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Northeast Feedstock Supply Technical and Economical Assessment

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March 2013

Idaho National Laboratory

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Milestone Completion Report

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Objective:

The objective of this collaborative task with the Pacific Northwest National Laboratory is to analyze the opportunities and the technical aspects of replacing petroleum derived heating oil in the Northeast U.S with biomass pyrolysis oil. This analysis will use the most economic, feedstocks available that will meet conversion in-feed target specifications which can be upgraded to abio-oil that will be infrastructure compatible with existing home heating infrastructure. INL will update the Renewable Heating Oil Supply Dynamics model in order to support this analysis with collaboration from PNNL.

Expected Outcome:

The goal is to verify a feedstock cost (e.g., <$65/dry ton) for >5% replacement of petroleum-based heating oil within 5 years (2017) and >20% replacement of petroleum heating oil within 10 years (by 2022). This will include verifying that the feedstock blends can meet the in-feed specification targets for the conversion process while meeting the cost targes of <$65/dry ton.

Progress:

This task has completed on schedule, and the results are presented below.

Key Results:

Key results to date are presented below.

Executive Summary:

This report is a follow-on report to the preliminary investigation of the potential to replace fossil fuel derived heating oil in the northeastern U.S. with a bio-derived substitute. This report summarizes the more in-depth analysis that has been conducted to further investigate the feasibility of this question.

This analysis identifies the amounts of the different biomass types that can be procured at the volumes needed to satisfy the requirement of replacing at least 5% of the current fossil fuel oil by 2017. This analysis also analyzes the blend of feedstocks required to meet the in-feed specifications for the pyrolysis conversion at the least cost. The end result is to acquire enough biomass that can be blended to meet in-feed specification and then convert to a bio-oil at a cost of <$65/dry ton. This analysis considered the total cost of the biomass purchased from the supplier, as well as the transportation and processing costs associated with delivery of a biomass feedstock at optimal specifications to the pyrolysis reactor. This analysis has included information from the ORNL Billion Ton Study Update for projected biomass availability at the different farm-gate prices.

An analysis was also conducted to determine the distribution of various types of biomass in the Northeastern United States, and the locations of the current heat oil distribution networks, and the locations of the large industrial consumers of heating oil. This was conducted to determine the most economical mode of replacement of heating oil, including home heating and industrial heating applications.

This analysis also considers the various processes that may be necessary to upgrade biomass to an economically feasible state for the production of a bio-derived heating oil replacement. This includes a consideration of the effect of various biomass properties on the pyrolysis process, and the properties of raw biomass typically available in the region.
The map in Figure 1 illustrates the states considered in the analysis. These states are commonly grouped by the Energy Information Administration (EIA) as PADD 1A and PADD 1B. PADD 1a encompasses the New England states Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont. PADD 1b encompasses Delaware, Maryland, New Jersey, New York, and Pennsylvania, as well as the District of Columbia (Washington D.C.).

Figure 1: States included in the analysis of the Northeastern United States. (U.S. Census Bureau 2010)

The results of the analysis of the feedstock supply system and the pyrolysis conversion process are presented in Table 1. This table summarizes the expected cost per dry ton of biomass based on farm-gate price from the ORNL BTS2 data, combined with modeled logistics costs from the Biomass Logistics Model.

Table 1: Expected Total Cost based on Expected Ash and Process Yield.

Year	Repl.%	Preproc. Op.	Feedstock Ash	Expected Yield	Required Biomass dt/yr	Feedstock Cost $/dt	Preprocessing Cost $/dt	Total Cost: $/dt
2017	5%	Leached	1%	75%	1.8M	$18.72	$61.24	$86.50
2017	5%	Raw	5%	60%	2.1M	$18.72	$32.89	56.43
2022	20%	Leached	1%	75%	7.3M	$25.26	$61.24	$80.96
2022	20%	Raw	5%	60%	9.1M	$25.26	$32.89	$62.96

This analysis demonstrates that there are enough volumes of waste stream material available at low enough farm-gate prices to meet the cost and volume targets in 2017 and in 2022. Purpose grown energy crops and woody biomass are only available at significantly higher farm-gate prices which make them less desirable under the current requirements. The amount of biomass available from agricultural waste streams for this region of the U.S. is quite small, and doesn't impact the overall volume available.

The actual characteristics of these biomass feedstocks have not explicitly been characterized, but based on data collected by the INL, representative comparable materials were used to establish the characteristics. This data is also limited by the relatively small amount of information available on the effect of ash on the yield of pyrolysis process. Research currently being explored suggests a potential catalytic benefit for the presence of some ash species, and this may ultimately determine what the appropriate ash specification is for biomass slated for pyrolysis processing.

Introduction

The northeastern U.S. consumes 5.5 billion gallons of heating oil annually to heat both private residences and non-manufacturing businesses and organizations. This heating oil is derived from fossil fuel, and is supplied from refineries by a network of pipelines as well as ships and barges which a significant portion is from foreign producers. This oil is typically stored and distributed by suppliers to end use customers who have heating oil tanks located on their property, and which are typically filled 3-6 times per year. Typical residences consume roughly 850 gallons of heating oil per year. The primary consumers of heating oil are located in the northeastern U.S. as shown in Figure 2.

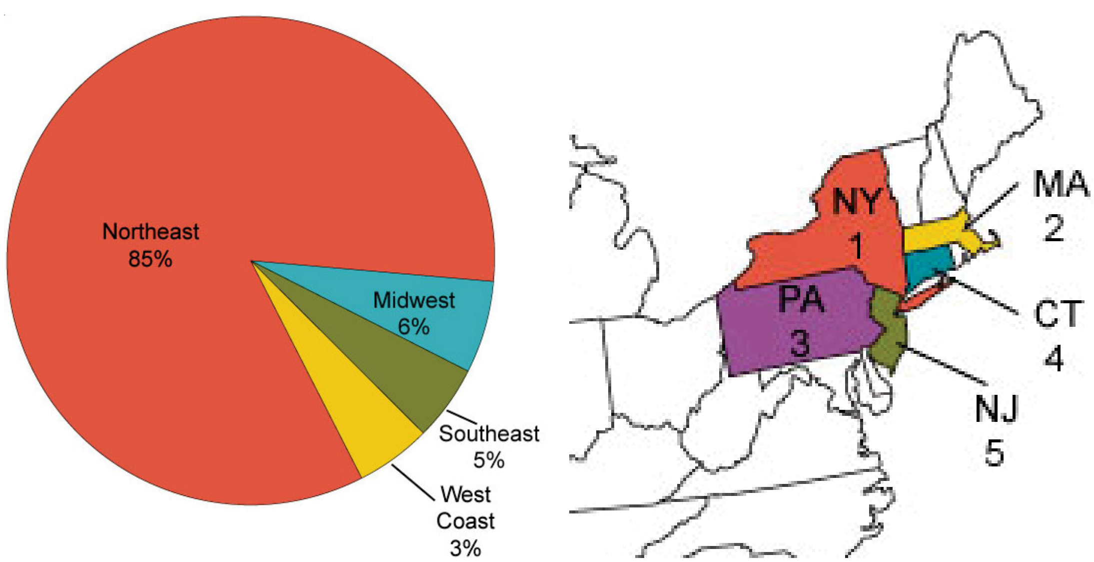

Figure 2: Heating Oil Consumption. Source: U.S. Energy Information Administration, *Fuel and Kerosene Sales 2010 (Feb. 2012).*

The fluctuation in cost of crude oil drives the cost of fossil derived heat oil, and recent increases in cost due to external factors such as weather fluctuations, etc. have driven the cost of heating oil up. Because the northeastern U.S. region is heavily dependent on heating oil, the recent cost fluctuations and increases impose a financial burden on residences in the area. If a locally produced supply of bio-derived heating oil were available, the price fluctuations and shortages could be mitigated to some extent.

