 0.805 million tons/year torrefied[46]
BTU for 300 MW - 2.6 million MWh/year
P_s- 0.1%

$$Em_{SO2} = \frac{(0.001 *\ 0.805 * 10^6 tons * 2000 lb/ton\ * 64\ g\ SO_2/32g\ S) *\ 0.954}{(2.6 *\ 10^6 MWh * (3.4 BTU/MWh))}$$

$$Em_{SO2} = 0.346\ lbs\ SO_2/mmBTU$$
$$Em_{SO2}\ with\ 75\%\ reduction\ \ = 0.086\ lbs\ SO_2/mmBTU$$
$$Em_{SO2}\ with\ 71.6\%\ reduction\ and\ leaching = 0.0247\ lbs\ SO_2/mmBTU$$

[46] Wood is not taken into account in further sections of this report because we assume Boardman will only use crop residues in their biomass combustion. This calculation is here as a comparison for a low sulfur fuel source.

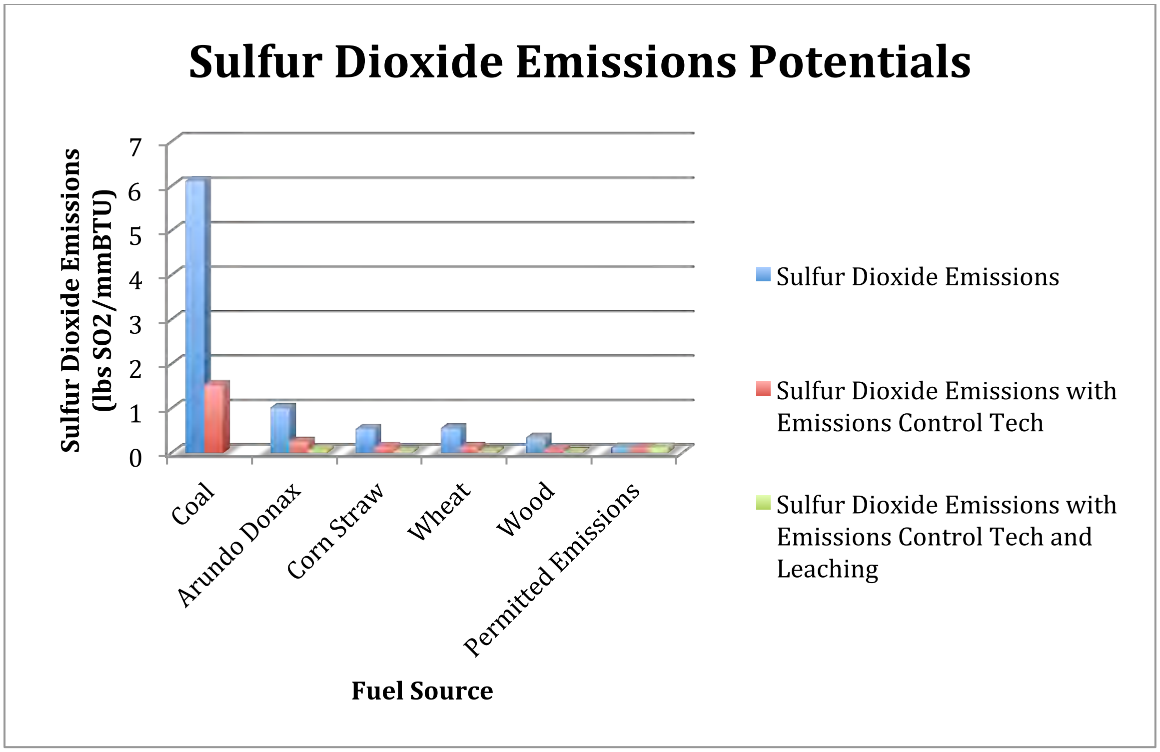

Figure 3. Sulfur dioxide emissions from coal and different potential fuel sources compared to the amount of sulfur dioxide emissions permitted by the Regional Haze Rule.

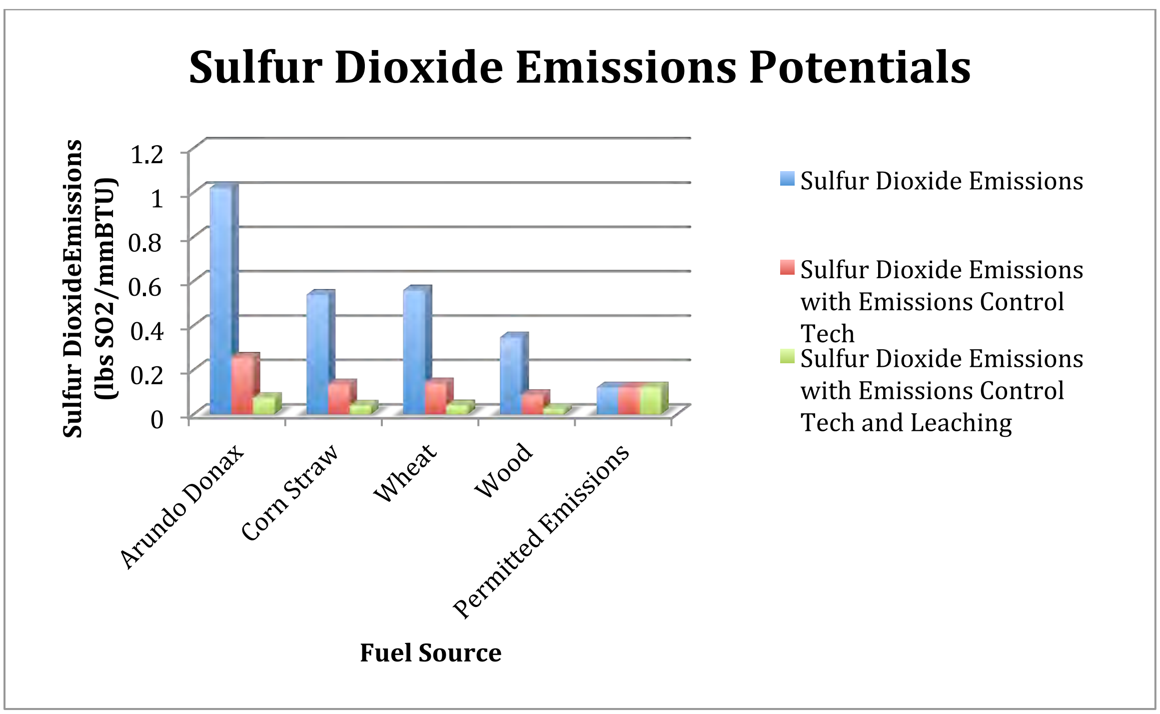

Figure 4. Sulfur dioxide emissions from biomass fuel crops, excluding coal so that their comparison to the permitted emissions levels is clearer. Blue, red and green bars represented the same as in Figure 3.

2.4.4 Carbon Emissions from Biomass[47]

$$Em_{CO2} = \frac{(M_{crop} * P_C * 44gCO_2/12gC)}{(E\ )} * 2000lb/ton$$

Combined corn and wheat biomass:

M_{crop} - 1.281 million tons of combined corn and wheat biomass

50% carbon content

2.6 * 10^6 MWh/year

$$Em_{CO2} = \frac{\left(1.281 * 10^6\ tons * 0.5 * \frac{44gCO_2}{12gC}\right)}{(2.6 * 10^6\ MWh)} * 2000lbs/ton$$

$$Em_{CO2} = 1808\ lbs \frac{CO_2e}{MWh}$$

Total annual CO_2 emissions:

$\mathbf{1808\ lbs \frac{CO_2e}{MWh} \times 300\ MWh \times 365\ days \times 24\ hours \times \frac{ton}{2000\ lbs}}$ = 2.38x10^6 tons CO_2

Arundo*:* 4.05 million tons CO_2 emissions

$$Em_{CO2} = \frac{(4.05\ million\ tons\ CO_2e)}{(2.6 * 10^6\ MWh)} * 2000lbs/ton$$

$$Em_{CO2} = 3115.3\ lbs\ CO_2/MWh$$

Total annual CO_2 emissions:

$\mathbf{3115\ lbs \frac{CO_2e}{MWh} \times 300\ MWh \times 365\ days \times 24\ hours \times \frac{ton}{2000\ lbs}}$ = 4.09x10^6 tons CO_2

These annual biomass CO_2 emissions are compared to coal in Figure 5 below.

[47] Numbers for these calculations can be found in Lewis et al 2012, Matyas et al. 2012, Medic 2012, and the Torrefaction section appendix.

