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

Final report of the Spring 2014 Environmental Studies Junior Seminar (ES300) at Reed College

Claire Brumbaugh-Smith (ES-Bio, '15), Adriana Escobedo-Land (ES-Bio, '15), Marisa Hazell (ES-Pol, '15), G Luhman (ES-Chem, '15), Riley McMath (ES-His, '15), Rennie Meyers (ES-His, '15), Helen Spencer-Wallace (ES-His, '15) Austin Weisgrau (Econ, '15)

Profs. Juliane Fry and Chris Koski

With support from the Environmental Studies Program, Reed College May 2014

## **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 A rundo danax 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 miton oming in

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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. 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-

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. 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.

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## 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. 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. 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.<sup>6</sup>

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.<sup>7</sup>

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.<sup>8</sup>

#### 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. 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. 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.

 $^{\rm 9}$  http://www.deanenergyvision.org/ dean-energy-vision-technical-report/western

## 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.<sup>11</sup>

Early in its history, Oregon had used a combination of hydroelectricity and biomass (known as "hog fuel") to produce electricity. / TTaa-ors(ors)1(it)1971(t[s)1y

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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. 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

# 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. 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. Thus, the application of current BART standards will last until 2020 when Boardman shuts down in

<sup>15</sup> Corson 2010.

<sup>&</sup>lt;sup>16</sup> PGE 2014.

<sup>&</sup>lt;sup>17</sup> 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"

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. 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. 9

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. 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 Serra Club lawsuit cited against Boardman. This will likely require that PGE Boardman make significant changes to the plant to cap carbon emissions; corresponding CO<sub>2</sub> emissions calculations follow in section 2.4 below.

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

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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.

Smilar  $NO_x$  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. 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. Unknown NO<sub>x</sub> 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<sub>2</sub> emissions.<sup>28</sup> Title V permits will be required for plants with a GHG of 100,000 tons/ year or more.<sup>29</sup> 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.<sup>30</sup> 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

 $^{26}$  Nordin and Merriam 1997. NO<sub>x</sub> can be emitted as NO, NO<sub>2</sub>, NO<sub>3</sub>, N<sub>2</sub>O, N<sub>2</sub>O<sub>4</sub>, or N<sub>2</sub>O<sub>5</sub>. Typically, the total process of combusting Powder River Basin coal produces NO, N<sub>2</sub>O, and NO<sub>2</sub>. hac.

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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.<sup>31</sup>

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.<sup>32</sup> However, this change will be coupled with stricter stationary source CO<sub>2</sub> emissions rules that the EPA will officially mandate in June 2014, rules which will require a highly significant reduction of Boardman's CO<sub>2</sub> emissions.

Excluding the CO

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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<sub>2</sub>e/ MWh. We found that the emissions will be 3115 lbs/ MWh and 1808 lbs/ MWh respectively for A rundo 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. 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.<sup>37</sup>

Our calculations suggest that 500,773 tons of Oregon crop residues that will be eligible for this subsidy.<sup>38</sup> 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

<sup>&</sup>lt;sup>35</sup> 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.

<sup>36</sup> Marten 2009.

<sup>37</sup> ODOE 2013.

<sup>38</sup> 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.<sup>39</sup>

#### 2.4 Emissions Calculations for different fuel sources

#### 2.4.1 Units

- $M_x = Mass fuel source used (x-fuel source) = T/ (BTU/Ib_{biomass grop})*2000lb/ton$
- T= BTU/ year
- E = Energy (MWh/ year )
- Em, = emissions (x fuel source)
- P<sub>s</sub>= Percent composition sulfur
- P<sub>c</sub>= Percent composition carbon
- ! = Efficiency (!!"#\$!! "#!

#### 2.4.2 Calculation Notes

- Boardman's energy generation per year is assumed to be 615 MW for coal and 300 MW for biomass.<sup>40</sup>
- Use of a dry sorbent injection system yields an assumed 75% reduction in SO<sub>2</sub> (sulfur) emissions from burning biomass.<sup>41</sup>
- Use of leaching technique results in a 71.6% reduction of sulfur content.<sup>42</sup>
- Total SO<sub>2</sub> emissions from burning biomass are multiplied by 0.95 due to the 4.6% sulfur lost during the torrefaction process.<sup>43</sup>
- Torrefied biomass has only 70% of the original mass of non-torrefied dry biomass.<sup>44</sup>

<sup>&</sup>lt;sup>39</sup> EIA 2014.

<sup>&</sup>lt;sup>40</sup> Lewis, M. et al 2012.

<sup>&</sup>lt;sup>41</sup> PGE 2014.

<sup>42</sup> J. Matyas et al 2012.

<sup>&</sup>lt;sup>43</sup> J. Matyas et al 2012.

<sup>&</sup>lt;sup>44</sup> See Torrefaction section of this report.

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<sup>&</sup>lt;sup>46</sup> Wood is not taken into account

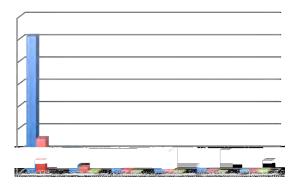


Figure 3. Sulfur dioxide emissions from coal and different potential fuel sources compared to the amount of sulfur dioxide emissions permitted by the Regional Haze Rule.