The Oak Ridge National Laboratory (ORNL) Billion Ton Biomass Update (BTS2) study projects that adequate amounts of biomass materials can be produced to replace as much as 30 vol% (depending on feedstock price) of the heating oil with renewable heating oil. The goal of this research is to demonstrate that 20 vol% replacement within 10 years is feasible, recognizing that not all of the available material would be economically well suited to the production of pyrolysis oil. A cost target of less than $65 per dry matter ton (<$65/DM ton) was selected by the program, based on cost-driven targets for renewable heat oil production that can be substituted for petroleum heat oil. Therefore, this preliminary study investigates amounts of biomass available in the region, as well as the logistics costs associated with the collection of this biomass to pyrolysis processing facilities.

Data on biomass supply for this preliminary report were obtained from the Oak Ridge National Laboratory (ORNL) Billion Ton Update (BTS2) Knowledge Discovery Framework (KDF) tool, available online. The BTS2 was used to estimate the amounts of each type of biomass that would be accessible at the various farm-gate prices from $20/dry ton up through $80/dry ton at the state level.

Project Goals

The goal of this project was to demonstrate that 5% of heating oil consumed in the northeast can be economically replaced by a renewable bio-oil within 5 years, and 20% within 10 years. To be able to reach this goal, a sufficient quantity of biomass must be available at a sufficiently low farm-gate price and be able to meet the in-feed specifications for the pyrolysis conversion at a overall cost of <$65/dry ton.

This project began by investigating the heating oil consumed in the northeastern U.S. in the recent past to determine the total quantity of pyrolysis oil that must be produced to meet the goals stated above. In a previous study the heating oil consumed was reported for this area for the past 5 years. This information is presented below.

Heat Oil Consumption:

The U.S. Energy Information Administration provides data on U.S. energy consumption. The use of heating oil (No.2 Fuel Oil) is not directly reported but included within the use of distillate fuel oil which encompasses No. 1, 2, & 4 diesel fuel and No. 1, 2 & 4 fuel oil. The distillate fuel oil usage is further broken down by usage as plotted in Figure 3 for the Northeast region. It is expected that the majority of the heating oil is consumed in the residential and commercial categories for heating of private residences and nonmanufacturing businesses and organizations.

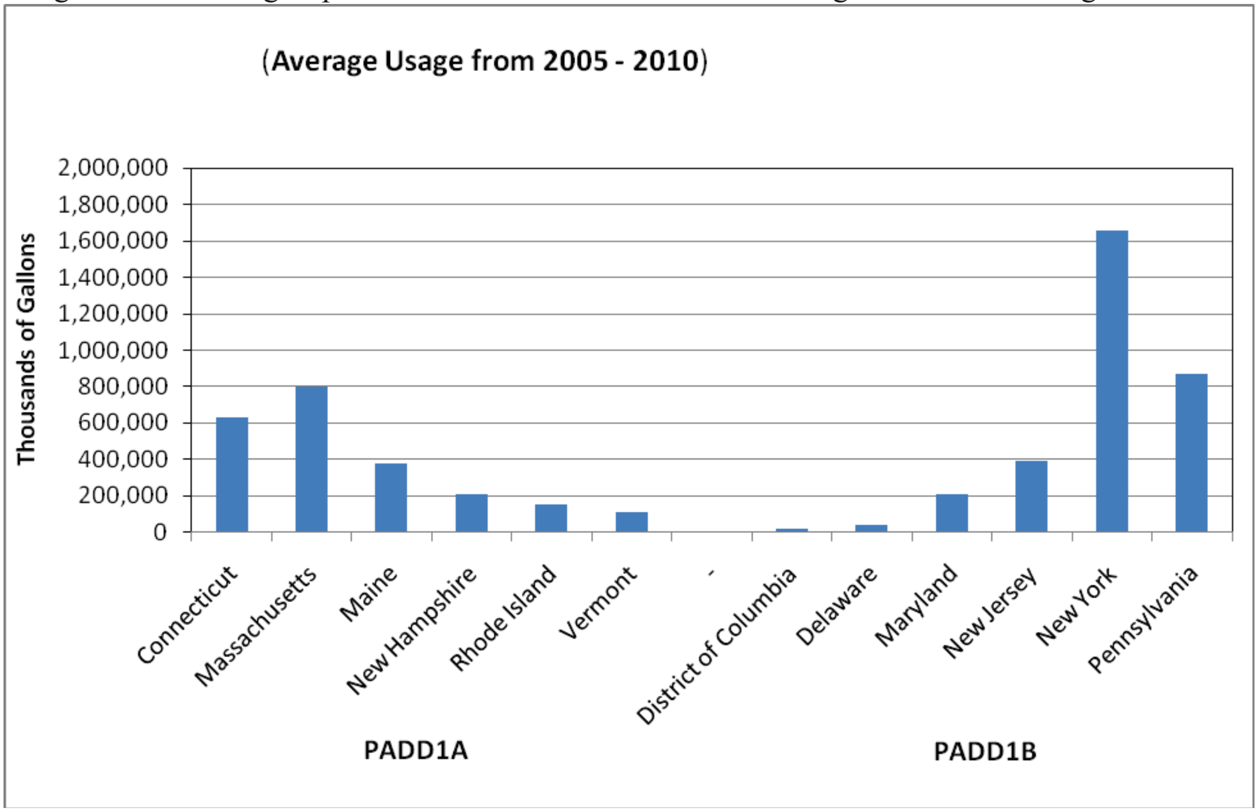

Figure 3: Heating oil usage by state for Northeastern U.S .

The total annual usage of heating oil from the Northeast U.S. is 5.5 billion gallons which makes up 72% of the U.S. total usage of 7.6 billion gallons. The goal is to demonstrate feasibility of replacing 5 vol% of consumption, or 280 million gallons per year within 5 years, and 20 vol%, or 1.1 billion gallons per year, within 10 years.