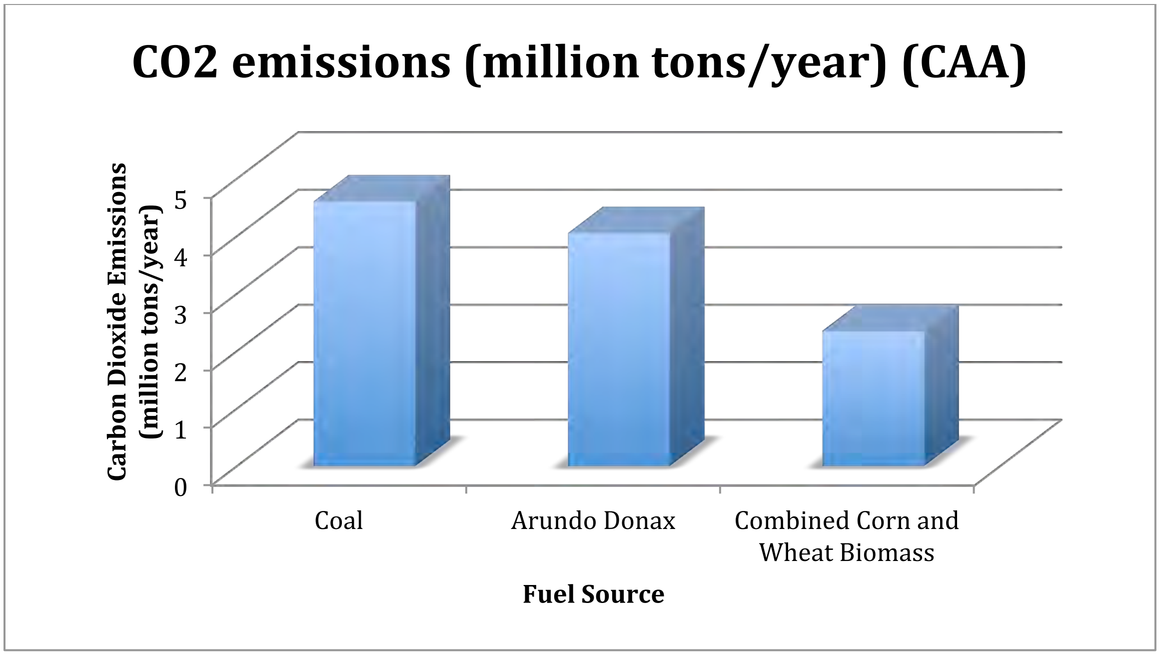

Figure 5. Carbon dioxide emissions per year from coal and biomass fuel sources burned at Boardman. This calculation takes into account that Boardman will be running at 300 MW with biomass and 615 MW with coal. The CAA and PSD emissions permitting are measured in million tons/year.

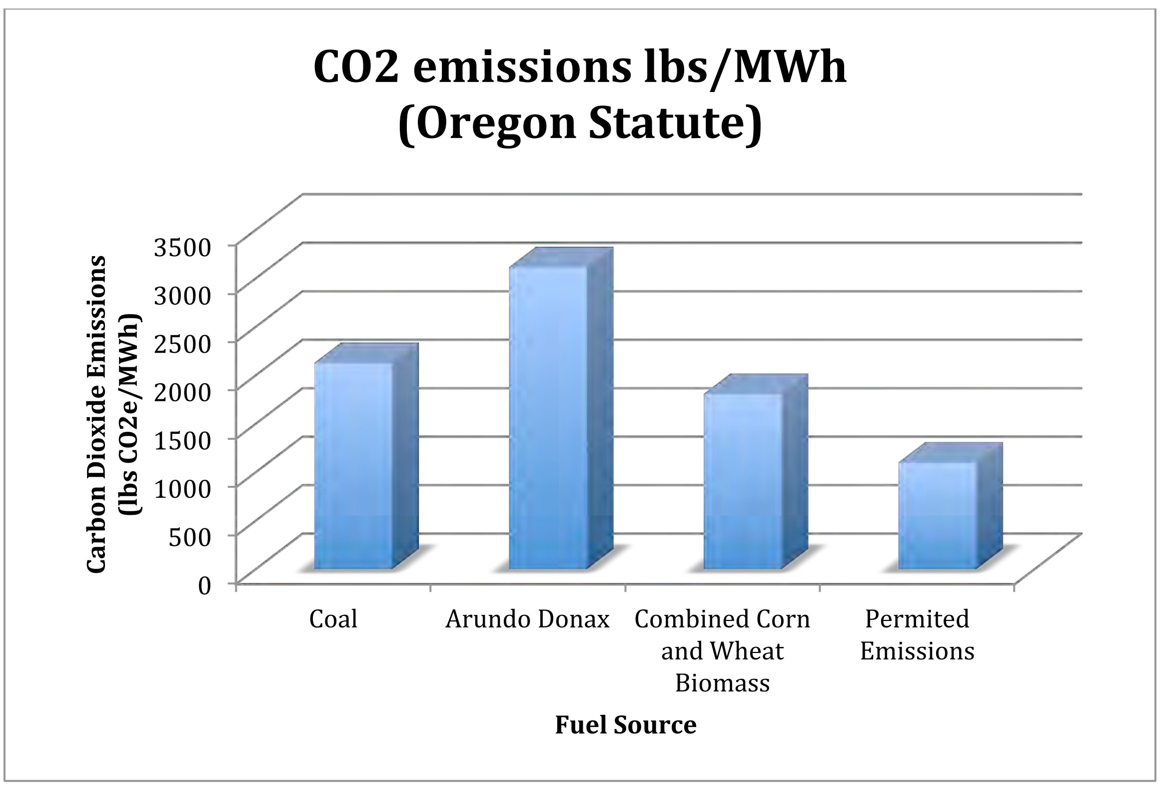

Figure 6. Carbon dioxide emissions in lbs/MWh from coal and biomass fuel sources compared to permitted emissions levels from Oregon SB 101.

3 Transportation and Acquiring Biomass: Costs and Carbon Implications

The following calculations were performed to estimate the transportation costs and carbon emissions generated by acquiring enough biomass residues for Boardman to generate 300 MW of power on average over the course of one year. In this scenario, PGE will use flatbed trucks to move crop residues from nearby farms to Boardman in bales. The residues would then need to be torrefied at Boardman.

To operate for one year, Boardman will need to import 1.83 million tons of crop residues: 230,000 tons of dry corn stover and 1.59 million tons of dry wheat straw. This ratio is derived from the relative availability of crops in the area – wheat straw is far more abundant than corn stover. This sum can be reached by transporting the total available corn stover and wheat straw residue production of 27 nearby counties to Boardman. Collecting this sum of residues will require driving 74,400 flatbed trucks a total of 10 million miles, which will cost $28.5 million. This transportation will generate 23,000 tons of carbon dioxide emissions.

It is probable that building a series of torrefiers distributed around the three states in areas of intense production would achieve higher efficiency than on-site torrefaction at Boardman. Distributed torrefiers would decrease both costs and carbon emissions of residue acquisition, because torrefied biomass is more energy dense and therefore more efficient to transport than pre-torrefied dry biomass. Torrefying can reduce mass by up to 30%, so a distributed torrefaction scenario could offer cost and emissions savings of up to 30%.[48]

3.1 Biomass requirements

Boardman plans to operate at 300MW averaged over the year, that is, at 600MW for half the year. We assume that Boardman's boilers convert 9911 BTU of chemical energy into 1 kWh. We can calculate Boardman's BTU needs as follows.[49]

$$300MW\ average\ over\ year = 2.63 * 10^6\ MWh$$

$$2.63 * 10^6 MWh * \frac{1000\ kWh}{1\ MWh} * \frac{9911\ BTU}{kWh} = 2.60 * 10^{13}\ BTU$$

Dry corn stover residues have an energy density of 7960 BTU/lb, and dry wheat straw residues have an energy density of 7710 BTU/lb.[50]

[48] Stelte 2012.
[49] Lewis et al. 2012, page 19.
[50] Clarke and Preto 2011.

Both of these crops lose about 10% of their stored chemical energy during torrefaction.[51] To produce 2.60*10[13] BTU of power, Boardman will need:

$$\frac{2.60*10^{13}\ \mathrm{BTU}}{0.9*7960\frac{\mathrm{BTU}}{\mathrm{lb}}} = 1.79 \text{ million tons of dry corn residues, or}$$

$$\frac{2.60*10^{13}\ \mathrm{BTU}}{0.9*7710\frac{\mathrm{BTU}}{\mathrm{lb}}} = 1.85 \text{ million tons of dry wheat straw,}$$

or some combination thereof.