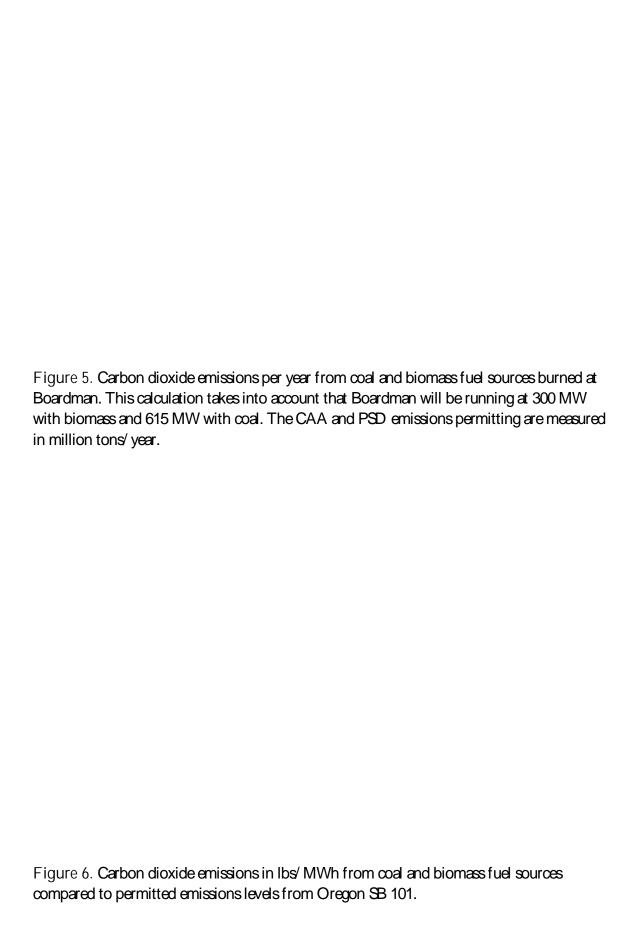
Figure 4. Sulfur dioxide emissions from biomass fuel crops, excluding coal so that their comparison to the permitted emissions levels is clearer. Blue, red and green bars represented the same as in Figure 3.

## 2.4.4 Carbon Emissions from Biomass<sup>47</sup>

Combined corn and wheat biomass:

 $M_{\mbox{\tiny grop}}\mbox{-} 1.281$  million tons of combined corn and wheat biomass

50% carbon content



# 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%.

## 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.<sup>49</sup>

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.<sup>50</sup>

<sup>48</sup> Stelte 2012.

<sup>&</sup>lt;sup>49</sup> Lewis et al. 2012, page 19.

<sup>50</sup> Clarke and Preto 2011.

Both of the crops lose about 10% of their stored chemical energy during torrefaction.<sup>51</sup> \*10<sup>13</sup> BTU of power, Boardman will need: To prody

! 1.79 million tons of dry corn residues, or

= 1.85 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.<sup>53</sup>

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.<sup>54</sup> 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.<sup>56</sup>

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.

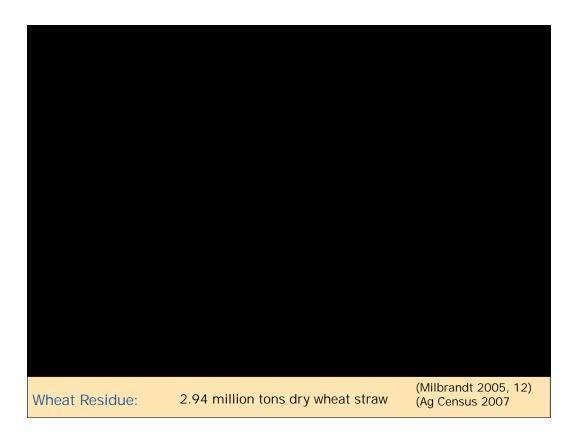


Figure 8. Estimated wheat residues (by county) that are available to Boardman.



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. 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.

<sup>&</sup>lt;sup>57</sup> 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 USDOT 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.<sup>58</sup> 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.<sup>59</sup> 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.

<sup>58</sup> U.S. Department of Transportation 2000, section III, page 9.

<sup>59</sup> 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. The same costs for preparing wheat straw are approximately \$16/ ton. 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. 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<sup>13</sup> 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<sub>2</sub>. 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. <sup>65</sup> Summing this

<sup>60</sup> Thompson and Tyner 2011.

<sup>61</sup> Johnson and Herget 2013.

<sup>62</sup> This rough method is a limitation of our data, which gives production data only at county-level specificity.

<sup>&</sup>lt;sup>63</sup> Davis et al. 2013, 91.

<sup>64</sup> Energy Information Administration 2013.

<sup>65</sup> USD epartment 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. 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.

The temperature regime of torrefaction can be outlined in five stages: initial heating, predrying, post-drying, torrefaction, and cooling. 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

## 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  $CO_2$  annually.<sup>73</sup>

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<sub>2</sub> and CO.<sup>74</sup> 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.<sup>75</sup> Raw biomass contains additional trace elements, such as sulfur, chlorine, calcium, magnesium, potassium, and, sodium, which can reduce torrefieh ce of "(at)1(t)1(he)1en(he)1(c)1(onde)teis tbo1(t)1r

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

In addition, 40% of the gaseous emissions are combustible gases that are added to help operate torrefaction, and hence combusted to CO<sub>2</sub> in the process. This adds up to:

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<sub>2</sub>/ acre for wheat and 0.42 tons CO<sub>2</sub>/ acre for corn.<sup>79</sup> Based on Boardman's annual biomass requirements, annual emissionTm [/ ac)1(re)1(for

## 6 GIS Table Appendix

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## 7 Bibliography

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 ( <a href="mailto:fry@reed.edu">fry@reed.edu</a> ) or C. Koski ( <a href="mailto:ckoski@reed.edu">ckoski@reed.edu</a> )