Figure 3 illustrates the consumption of heating oil in the states of interest. While data exists for 2011 and 2012, this data was not included in the average, and the average reflects only the years from 2005 to 2010. This was decided because the winter of 2011-2012 was unusually mild, resulting in heating oil consumption that was significantly lower than historical norms. This analysis does not consider any warming trends that may ultimately reduce the consumption of heating oil in the longer term, nor does it consider potential increases in heating oil consumption which may attend new construction, population growth, increases in building energy efficiency, etc., and is restricted to a consideration of recent historical data.

Pyrolysis Process

Given an end goal of gallons of heating oil that are to be replaced with a bio-derived substitute (as described above) this section now considers the production of pyrolysis oil from biomass.

Raw Pyrolysis Oil

Raw pyrolysis oil requires upgrading to render it miscible and infrastructure compatible with heating oil. This paper does not consider the yield of upgrading, or the costs associated with this upgrading, and considers only the feedstock, and the effect of ash preprocessing on the ultimate cost of that feedstock delivered to the throat of the pyrolysis reactor.

Pyrolysis Process Yields

Pyrolysis process yields have been studied and documented in recent times. When a given mass of biomass is pyrolyzed, the process produces a majority of pyrolysis oils, some char, and some gases.

Char is a carbonaceous byproduct that can be used as a soil amendment, or may be otherwise utilized as a value-added product of the process. Gases produced during pyrolysis may be used to provide process heat, or for other purposes in a pyrolysis plant. Because the goal of this analysis was to model and predict the cost of a processed biomass material delivered to a pyrolysis reactor, the pyrolysis process was only examined as it pertains to the necessary properties of the biomass feedstock supplied to the reactor. These properties include the ash content and biomass physical format (particle size and moisture content).

Researchers have investigated the yield of the pyrolysis process as a function of different pyrolysis conditions, catalysts, etc, as well as the type and properties of the biomass fed into the process. The results from two studies are presented in Figure 4, with the pyrolysis process liquid yield (mass %) plotted against the feedstock biomass ash content. Note that P. Das et al. reported results for the pyrolysis of sugarcane bagasse, and R. Fahmi et al. report on a variety of biomass feedstock types.

Note that for the linear curves fit to both charts the slope is similar, and is around -5. This suggests that for an increase of 1% in the input biomass ash content, a 5% decrease in yield can be expected.

Envergent also investigated the pyrolysis oil yield associated with various biomass types. Their results are presented in Table 2. While the yields are different than those reported in the above articles, the trends observed are similar, i.e. the yield for a softwood (low ash) is reported as between 70%-80%, while the softwood bark (higher ash) yield is reported as 55%-65%. Testing at the INL has demonstrated that typical softwood ash contents are in the range of 1%, while the bark can be as high as 18% or higher. While the ash content of the particular bark samples tested by Engergent is not reported, the general trend of higher ash biomass producing a lower yield is demonstrated as it is in Figure 44.

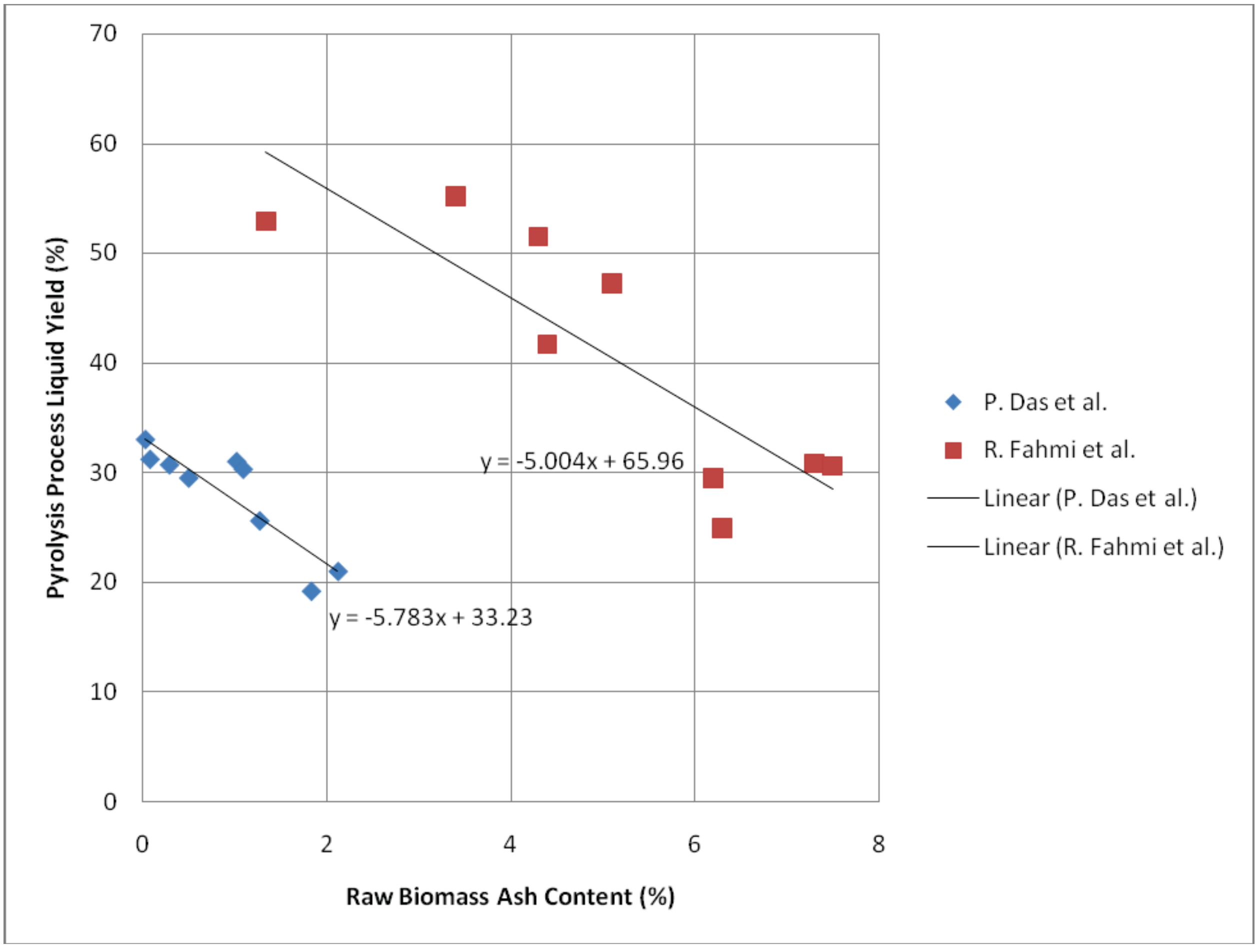

Figure 4: Pyrolysis process yield as a function of feedstock ash content.

Table 2: Examples of Pyrolysis oil yields from fast pyrolysis (Envergent 2012).