3.2 Crop residues

Corn and wheat are two of the top three field crops by production in the state of Oregon.[52] Corn and wheat residues are currently part of a market for livestock forage and bedding. Cereal grain residues, or straw, are primarily used for animal and livestock bedding. The estimated cost for removing these from the fields includes the cost of harvesting, baling, and replacement fertilizer. Fertilizer replacement is the most environmentally and economically costly of these. Additionally, removing crop residues reduces the protection and quality of soil, which results in increased water run-off and soil erosion. Planting cover crops to take the place of the removed biomass can help mitigate these issues, but there are added costs associated with them.[53]

Crop residues are estimated on the county level. The agricultural census from 2007 provides county-level data on annual corn and wheat production in bushels.[54] Our residue estimates assume that a sustainable amount of biomass will be left on the field to maintain a healthy, nutrient-filled soil, and they also assume that some of the residues will be reserved for livestock.[55] With these parameters, the estimated available biomass for purchase is only about 35% of actual crop residue production.[56]

$$Dry\ residue = Grain\ mass * \frac{stover}{grain} * moisture\ deflation * fraction\ residue\ available$$

[51] Stelte 2012, page 3.
[52] Losh 2013.
[53] Wortmann et al. 2012.
[54] Census of Agriculture 2007. See http://www.agcensus.usda.gov/Publications/2007/index.php
[55] Our estimation strategy and parameters are borrowed from a study published by the National Renewable Energy Laboratories. Milbrandt 2005,page 12.
[56] *Ibid.*

For corn,

$$Dry\ residue = Grain\ bushels * \frac{0.028\ tons}{bushel} * \frac{1\ stover}{1\ grain} * 0.85 * 0.35$$

For wheat,

$$Dry\ residue = Grain\ bushels * \frac{0.03\ tons}{bushel} * \frac{1.3\ stover}{1\ grain} * 0.865 * 0.35$$

These calculations are carried out for every county and summed over wheat and corn and are given in column Q, "total_res," in the Table Appendix. These estimates can be compared to biomass estimates given by NREL in column R, "CropRes."

We estimate that 9.54 million tons of dry corn and wheat biomass are produced in the three states area every year. 3.34 million tons of that amount are not put to other uses like animal feed and soil cover and are therefore available to purchase for Boardman.

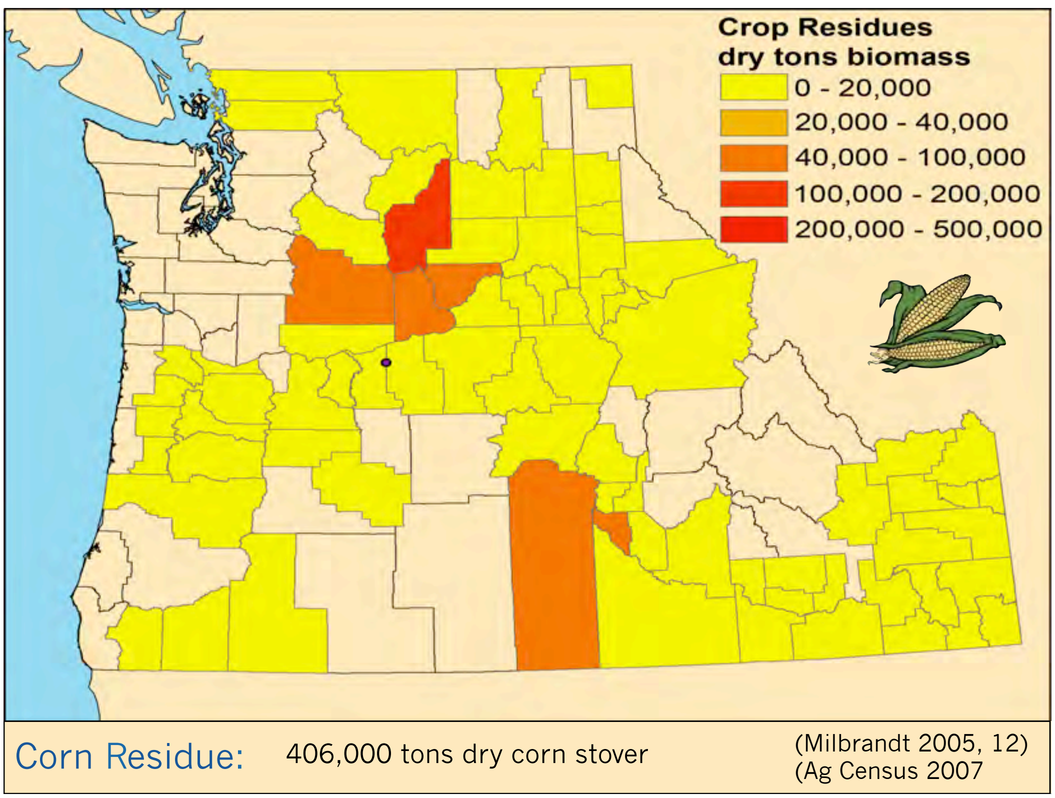

Figure 7. Estimated corn residues (by county) that are available to Boardman.

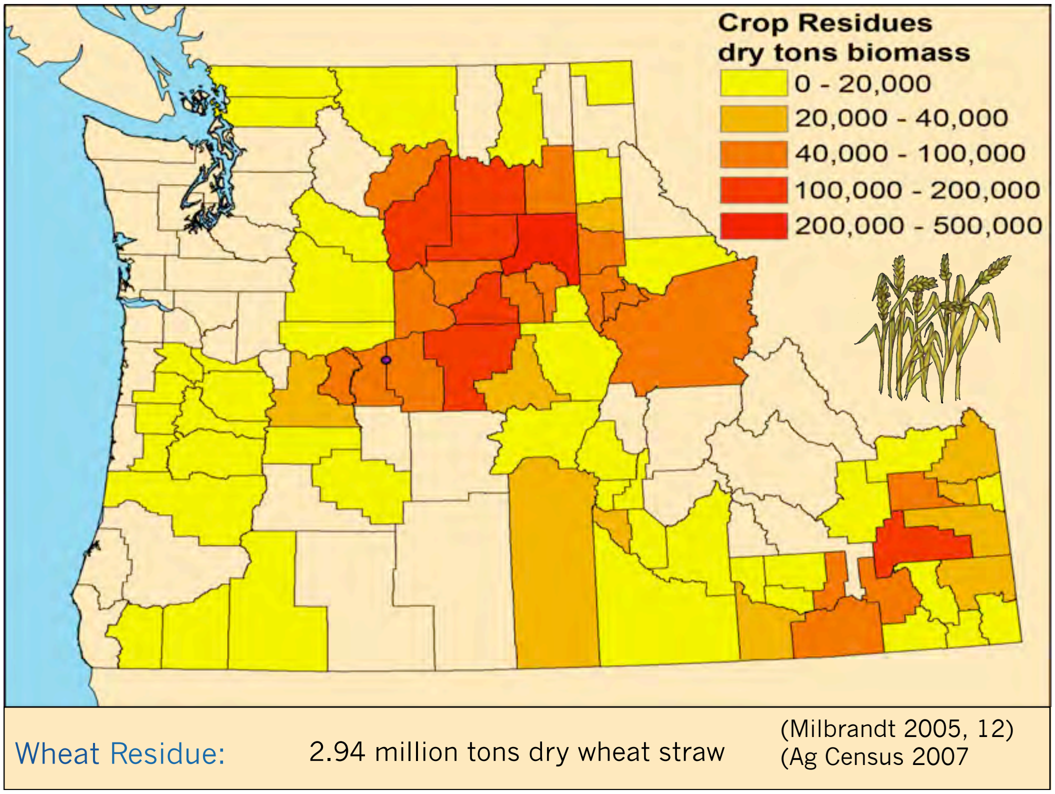

Figure 8. Estimated wheat residues (by county) that are available to Boardman.

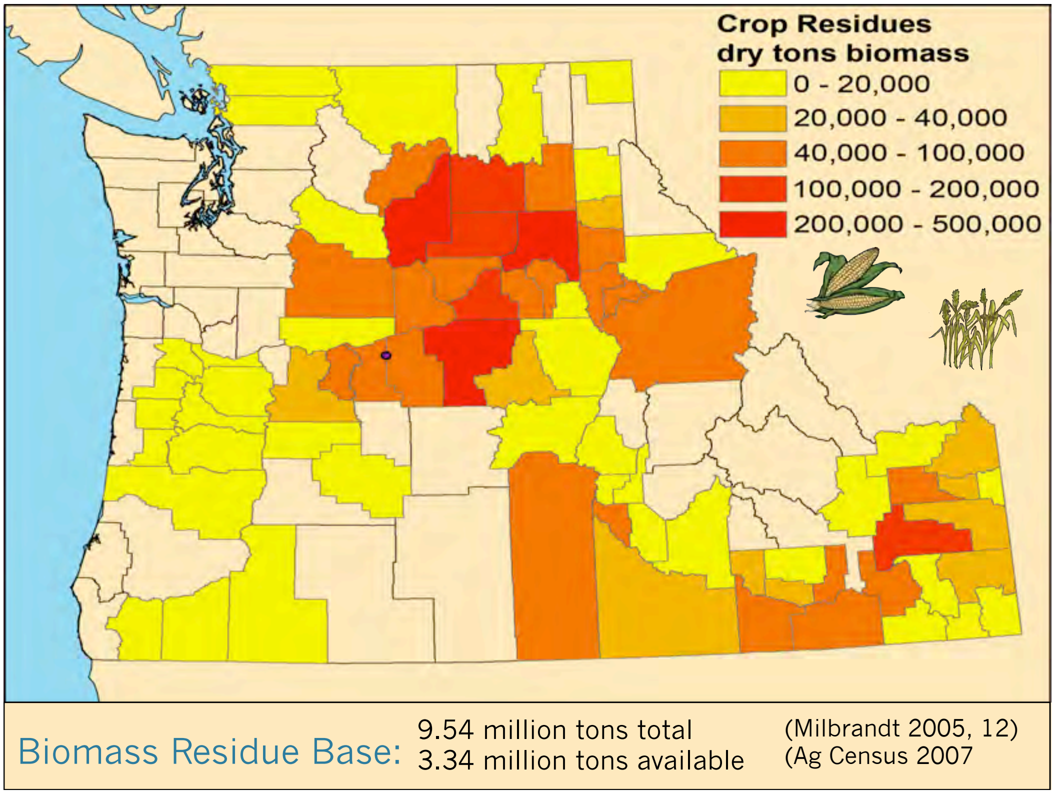

Figure 9. Estimated residues of both corn and wheat residues (by county) that are available to Boardman.

3.3 Crop distance from Boardman

Network analysis was carried out in ArcGIS to estimate transportation distances between crops and Boardman. Routes were simulated in ArcGIS and transportation distances were estimated for each county.[57] These values are recorded in column S, "Total_Miles," in the table in the Table Appendix. County centers range from 24 to 630 miles away from Boardman based on travel distance along major highways.

[57] ArcGIS ran an OD Cost Matrix using the network analysis extension to calculate these distances along the highway network. Counties of production were approximated as points located in the geometric centroid of each county polygon. This approximation should be reasonable for the scale of our analysis. County shapefiles were provided by NREL 2008, "Crop Residues." The highway network layer was provided by the US DOT Federal Highway Administration, from Sarmiento and Noch 2013.

3.4 Transportation Costs of moving biomass to Boardman

We assume that one flatbed truck can carry one 49,000 lb payload at a time.[58] The number of trucks required to transport each county's biomass production is calculated by dividing that production by 24.5 tons/truck. The number of trucks needed annually is estimated for each county in column U, "Trucks/Route," of the table in the Table Appendix. This figure ranges from 1 to 4700.

We assume that it costs $2.76 per mile to drive a truck with a full payload.[59] The cost of transport can be calculated by multiplying the number of trucks needed for each county by the transportation distance from the county center to Boardman, multiplied by $2.76. These estimates are given for each county in column W, "TransCost," in the Table Appendix. As mentioned above, for the 27 counties needed, these transport costs total to $28.5 million.

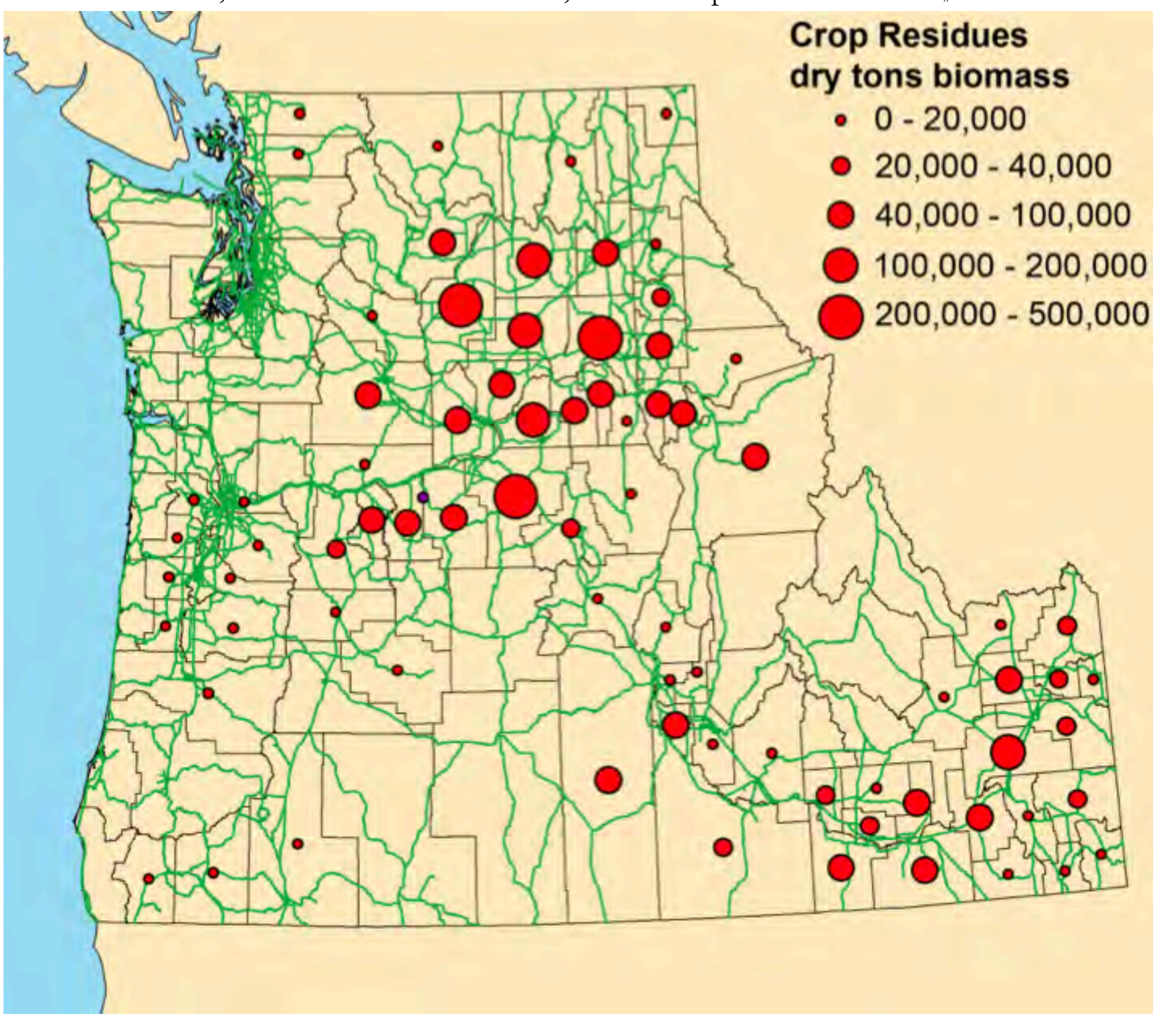

Figure 10. Estimated residues available to Boardman (by county) with highway network overlaid.

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[58] U.S. Department of Transportation 2000, section III, page 9.

[59] Flatbed Freight Trends 2014. See http://www.dat.com/resources/trendlines/national-flatbed-rates.aspx

3.5 Purchasing costs of crop residues

Our estimation refers to crop residues that are not used for animal feed or soil cover. The price commanded by these residues may differ from market prices for these uses. However, minimum cost estimates can be generated based on the costs of harvesting and baling. The fuel, labor, and storage cost of preparing corn stover is estimated to be $17/ton of stover with 15% moisture content.[60] The same costs for preparing wheat straw are approximately $16/ton.[61] Adjusting these prices for the production of dry residue results in $20/ton of stover, and $18.8/ton of straw. Based on our estimates of necessary residues (230,000 tons of corn and 1.59 million tons of wheat), the purchase cost of the biomass fuel is $34.5 million annually.

3.6 Meeting Demand

We assume that Boardman will acquire either all or none of the biomass residue of wheat and corn produced in any given county.[62] Again, we assume that only 35% of biomass produced is made available, allowing for 65% to remain on the fields or put to other use.

To pick the most cost effective counties from which to import crop residues, we order each county by the ratio of available crop residue to transportation costs. To meet Boardman's requirements of $2.60*10^{13}$ BTU/year, all of the corn and wheat residues must be imported from 27 of the nearest counties.

These 27 counties produce a total of 1.83 million tons of crop residues - 230,000 tons of corn residues and 1.59 million tons of wheat residues. These residues will require 74,400 trucks to drive a total of 10 million miles. This transportation will cost an estimated $28.5 million annually.

3.7 Carbon Emissions Associated with Biomass Transport

The EPA estimates that heavy duty trucks average 6.5 gallons of diesel consumed per thousand mile-tons traveled.[63] The Energy Information Administration estimates that every gallon of diesel fuel emits 22.38 pounds of CO_2.[64]

County level crop residue productions are multiplied by transportation distance from Boardman to generate mile-ton estimates for each county, slightly inflated to account for the weight of the truck itself. Loaded trucks are estimated to weigh 31.5 tons.[65] Summing this

60 Thompson and Tyner 2011.
61 Johnson and Herget 2013.
62 This rough method is a limitation of our data, which gives production data only at county-level specificity.
63 Davis et al. 2013, 91.
64 Energy Information Administration 2013.
65 US Department of Transportation 2000, III-9.

figure over each of the 27 required counties gives a total of 325 million mile-tons of transportation annually. Multiplying this figure by 0.0065 gallons diesel per mile-ton and 22.38 pounds of CO_2 per gallon diesel generates the total carbon emission estimate.