Biomass Material	Wet Oil Yield (wt%) on dry feedstock	Gross Caloric Value (MJ/kg)	Higher Heating Value (Btu/lb)
Hardwood	70-75	17.2 - 19.1	7,400 - 8,000
Softwood	70-80	17.0 - 18.6	7,300 - 8,000
Hardwood Bark	60-65	16.7 - 20.2	7,180 - 8,680
Softwood Bark	55-65	16.7 - 19.8	7,180 - 8,500
Corn Fiber	65-75	17.6 - 20.2	7,570 - 8,680
Bagasse	70-75	18.9 - 19.1	8,100 - 8,200

This collection of data on the yield of various pyrolysis processes as a function of ash content demonstrates the economic impact of higher levels of ash in the biomass feedstock. This data demonstrates that the cost of higher ash feedstock material is expected to be a reduction of yield. This will inform the selection of biomass types, and will also enable the comparison of the costs and benefits for different preprocessing operations. This will in turn enable the selection of a more optimal set of preprocessing operations to produce a maximal amount of pyrolysis oil for a minimal cost.

As a first order approximation of biomass quantities needed to meet the goals of this work, a pyrolysis process nominal yield for clean biomass will be estimated to be roughly 65%. This will enable a first approximation of the amount of biomass that will be needed to meet the proposed targets of heat oil production in the northeastern U.S. This may be conservative, depending on the quality of the feedstock available, but will serve as a first order approximation.

Biomass Properties - Ash Content

Given significant impact of ash on the pyrolysis process yield, an understanding of the expected ash content of various types of biomass is necessary to predict the optimal set of preprocessing operations.

INL maintains a substantial database of biomass materials and properties. This biomass library is commonly referred to as the INL Sample Library. The database is divided in two parts. One part contains a substantial set of biomass properties that have been extracted from literature sources, and the other part contains the results of analysis conducted at the INL on various physical biomass samples.

Types of biomass which are typically available in the northeastern U.S. were selected, and searched for in the sample library. The biomass types selected include willow, poplar, pine, maple, oak, wheat straw, and corn stover. The northeastern region currently supplies woody material for the pulp and paper industry and hardwoods for the wood products industry. These are represented in the hardwood materials and pine. The agricultural industry in the region produces substantial amounts of corn, as well as wheat, so the crop residues from these sources were included. Experimentation is ongoing in the production of woody energy crops, and work to date has focused on willow. INL has received some willow samples, and some poplar samples were included to increase the sample size, as both are harvested in a similar manner for energy crop production.

The INL Biomass Sample Library database was queried for samples of biomass both in the library of INL tested samples, as well as the literature samples, and the results are presented in Table 3.

Table 3: Biomass types and ash content.

Type:	Source:	Ash % Mean	St. Dev.	Median	Min	Max	# of Samples
Willow	SL	1.76					1
Willow	LDB	1.37					3
Poplar	SL	0.78					2
Hybrid Poplar	LDB	0.82					2
Loblolly Pine	SL	0.87	1.05	0.57	0.27	5.54	23
Pine	SL	1.32					1
Pine	LDB	3.72					6
Maple	SL	0.39					1
Oak	SL	1.68					1
Wheat Straw	SL	11.76	7.10	9.80	0.54	49.46	192
Wheat Straw	LDB	5.76					5
Corn Stover	SL	14.64	10.09	10.81	0.83	59.35	1608
Corn Stover	LDB	7.09					3

SL = INL Sample Library
LDB = INL Literature Database

Table 3 contains a listing of the particular biomass type, its source, the number of samples of biomass tested or reported, and some statistical information. For biomass types with more than 20 samples, some statistical data is reported on the total ash content of the samples.
When selecting a statistical measure of a representative ash content of the samples selected, both the mean with standard deviation, and the median values are presented. For samples with large datasets, a sample median is less affected by outliers in the data set, and is taken as the preferred representative measure of ash content for that material. For samples for which samples are reported in both literature and in the sample library, the median is typically much nearer the mean of the literature reported samples. In order to illustrate the range of values, and where the datasets represent more than a few samples, the maximum and minimum values are also presented.

With the substantial datasets presented, particularly for agricultural residues, it is possible to formulate an expected range of ash content that may be delivered to the biomass depot from suppliers, as well as the expected properties of that biomass in a real-world scenario. This enables an understanding of what pre-processes may be necessary, or important to consider in the selection of the appropriate and optimized supply chain for the production of the optimal yield of pyrolysis oil for a given cost of input biomass.

Ash Reduction Processes

Reducing the ash in biomass is typically accomplished with either wet or dry separation processes. Dry separation processes include processes to separate higher inorganic content fines from larger particle size biomass, and may be subsequent to a grinding operation. Wet separation processes used include washing and/or leaching process operations. Recently, research has developed other novel means of ash reduction such as hot water separation, and steam torrefaction.

Dry Separation

In a mechanical separation process, biomass is separated from inorganic materials that cause ash via mechanical means. This is often accomplished after biomass has undergone initial size reduction to render it flowable and transportable. Biomass is then either passed through a trommel screen, or other pneumatic separation operations to remove fines.

Because the fines generated during the initial processing of biomass often contain the majority of surface inorganic material, this is effective in removing a portion of ash from the surface of the biomass, however, this method has no effect on the inorganics that are bound in the structure of the biomass itself.

Dry separation also has the disadvantage that the process separates biomass material along with inorganics, resulting in a loss of biomass material which increases the cost of this operation.

Wet Separation

Washing and leaching are typically more effective at removing inorganic materials from biomass. Wet methods of ash reduction, however, result in biomass with high moisture content. Typically a mechanical dewatering stage is necessary to remove the bulk of moisture in the biomass, often resulting in a biomass material that is roughly 40% water. The remaining biomass must then be driven off by means of a drying operation. It may be beneficial for down-stream processes to include a deep drying operation for the reduction of grinding energy or other desirable outcomes, however, drying is typically very energy intensive.

Washing typically involves submerging biomass in a water bath, or passing water through the biomass to remove surface inorganics. This process is effective at removing surface contamination, and the majority of water used in the process can be filtered and re-circulated in the process to reduce water consumption.

Leaching involves the use of solvents, typically in an aqueous solution to dissolve and remove inorganic material bound in the structure of the plant cells. This method can be very effective at removing the vast majority of inorganic materials, and the leachate can often be recycled, and the solvent reused for subsequent leaching, which can greatly reduce the cost of this type of operation. Leaching operation effectiveness has been studied by many researchers, and the results of some operations are shown in Figure 4 demonstrating pyrolysis process yield as a function of ash content. Figure 5 shows the same information, presented as the ash reduction amounts as a function of leaching process and solvent.

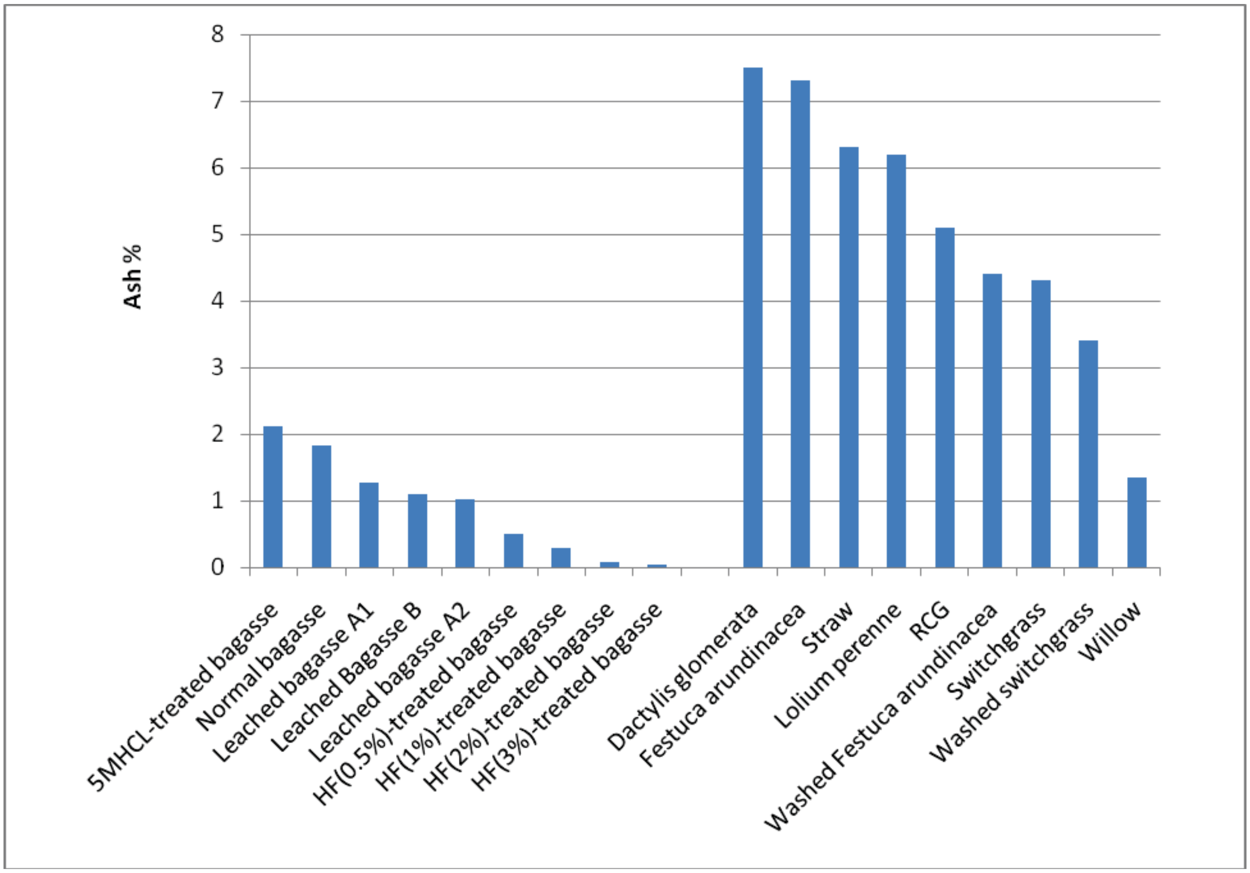

Figure 5: Ash % as a function of biomass type and wet separation operation.

Note that all values in the group of Bagasse are reported from P. Das et al., and values in the subsequent group are reported from R. Fahmi et al.R. Fahmi et al. presents data for the difference between a washed, and non washed biomass sample, demonstrating that for a washing operation for switchgrass, for example, the ash is reduced from 4.3% to 3.4%, and for *Festuca arundinacea* from 7.3% to 4.4%. For bagasse (residue from sugarcane processing) the material is leached to remove bound ash. Depending on the solvent used, the material produced can have extremely low ash. This same trend holds for other biomass types.

Novel Ash Reduction Processes

Other research continues in the development of ash reduction in biomass via novel means. High temperature washing, typically at temperatures above 100, but below 200C have been demonstrated to remove significant amounts of inorganic species. Other operations designed to combine several operations have also shown good promise, including steam torrefaction.

These operations are not considered in this analysis, where more conventional operations have been demonstrated and where the costs can be better characterized.

Biomass Required:

Based on heat oil consumption as reported above (Heat Oil Consumption:) to replace 5% of the reported average 5.5 billion gallons consumed annually in the northeastern US, a total of 274 million gallons of bio-derived heating oil would need to be produced. To meet the 20% goal, a total of 1.1 billion gallons of bio-derived heating oil would be needed. Based on work conducted by the University of Arkansas (Univ of Arkansas FSA-1052), raw pyrolysis oil has an average specific gravity of between 1.1 and 1.25, which translates to roughly 9-10.5 lbs/gal. If an average density is assumed to be 10 lbs/gal, the amount of oil that must be produced for the 5% and 20% cases is 2.7 billion lbs, and 11 billion lbs respectively.

If it is expected that the pyrolysis process yield is in the ranges stated above (Pyrolysis Process Yields), and a conservative yield estimate of 65% is used as stated above, the amount of biomass needed can be approximated. Note that this also assumes that the yield of any subsequent operations for upgrading and treating the pyrolysis oil is high, and any loss of material can be accommodated in the conservative approximation of the pyrolysis process yield.
Given the above assumptions, for the 5% and 20% targets, 4.2 and 16.8 billion dry lbs of biomass are necessary, which translates to 2.1 and 8.4 million dry tons of biomass annually.
If the yields reported in literature are considered for a given ash content of biomass, the Table 4 can be generated.

Table 4: Biomass required as a function of pyrolysis process yield.

Pyrolysis and Upgrading Yield	Lbs Biomass Required		Tons Biomass Required	
	5% Case	20% Case	5% Case	20% Case
30%	8,654,646,458	34,618,585,833	4,327,323	17,309,293
35%*	7,418,268,393	29,673,073,571	3,709,134	14,836,537
40%	6,490,984,844	25,963,939,375	3,245,492	12,981,970
45%	5,769,764,306	23,079,057,222	2,884,882	11,539,529
50%	5,192,787,875	20,771,151,500	2,596,394	10,385,576
55%	4,720,716,250	18,882,865,000	2,360,358	9,441,433
60%	4,327,323,229	17,309,292,917	2,163,662	8,654,646
65%**	3,994,452,212	15,977,808,846	1,997,226	7,988,904

* MYPP 2012 fully upgraded, fully stable bio fuel (2017 Projection).
** MYPP 2012 Pyrolysis oil yield (2017 Projection).

Note that the amount of biomass required fluctuates significantly as a function of the pyrolysis process yield.

Biomass property information from both Table 2 and Table 3 were combined to generate Table 5. This table combines information from different sources, and does not necessarily represent the ash content of the biomass tested, but may enable a general comparison of expected yield based on a given biomass type. This comparison will aid in the determination of the amount of biomass from a given source, and with a given ash content that will be necessary to produce the amounts of pyrolysis oil required.