Moving 1.83 million tons of dry biomass to Boardman generates 24,000 tons of carbon dioxide emissions.

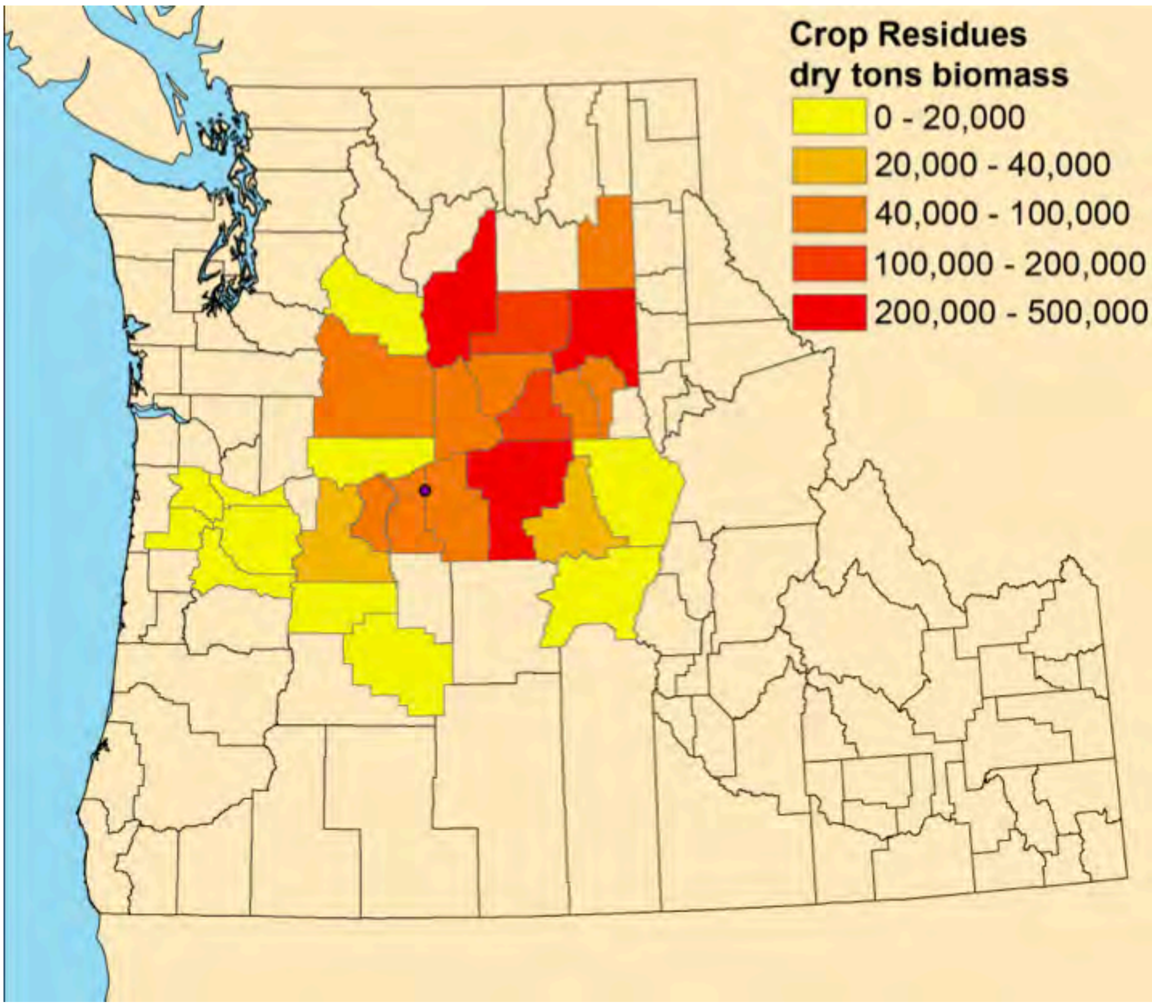

Figure 11. Extent of counties necessary to acquire sufficient biomass residues. This selection of counties minimizes transportation costs.

4 Torrefaction: Scenarios and Development

4.1 Current Torrefaction Technology

The process of torrefaction transforms raw biomass into a suitable substitute for coal. The torrefaction unit heats the biomass without the presence of oxygen, removing much of the water content and volatile organic compounds. The process creates hydrophobic fuel stock from nutritive plant tissue: the heat breaks down the three major compositional structures in plant material (cellulose, hemicellulose, and lignin). Hemicellulose experiences devolatilization and carbonization at around 250°C, whereas lignin and cellulose experience devolatilization and carbonization at around 300°C.[66] This process breaks down hemicellulose, which links cellulose in raw biomass. Depolymerization of cellulose also decreases fiber length, allowing the torrefied product to be more easily ground than raw biomass.[67]

The temperature regime of torrefaction can be outlined in five stages: initial heating, pre-drying, post-drying, torrefaction, and cooling.[68] In stages 1 and 2, the biomass is heated to 100°C and all the free water is evaporated. Stage 3 occurs under conditions of 100 to 200°C and physically bound water is released along with some light organics. Stage 4 is where the maximum temperature is reached and the biomass undergoes devolatilization, carbonization, and depolymerization. These processes result in the release of volatiles in the form of condensable and noncondensable gases. The torrefied product is allowed to return to room temperature during stage 5.[69] As every species of plant has different compositional characteristics, studies on optimizing temperature and length of time of the torrefaction process for wheat and stover residues are required to project whether theses biomass forms are a viable option for torrefaction and subsequent combustion.

The product of torrefaction possesses 70% its initial mass while maintaining 90% of its energy content.[70] Thus torrefaction improves the energy content to mass ratio, which allows for easier transportation and storage. Torrefied products are hydrophobic due to the removal of hydroxyl groups that would allow hydrogen bonds to form with water.[71] These hydrophobic properties allow for outdoor storage and reduce the chances of microorganism growth in the torrefied biomass.[72]

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66 Bergman & Kiel 2005.
67 *Ibid.*
68 Bergman et al. 2005.
69 *Ibid.*
70 Stelte 2012.
71 Acharjee et al. 2011.
72 Sadaka & Negi 2009.

4.2 Future Torrefaction Technology

Current torrefaction research aims to optimize the grindability of the torrefied product while maintaining high energy concentrations. Optimization can be achieved by varying the raw biomass moisture content, the particle size, and the residence time and heat within the torrefier itself. Also of concern to torrefaction developers are the large amounts of energy input and the CO_2 emissions associated with the process. Torrefaction of the 1.83 million tons of biomass needed to power Boardman is expected to produce 403,150 tons CO_2 and over 47,124 tons CO annually.[73]

Another area of interest in torrefaction development and optimization is the potential for harnessing the potential uses of the volatiles emitted as condensable gases and noncondensable gases produced in stages 3 and 4. The condensable gases are composed mostly of "water, acetic acid, aldehydes, alcohols, ketones and a wide range of lipids such as terpenes, phenols, fatty acids, waxes etc." while the noncondensables are mostly composed of CO_2 and CO.[74] The noncondensable gases can be captured, combusted on site, and used to heat the torrefier, whereas some of the condensable gases could be used as precursors to marketable chemicals such as methanol, furfural, formic acid, and acetic acid.[75] Raw biomass contains additional trace elements, such as sulfur, chlorine, calcium, magnesium, potassium, and, sodium, which can reduce the efficiency of heat transfer in the combustion boiler and even cause corrosion.[76]

Torrefaction is still a young technology, and it requires a significant amount of research and development in order to determine the exact cost and specifications of a full-scale system that would serve Boardman's needs by converting 1.83 million tons of dry biomass into 1.28 million tons of torrefied biomass fuel.

4.3 Distribution of Torrefaction for Boardman

The conceptual torrefaction unit proposed by Matyas et al.'s report on Arundo Donax Biomass has a capacity of 100 tons of dry biomass per hour, which is approximately half of the capacity needed to torrefy the 5,014 tons of dry biomass per day required to run the plant. One large torrefaction unit at Boardman might prove to be more efficient in terms of energy input and collection of byproducts than distributed torrefaction centers. However, torrefaction dispersed throughout the 27 counties would reduce the transportation costs by $8.5 million annually and the carbon budget by 6,900 tons CO_2 annually.

[73] See Torrefaction Calculations appendix.
[74] Stelte 2012.
[75] *Ibid.*
[76] Matyas et al. 2012.

These reductions are based on the model's rough assumption that all biomass is coming from the centroid of each county, and that biomass would be torrefied at each centroid before any transportation occurred. This constitutes a very unlikely scenario given the initial cost, energy requirements, and permitting needed for each unit. A more realistic scenario would entail several large torrefaction units distributed across a few counties, which could optimize efficiency while reducing transportation costs. However, this would require additional transportation between fields and torrefaction units, reducing the benefits of building distributed units.