Table 5: Augmented yield vs. ash content table.

Biomass Material	Wet Oil Yield (wt%) on dry feedstock*	Expected Ash Content**	
		Mean Range	Expected Value
Hardwood	70-75	0.39%-1.68%	0.85%
Softwood	70-80	0.57%-3.72%	0.87%
Hardwood Bark	60-65		
Softwood Bark	55-65		
Corn Fiber	65-75	7.09%-14.64%	10.81%
Bagasse	70-75		

* Yield values reported by Envergent.
** Ash content expected based on INL sample library.

Again, note that the data presented in Table 5 represents the combination of data from two disparate sources, and therefore, will only be taken as a guideline for the estimation of biomass quantities necessary to meet the 5% and 20% goals described previously.

Biomass Availability

Biomass availability predictions have been made with respect to expected demands and future market activity. Most notably, the Oak Ridge National Laboratory (ORNL) Billion Ton Study Update (BTS2). This data set takes into account the expected amount of energy crops that will be produced, based on an expected demand, and this is then used to formulate a cost for biomass on a per-ton basis. These estimates ultimately don't take into account the difference in a given biomass feedstock, or variation in biomass feedstock properties, and so when data presented by the BTS2 is agglomerated, it is considered fungible, and the agglomerated price for biomass is taken as the price of biomass at the desired quantities, regardless of biomass specifications. This data is reported below, and is reported for various regions, and for various biomass types.

Market forces will ultimately determine the price that must be paid for a given quantity of biomass, and may ultimately include specifications and grades of biomass that a given supplier or biomass source must meet for a given price. This is pertinent to this analysis because the ash content of the incoming biomass has a significant impact on the process yield, and on the process economics.

Current market trends may vary for a given area from what is predicted by the BTS2 data, and it was therefore deemed important to consider the current availability and cost of biomass in the area, and compare that with what is projected to be available by the BTS2.

Future BTS2 Data:

The ORNL BTS2 Data was queried to determine the amount of biomass that is projected to be available for the target years of the heating oil project, namely, 2017, and 2022 (5 and 10 years from 2012, respectively). The data reported was then agglomerated into five main categories, Woody Biomass, Woody Biomass Residue (thinnings, logging residue such as slash, etc.), Wood Waste (mill residue, woody MSW, C&D Wood Waste), Agricultural Residue, and Dedicated Energy Crops. These categories were selected to enable prediction of the expected ash content of each type of biomass. This will enable the determination of what types of biomass can and should be utilized based on the economic trade-offs of pyrolysis process yield, and pretreatment operations to reduce ash.

5 Years:

The BTS2 data was surveyed to determine the amount of biomass that was expected to be available in the northeastern U.S. in 2017. This data was grouped into five categories as described above. This is presented in Figure 6.

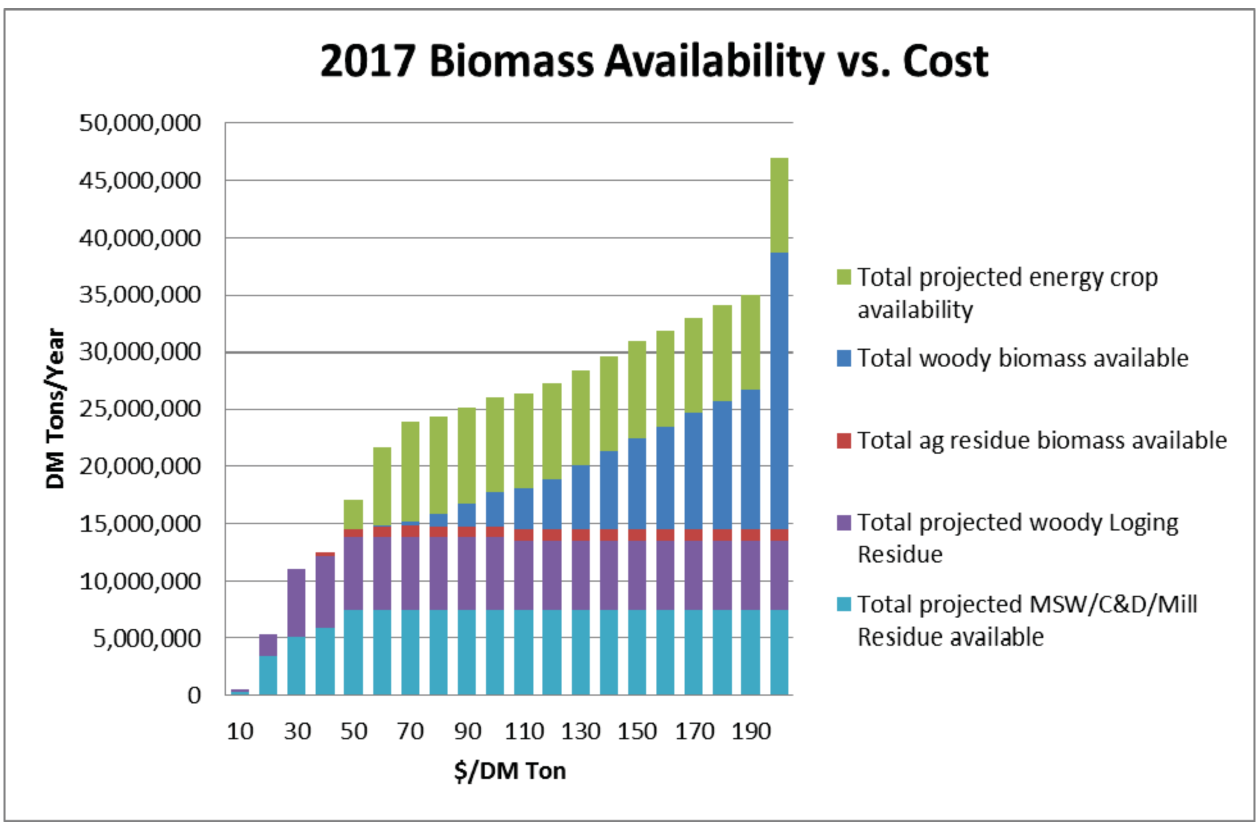

Figure 6: BTS2 Northeastern U.S. biomass Availability in 2017.

The predicted biomass available from woody residues, including waste streams from logging, MSW, etc. are finite, and therefore, after a given quantity has been collected, there isn't more biomass that can be collected from these sources, even if the price paid is increased. This seems to occur at roughly $50/dry ton. If these sources are all collected, the required biomass for replacing 5% of heating oil in the northeast can be readily achieved. Predictions based on yield discussed above show that even at lower pyrolysis process yields, 5 million dry tons of biomass would meet the required demand. Figure 6 shows that this quantity of biomass is available in the northeastern U.S. region at, or below $20/dry ton.

It should also be noted that the amount of agricultural residue biomass (corn stover, wheat straw, etc) is only a minor component of the total available biomass in the area, and isn't a large source of material for this application. It may still be worth collecting this biomass based on the economics of each specific case, and regional dependencies may drive the collection of more of this type of biomass.

Figure 6 also shows that purpose grown woody biomass (such as for pulp and paper mills) is rather expensive, and although large quantities are available at higher prices, the cost of this type of biomass limits its utility for this project.

Energy crops are also shown in Figure 6. The cost of producing energy crops, while lower than the cost for woody biomass, is greater than wood waste. There is also a point at roughly $70-$80/DM Ton where the total amount of this type of biomass that can be produced is maximized, and higher prices will not necessarily facilitate more production.

10 Years:

BTS2 data was also surveyed for the expected biomass available in 2022 in the northeastern U.S. The substantial difference biomass predicted to be available in 2022 over 2017 is primarily in the amount of energy crops. Again, this peaks somewhere around $70-$80/DM Ton.

For the production goals at the 10 year mark of 20% bio derived heating oil, it will be necessary to convert between 6.8 and 12 million dry tons of biomass to heating oil.
BTS2 data for biomass available in 2022 is presented in Figure 7.

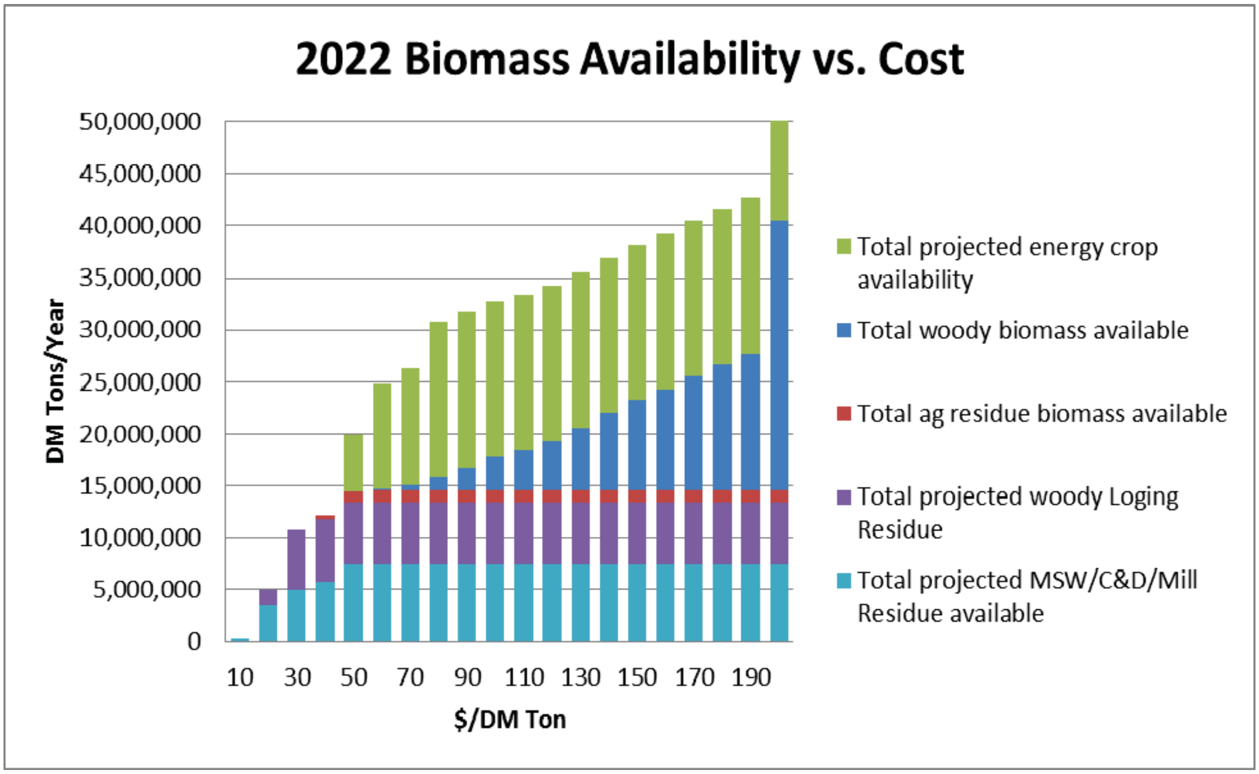

Figure 7: BTS2 Northeastern U.S. biomass predicted available in 2022.

If a conservative estimate of biomass required is taken to be around 12 million dry tons, Figure 7 illustrates that this amount of biomass can be collected for around $40/DM ton. Sources of biomass that must be collected to meet this target include woody waste, agricultural residues, and logging residue/forest thinnings.

As was stated previously, primary woody biomass is more expensive, and its participation in meeting the targets of this analysis is, therefore, limited. It should be noted that at a cost of $50/DM ton, a significant quantity of energy crop biomass becomes available. This represents a level of choice in the selection of biomass of different types, based on process needs, and optimal pyrolysis performance. It is also possible, given a variety of available biomass types, to locate depots or pyrolysis oil production and upgrading facilities near biomass, or to select globally optimal locations for such facilities to coincide with heat oil consumption and/or distribution hubs.

Biomass Distribution

Based on the amounts of biomass available, the next question of importance is where are the biomass types reported in Figure 6 and Figure 7 primarily located. This will inform the selection of where biomass processing depots should be located, and possibly what processing operations will be best suited for those specific locations.

The biomass types of primary interest are wood waste from forestry operations and saw mills, wood waste from urban waste streams, agricultural residues, and energy crops. Data from the BTS2 database were collected to demonstrate where these types of biomass are grown.

Figure 8 and Figure 9 show the distribution of both primary woody biomass, as well as woody residue from forestry operations. Note tat the distribution of these types of biomass are both very similar. This reflects the fact that woody residue is often a by-product of forestry operations, and is, therefore a component of that biomass stream. Note, however, that the costs at which these types of biomass are available. This demonstrates that the residue stream of biomass is heavily reliant on other industrial sectors, such as paper and wood products industries, to consume the primary crop, resulting in a waste stream that can be captured.