Further development in torrefaction technology is necessary for a comprehensive optimization analysis of torrefaction unit distribution. Unit size, cost, energy and carbon efficiency, lifetime, and pollution controls are essential factors to consider both when projecting and when implementing the distribution of torrefaction units.

4.4 Torrefaction Calculations

The above calculation shows a need for $2.60*10^{13}$ BTU annually, which corresponds to 1.83 $*10^6$ tons of dry biomass annually from the 27 counties (see section 3.1).

Since 70% mass is retained upon torrefaction, this corresponds to annually:

$$1.83 \ * 10^6 \ tons\ of\ dry\ biomass\ * \ 0.7 = 1.28 * 10^6 \ tons\ \ torrefied\ biomass$$

Daily requirements:

$$\frac{1.83 \ * 10^6 \ tons\ of\ dry\ biomass}{365} days = 5010\ tons\ dry\ biomass\ per\ day$$

Gaseous emissions:

$$1.83 \ * 10^6 \ tons\ of\ dry\ biomass\ * \ 0.3 = 5.49 * 10^5 \ tons\ \ gaseous\ emissions$$

Annual CO_2 emissions are 7.3% of total gaseous emissions:

$$5.49 * 10^5 \ tons\ \ gaseous\ emissions * 0.073 = \mathbf{4.01 * 10^4 \ tons\ \ CO_2}$$

$$= 2.19 * 10^{-2} \ tons\ CO_2\ per\ ton\ biomass$$

Annual CO emissions are 2.6% of total gaseous emissions:

$$5.49 * 10^5 \ tons\ \ gaseous\ emissions * 0.026 = \mathbf{1.43 * 10^4 \ tons\ \ CO}$$

$$= 7.8 * 10^{-3} \ tons\ CO\ per\ ton\ biomass$$

In addition, 40% of the gaseous emissions are combustible gases that are added to help operate torrefaction, and hence combusted to CO_2 in the process. This adds up to:

$$5.49 * 10^5 tons * 0.40 = 2.20 * 10^5 tons\ combustible\ gases$$

The composition of this gas determines the tons C which are thus converted to CO_2:

Acetic Acid (50%)

$$2.20 * 10^5 tons * 0.5 * \frac{24\ g\ C}{60\ g\ acetic\ acid} = 4.39 * 10^4 tons\ C$$

Methanol (24%)

$$2.20 * 10^5 tons * 0.24 * \frac{12\ g\ C}{32\ g\ methanol} = 1.98 * 10^4 tons\ C$$

Furfural (24%)

$$2.20 * 10^5 tons * 0.24 * \frac{60\ g\ C}{96\ g\ furfural} = 3.30 * 10^4 tons\ C$$

1-hydroxy-2-butanone (2%)

$$2.20 * 10^5 tons * 0.02 * \frac{48\ g\ C}{88\ g\ 1h2b} = 2.40 * 10^3 tons\ C$$

Net combustion output:

$$9.90 * 10^4 tons * \frac{44\ g\ CO2}{12\ g\ C} = 3.63 * 10^5 tons\ CO_2$$

Overall torrefaction CO_2 emissions:

$$4.01 * 10^4\ tons\ gaseous + 3.63 * 10^5\ tons\ combusion\ of\ assisting\ gases$$
$$= 4.03 * 10^5\ tons\ CO_2\ released\ annually$$

5 Carbon Balance of Biomass to Boardman

Proponents of biomass often envision the energy source as a carbon neutral fuel solution, and in some ways this is a fair idealization. The large amount of carbon dioxide emitted both during biomass combustion, 2.4 million tons (section 2.4.4), and torrefaction, 403,000 tons (section 4.4), was sequestered from the atmosphere during the growing season of wheat and corn.[77] Under no-till farming conditions, additional carbon is sequestered in the roots and residues left in the field (up to 0.91 tons C/acre).[78] Under conventional farming, which involves tilling, no such additional carbon sequestration occurs. Therefore the two tilling methods described above could be framed as either "carbon positive" or "carbon neutral", respectively, but these descriptions do not necessarily take into account the carbon dioxide emitted in the process of converting that biofuel into a useable energy source for facilities like Boardman. The transportation of said biomass, or even parts of the farming process like irrigation, fertilization, seed preparation, and crop harvesting and baling, all have negative

[77] See Torrefaction Calculations. Also see Lewis et al. 2012, page 20.
[78] West and Marland 2002, page 228.

implications for the carbon budget of biomass combustion. The machinery necessary for these processes relies on non-carbon neutral fossil fuels; the balanced or positive carbon budget of the tilling methods should not be considered separately from these concomitant processes.

Accounting for the carbon budget of biomass fuel to Boardman requires close consideration at every step, even in the fields. Assuming conventional tilling practices, growing and harvesting the crop results in the emission of 0.27 tons CO_2/acre for wheat and 0.42 tons CO_2/acre for corn.[79] Based on Boardman's annual biomass requirements, annual emissions of CO_2 from biomass harvest add up to 16,000 tons CO_2 from corn and 55,700 tons CO_2 from wheat. Then, transporting the crops will result in the emission of 24,000 tons of CO_2.[80] The torrefaction process itself also results in an additional 403,000 tons CO_2 emissions. However, considering the biogenic source of this carbon emitted during torrefaction, as well as the 2.4 million tons of CO_2 emitted during combustion of the torrefied fuel in the power plant, we omit it from the carbon balance. Thus, the overall annual emissions from harvesting and delivering to Boardman sufficient conventionally farmed corn and wheat to generate 300 MW annual average is roughly 96,000 tons of CO_2. Boardman's current annual CO_2 output is 4,680,000 tons of CO_2 equivalent, which is emitted during the processes of transportation and combustion of Powder River Basin coal.[81]

Avoiding CO_2 emissions is an important consideration for the new Boardman, and will pose a challenge if the facility is bound by stringent emissions policies – but converting to biomass will aid in the statewide effort to shift to lower-carbon, renewable energy. As decisions for the new plant move forward, PGE is faced with a complex political landscape situated in an age-old carbon cycle. The degree to which Boardman concerns itself with that cycle will dictate the next steps.

[79] *Ibid.,* page 226.
[80] See Transportation Calculations.
[81] Lewis et al. 2012, page 4.

6 GIS Table Appendix

	A	B	C	D	E	F	G	H
	OBJECTID	NAME	STATE_NAMI	FIPS	POP2000	SQMI	ag_district	ag_district_code
1	69	Morrow	Oregon	41049	10995	2048.5	NORTH CENTRAL	20
2	72	Sherman	Oregon	41055	1934	831.3	NORTH CENTRAL	20
3	74	Umatilla	Oregon	41059	70548	3231.5	NORTHEAST	30
4	55	Gilliam	Oregon	41021	1915	1222.8	NORTH CENTRAL	20
5	100	Klickitat	Washington	53039	19161	1904.3	CENTRAL	20
6	83	Benton	Washington	53005	142475	1760	CENTRAL	20
7	91	Franklin	Washington	53021	49347	1264.8	EAST CENTRAL	50
8	77	Wasco	Oregon	41065	23791	2395.4	NORTH CENTRAL	20
9	116	Walla Walla	Washington	53071	55180	1299.1	SOUTHEAST	90
10	87	Columbia	Washington	53013	4064	873.6	SOUTHEAST	90
11	119	Yakima	Washington	53077	222581	4311.6	CENTRAL	20
12	75	Union	Oregon	41061	24530	2038.6	NORTHEAST	30
13	81	Adams	Washington	53001	16428	1930	EAST CENTRAL	50
14	70	Multnomah	Oregon	41051	660486	465.5	NORTHWEST	10
15	60	Jefferson	Oregon	41031	19009	1791.2	SOUTHEAST	80
16	93	Grant	Washington	53025	74698	2791.5	EAST CENTRAL	50
17	47	Clackamas	Oregon	41005	338391	1878.9	NORTHWEST	10
18	92	Garfield	Washington	53023	2397	718.2	SOUTHEAST	90
19	78	Washington	Oregon	41067	445342	726.4	NORTHWEST	10
20	118	Whitman	Washington	53075	40740	2178	SOUTHEAST	90
21	99	Kittitas	Washington	53037	33362	2333.1	CENTRAL	20
22	45	Baker	Oregon	41001	16741	3088.4	NORTHEAST	30
23	51	Crook	Oregon	41013	19182	2987.4	SOUTHEAST	80
24	76	Wallowa	Oregon	41063	7226	3151.7	NORTHEAST	30
25	80	Yamhill	Oregon	41071	84992	718.2	NORTHWEST	10
26	68	Marion	Oregon	41047	284834	1194.4	NORTHWEST	10
27	112	Spokane	Washington	53063	417939	1780.7	NORTHEAST	30

I	J	K	L	M	N	O	P
corn_grain_acres	corn_silage_acres	corn_silage_tons	wheat_acres	CornBushel	CornRes	WheatBushe	WheatRes_1
6,652	(D)	(D)	170,060	1516236	12,630	6,449,631	76,152
0	0	0	115,237	0	0	5,341,013	63,063
9,332	806	11,366	303,203	2044674	17,032	16,284,987	192,281
(D)	0	0	97,710	0	0	3,813,285	45,024
0	0	0	38,668	0	0	1,126,093	13,296
12,672	(D)	(D)	94,268	2943121	24,516	4,512,161	53,276
16,369	6,126	170,971	76,863	3355745	27,953	4,584,764	54,133
0	0	0	56,091	0	0	2,321,189	27,407
4,758	(D)	1,042	190,973	1210644	10,085	12,661,018	149,492
(D)	0	0	77,970	0	0	5,095,533	60,164
16,755	25,047	679,666	20,427	3442047	28,672	1,519,644	17,943
361	(D)	(D)	26,930	47000	392	2,086,967	24,641
8,603	4,034	117,467	262,101	1696947	14,136	12,765,373	150,724
(D)	(D)	(D)	826	0	0	68,845	813
0	0	0	7,542	0	0	815,576	9,630
57,432	8,334	223,139	145,979	11598665	96,617	10,295,197	121,558
(D)	225	4,672	843	0	0	64,650	763
0	0	0	68,447	0	0	3,482,031	41,113
101	1,679	35,869	9,752	13043	109	895,325	10,571
(D)	0	0	457,973	0	0	30,592,763	361,216
(D)	(D)	(D)	911	0	0	69,292	818
0	367	9,045	8,481	0	0	703,882	8,311
0	0	0	1,149	0	0	107,567	1,270
0	0	0	8,117	0	0	404,672	4,778
(D)	1,490	35,818	2,658	0	0	210,535	2,486
(D)	3,584	88,207	3,741	0	0	292,203	3,450
(D)	115	(D)	140,746	0	0	8,115,549	95,822
				Totals:	232,141		1,590,197

Q	R	S	T	U	V	W	X
TotalResEst	NRELRes	Total_Miles	EstBTU	Trucks/Route	Mile-Tons	TransCost	BTU/TransCost
88,783	116,816	25	1.24E+12	3,624	2,192,056	246,942	5,012,558
63,063	63,890	81	8.75E+11	2,574	5,133,435	578,297	1,513,381
209,313	224,997	82	2.91E+12	8,543	17,193,695	1,936,922	1,503,679
45,024	42,748	84	6.25E+11	1,838	3,762,364	423,842	1,474,251
13,296	14,237	86	1.85E+11	543	1,141,928	128,642	1,434,396
77,792	154,294	92	1.09E+12	3,175	7,125,710	802,733	1,358,658
82,087	152,644	108	1.15E+12	3,350	8,847,126	996,656	1,155,645
27,407	41,028	115	3.80E+11	1,119	3,148,346	354,671	1,072,409
159,576	171,312	124	2.22E+12	6,513	19,826,449	2,233,510	993,566
60,164	54,710	142	8.35E+11	2,456	8,525,842	960,462	869,330
46,615	32,118	145	6.60E+11	1,903	6,774,910	763,214	864,536
25,033	34,471	143	3.48E+11	1,022	3,589,797	404,402	859,497
164,860	236,804	144	2.29E+12	6,729	23,781,211	2,679,026	856,386
813	790	146	1.128E+10	33	118,698	13,372	843,570
9,630	11,482	153	1.34E+11	393	1,471,572	165,777	806,149
218,175	269,293	163	3.07E+12	8,905	35,587,902	4,009,086	766,087
763	1,006	176	1.059E+10	31	134,366	15,137	699,622
41,113	39,500	182	5.71E+11	1,678	7,466,125	841,082	678,375
10,680	13,957	186	1.48E+11	436	1,988,374	223,996	661,912
361,216	335,082	191	5.01E+12	14,744	69,143,907	7,789,273	643,572
818	419	192	1.135E+10	33	156,947	17,681	641,949
8,311	17,201	192	1.15E+11	339	1,596,044	179,799	641,488
1,270	2,261	199	1.763E+10	52	252,666	28,464	619,388
4,778	9,489	208	6.631E+10	195	993,419	111,912	592,521
2,486	8,110	208	3.45E+10	101	517,497	58,298	591,791
3,450	5,721	219	4.788E+10	141	756,393	85,210	561,906
95,822	84,298	219	1.33E+12	3,911	21,031,479	2,369,261	561,281
1,822,339	2,138,678		2.54E+13	74,381	252,258,256	28,417,665	

	A	B	C	D	E	F	G	H
	OBJECTID	NAME	STATE_NAMI	FIPS	POP2000	SQMI	ag_district	ag_district_code
28	102	Lincoln	Washington	53043	10184	2339.4	EAST CENTRAL	50
29	71	Polk	Oregon	41053	62380	744.2	NORTHWEST	10
30	35	Nez Perce	Idaho	16069	37410	856.6	NORTH	10
31	89	Douglas	Washington	53017	32603	1848.7	EAST CENTRAL	50
32	82	Asotin	Washington	53003	20551	640.7	SOUTHEAST	90
33	29	Latah	Idaho	16057	34935	1076.8	NORTH	10
34	31	Lewis	Idaho	16061	3747	479.9	NORTH	10
35	46	Benton	Oregon	41003	78153	679	NORTHWEST	10
36	28	Kootenai	Idaho	16055	108685	1315.7	NORTH	10
37	66	Linn	Oregon	41043	103069	2309.9	NORTHWEST	10
38	38	Payette	Idaho	16075	20578	409.9	SOUTHWEST	70
39	44	Washington	Idaho	16087	9977	1473.5	SOUTHWEST	70
40	5	Benewah	Idaho	16009	9171	783.9	NORTH	10
41	113	Stevens	Washington	53065	40066	2540.8	NORTHEAST	30
42	64	Lane	Oregon	41039	322959	4617.6	NORTHWEST	10
43	104	Okanogan	Washington	53047	39564	5315	CENTRAL	20
44	14	Canyon	Idaho	16027	131441	603.6	SOUTHWEST	70
45	23	Gem	Idaho	16045	15181	565.9	SOUTHWEST	70
46	62	Klamath	Oregon	41035	63775	6135.4	SOUTHEAST	80
47	18	Clearwater	Idaho	16035	8930	2488.1	NORTH	10
48	1	Ada	Idaho	16001	300904	1060.5	SOUTHWEST	70
49	67	Malheur	Oregon	41045	31615	9930	SOUTHEAST	80
50	11	Boundary	Idaho	16021	9871	1277.9	NORTH	10
51	25	Idaho	Idaho	16049	15511	8503	NORTH	10
52	20	Elmore	Idaho	16039	29130	3100.6	SOUTHWEST	70
53	109	Skagit	Washington	53057	102979	1753.1	WESTERN	10
54	37	Owyhee	Idaho	16073	10644	7696.7	SOUTHWEST	70
55	24	Gooding	Idaho	16047	14155	733.8	SOUTH CENTRAL	80
56	59	Jackson	Oregon	41029	181269	2801.8	SOUTHWEST	70

I	J	K	L	M	N	O	P
corn_grain_acres	corn_silage_acres	corn_silage_tons	wheat_acres	CornBushel	CornRes	WheatBushe	WheatRes_1
0	(D)	(D)	313,441	0	0	16,754,595	197,826
0	2,388	60,273	2,374	0	0	209,901	2,478
0	0	0	106,270	0	0	6,581,267	77,707
(D)	(D)	(D)	157,898	0	0	6,760,910	79,828
0	0	0	25,642	0	0	1,014,605	11,980
(D)	0	0	91,834	0	0	6,279,048	74,138
0	0	0	98,866	0	0	4,881,944	57,642
(D)	239	4,157	3,615	0	0	373,901	4,415
0	(D)	(D)	9,585	0	0	626,910	7,402
(D)	1,370	36,013	4,234	0	0	368,376	4,350
3,808	5,161	129,561	5,346	701392	5,843	517,287	6,108
1,382	1,028	29,638	7,705	213898	1,782	614,617	7,257
0	0	0	35,996	0	0	2,257,031	26,649
0	0	0	5,121	0	0	223,669	2,641
12	1,146	27,503	1,407	1860	15	147,964	1,747
(D)	795	16,726	11,621	0	0	487,433	5,755
20,301	16,206	430,850	23,208	3725465	31,033	2,519,780	29,752
3,158	2,129	52,750	3,001	537522	4,478	325,827	3,847
0	(D)	(D)	5,654	0	0	497,368	5,873
0	0	0	11,123	0	0	553,002	6,529
2,537	7,829	217,654	4,576	489128	4,074	491,491	5,803
17,744	5,880	156,790	22,927	3146800	26,213	2,389,511	28,214
0	0	0	16,063	0	0	1,096,223	12,943
0	0	0	86,889	0	0	5,151,115	60,821
5,847	6,126	183,593	10,058	1015825	8,462	863,248	10,193
(D)	7,395	186,154	4,686	0	0	401,904	4,745
11,600	9,264	263,939	6,828	2100889	17,500	708,486	8,365
12,178	45,065	1,309,343	2,845	1979872	16,492	299,710	3,539
(D)	118	2,594	264	0	0	14,512	171

Q	R	S	T	U	V	W	X
TotalResEst	NRELRes	Total_Miles	EstBTU	Trucks/Route	Mile-Tons	TransCost	BTU/TransCost
197,826	232,478	220	2.75E+12	8,075	43,552,972	4,906,376	559,562
2,478	8,872	222	3.4395E+10	101	549,921	61,950	555,197
77,707	83,975	227	1.08E+12	3,172	17,609,530	1,983,768	543,617
79,828	70,328	230	1.11E+12	3,258	18,350,788	2,067,272	535,899
11,980	9,566	232	1.66E+11	489	2,775,366	312,653	531,752
74,138	83,091	240	1.03E+12	3,026	17,799,765	2,005,198	513,111
57,642	64,420	251	8.00E+11	2,353	14,469,243	1,630,005	490,772
4,415	2,684	251	6.1268E+10	180	1,108,958	124,927	490,427
7,402	10,412	252	1.03E+11	302	1,866,955	210,318	488,431
4,350	6,263	259	6.0362E+10	178	1,126,797	126,937	475,530
11,950	15,680	267	1.68E+11	488	3,187,006	359,026	469,259
9,039	9,279	268	1.26E+11	369	2,424,255	273,100	462,252
26,649	26,428	268	3.70E+11	1,088	7,141,491	804,511	459,707
2,641	4,069	273	3.6651E+10	108	720,539	81,171	451,524
1,763	2,322	280	2.4468E+10	72	494,082	55,660	439,590
5,755	4,649	282	7.9871E+10	235	1,623,315	182,871	436,762
60,785	80,590	287	8.58E+11	2,481	17,439,615	1,964,626	436,488
8,325	8,319	296	1.18E+11	340	2,464,119	277,591	423,447
5,873	35,239	296	8.1499E+10	240	1,735,550	195,515	416,844
6,529	6,729	301	9.0615E+10	267	1,963,594	221,205	409,645
9,878	12,870	313	1.39E+11	403	3,089,830	348,079	399,091
54,426	70,903	329	7.67E+11	2,221	17,909,287	2,017,536	380,229
12,943	17,055	324	1.80E+11	528	4,193,996	472,467	380,192
60,821	54,538	334	8.44E+11	2,482	20,323,203	2,289,471	368,673
18,654	41,018	370	2.63E+11	761	6,899,023	777,196	338,002
4,745	19,265	370	6.5856E+10	194	1,753,702	197,560	333,349
25,866	30,245	388	3.67E+11	1,056	10,037,889	1,130,799	324,407
20,031	28,907	400	2.85E+11	818	8,005,732	901,870	316,468
171	386	393	2377951057	7	67,294	7,581	313,678

	A	B	C	D	E	F	G	H
	OBJECTID	NAME	STATE_NAMI	FIPS	POP2000	SQMI	ag_district	ag_district_code
57	117	Whatcom	Washington	53073	166814	2162.3	WESTERN	10
58	61	Josephine	Oregon	41033	75726	1641.4	SOUTHWEST	70
59	27	Jerome	Idaho	16053	18342	601.9	SOUTH CENTRAL	80
60	32	Lincoln	Idaho	16063	4044	1205.9	SOUTH CENTRAL	80
61	42	Twin Falls	Idaho	16083	64284	1928.4	SOUTH CENTRAL	80
62	34	Minidoka	Idaho	16067	20174	763.1	SOUTH CENTRAL	80
63	16	Cassia	Idaho	16031	21416	2580.3	SOUTH CENTRAL	80
64	12	Butte	Idaho	16023	2899	2233.6	EAST	90
65	39	Power	Idaho	16077	7538	1442.8	EAST	90
66	6	Bingham	Idaho	16011	41735	2120.2	EAST	90
67	26	Jefferson	Idaho	16051	19155	1105.6	EAST	90
68	3	Bannock	Idaho	16005	75565	1147.4	EAST	90
69	36	Oneida	Idaho	16071	4125	1201.7	EAST	90
70	17	Clark	Idaho	16033	1022	1765.1	EAST	90
71	33	Madison	Idaho	16065	27467	473.4	EAST	90
72	10	Bonneville	Idaho	16019	82522	1900.6	EAST	90
73	15	Caribou	Idaho	16029	7304	1798.6	EAST	90
74	22	Fremont	Idaho	16043	11819	1895.6	EAST	90
75	21	Franklin	Idaho	16041	11329	668.4	EAST	90
76	41	Teton	Idaho	16081	5999	450.6	EAST	90
77	4	Bear Lake	Idaho	16007	6411	1049.4	EAST	90

I	J	K	L	M	N	O	P
corn_grain_acres	corn_silage_acres	corn_silage_tons	wheat_acres	CornBushel	CornRes	WheatBushe	WheatRes_1
0	16,478	387,648	430	0	0	24,263	286
6	0	0	(D)	929	8	0	0
3,763	28,172	762,759	11,703	622501	5,185	1,294,056	15,279
2,772	7,459	212,551	8,154	444192	3,700	732,722	8,651
13,461	34,690	878,424	24,464	2203349	18,354	2,651,024	31,301
6,711	5,663	152,131	35,770	1113811	9,278	3,656,390	43,172
2,507	20,399	512,859	72,640	328461	2,736	6,402,127	75,592
0	(D)	(D)	2,288	0	0	205,263	2,424
4,434	1,210	30,680	88,231	699866	5,830	5,746,383	67,849
1,560	3,846	106,805	118,896	304650	2,538	12,369,771	146,053
4,439	8,898	217,594	36,831	694514	5,785	3,614,207	42,674
0	(D)	(D)	30,522	0	0	1,303,908	15,396
0	(D)	(D)	31,502	0	0	864,097	10,203
0	(D)	(D)	5,382	0	0	505,137	5,964
(D)	(D)	(D)	40,932	0	0	3,344,649	39,491
1,905	4,200	101,153	51,322	247228	2,059	2,909,716	34,356
0	(D)	(D)	41,059	0	0	1,712,559	20,221
1,278	585	11,793	33,689	193260	1,610	2,226,929	26,294
644	2,443	58,585	18,450	103512	862	709,034	8,372
0	0	0	11,673	0	0	426,508	5,036
0	0	0	5,063	0	0	74,758	883

Q	R	S	T	U	V	W	X
TotalResEst	NRELRes	Total_Miles	EstBTU	Trucks/Route	Mile-Tons	TransCost	BTU/TransCost
286	3,955	407	3975759823	12	116,614	13,137	302,640
8	85	429	110878231	0	3,322	374	296,240
20,465	59,844	433	2.86E+11	835	8,855,356	997,583	287,036
12,352	15,756	435	1.73E+11	504	5,371,183	605,080	286,045
49,655	110,274	448	6.97E+11	2,027	22,226,190	2,503,848	278,521
52,450	120,884	463	7.32E+11	2,141	24,259,685	2,732,928	267,872
78,328	169,328	492	1.09E+12	3,197	38,537,759	4,341,397	250,670
2,424	13,800	513	3.3635E+10	99	1,243,500	140,084	240,103
73,679	169,459	515	1.03E+12	3,007	37,936,156	4,273,624	239,876
148,591	259,569	550	2.06E+12	6,065	81,688,566	9,202,467	224,209
48,459	127,088	555	6.75E+11	1,978	26,895,059	3,029,811	222,825
15,396	27,636	560	2.14E+11	628	8,623,850	971,503	219,927
10,203	14,268	561	1.42E+11	416	5,727,895	645,265	219,432
5,964	6,211	577	8.2772E+10	243	3,438,600	387,369	213,678
39,491	108,034	584	5.48E+11	1,612	23,058,475	2,597,608	210,986
36,415	128,635	600	5.06E+11	1,486	21,852,845	2,461,790	205,662
20,221	57,272	604	2.81E+11	825	12,223,215	1,376,983	203,795
27,904	114,046	606	3.88E+11	1,139	16,904,459	1,904,339	203,731
9,234	12,976	612	1.29E+11	377	5,651,375	636,645	201,898
5,036	30,050	619	6.9888E+10	206	3,119,272	351,396	198,887
883	3,991	627	1.225E+10	36	553,701	62,376	196,388

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The authors (Spring 2014 Environmental Studies Junior Seminar class at Reed College) visit Boardman and inspect some biofuels. Thanks, Wayne Lei, Dave Rodgers, and Jim Brewer! Contacts for this report: J. Fry (fry@reed.edu) or C. Koski (ckoski@reed.edu)