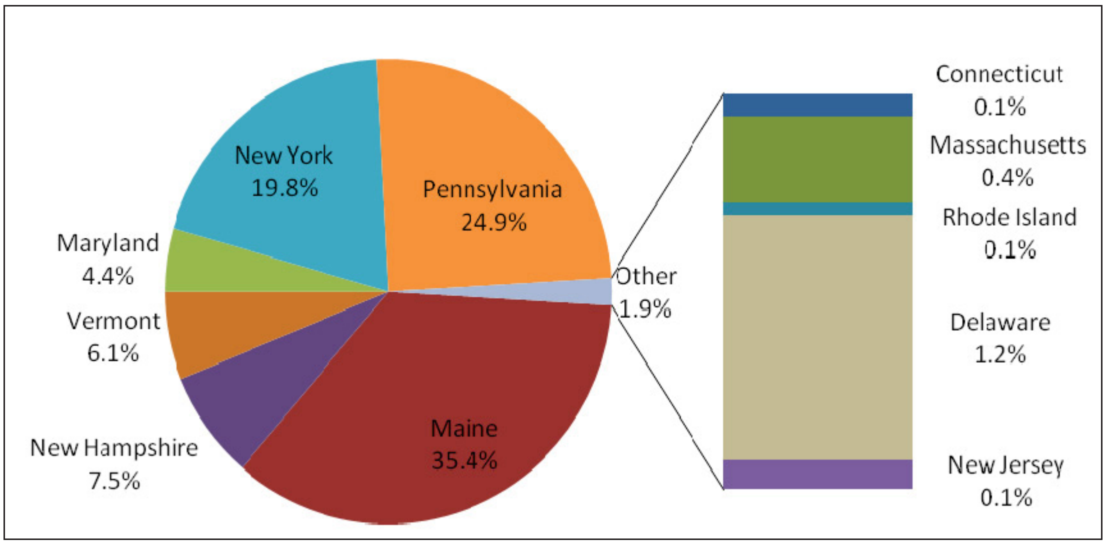

Figure 8: Primary Woody Biomass Distribution 2017, $140/DM Ton.

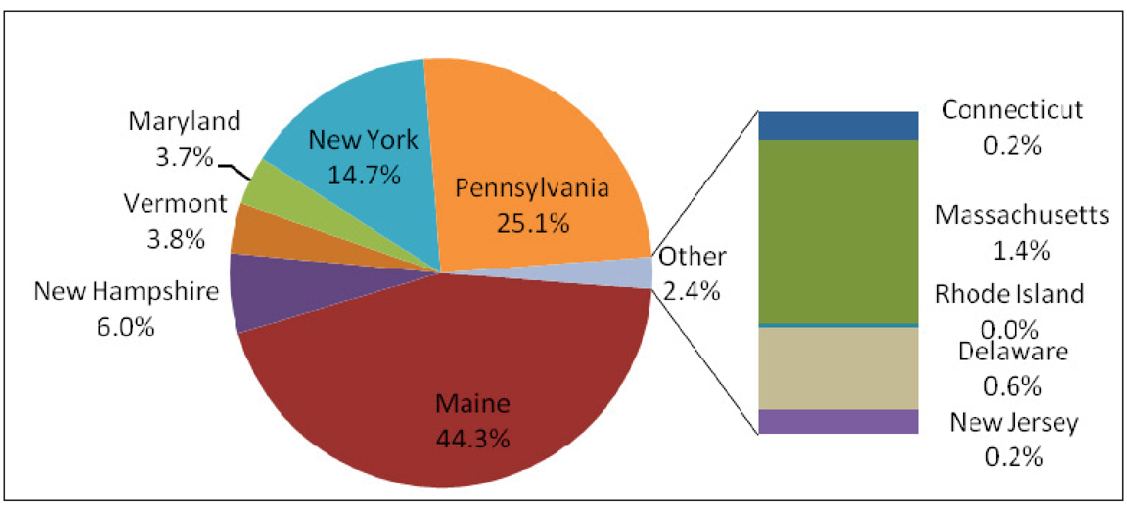

Figure 9: Woody Residue Biomass Distribution 2017, $40/DM Ton.

Figure 10 shows the distribution of wood waste available from municipal solid waste, construction and demolition, and mill operations. This is the only category where the Washington D.C. contributes biomass. This category of biomass is fairly evenly distributed throughout the northeastern U.S., but New York and Pennsylvania are the largest contributors.

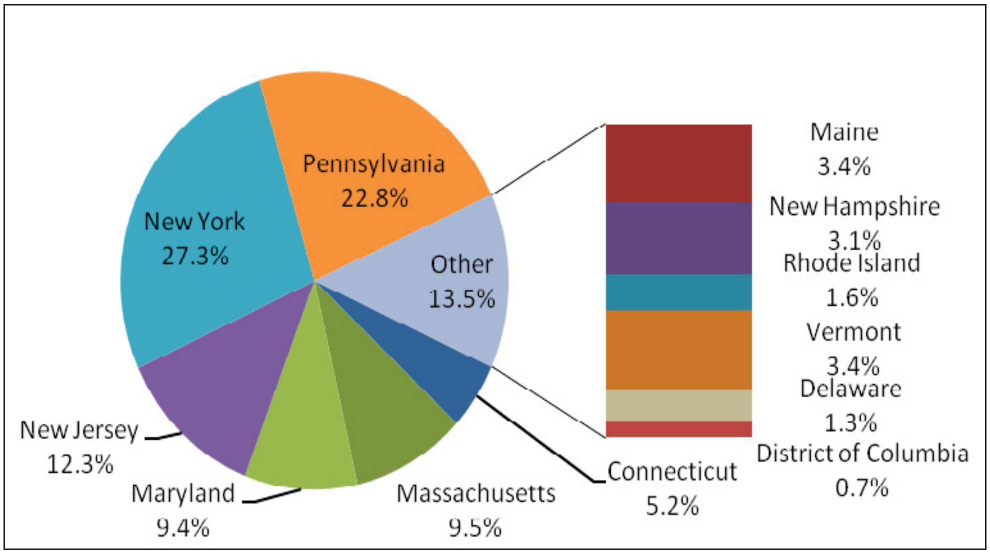

Figure 10: Wood Waste Distribution 2017, $50/DM Ton.

The distribution of agricultural residues, including corn stover, wheat straw, and barley straw are shown in Figure 11. Maryland is the largest agricultural residue producer, followed by Delaware, Pennsylvania, and New York. These are the more southern of the states in this region, and land in these states is more suited to the production of agricultural products, as is the growing season.

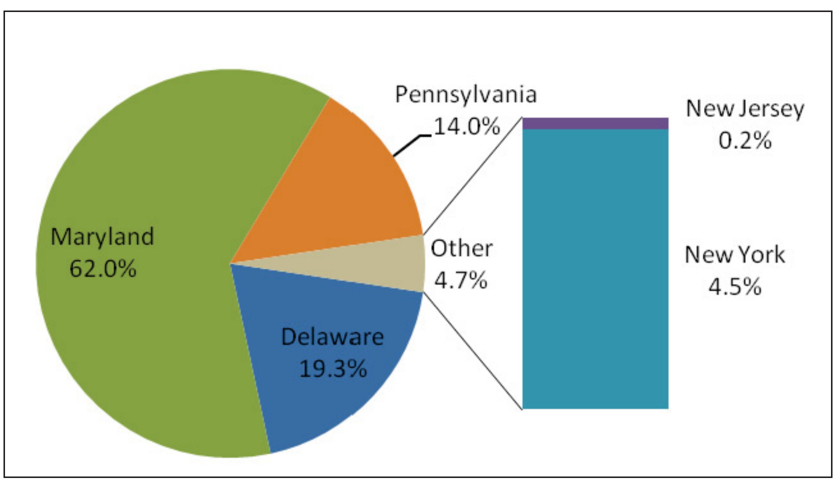

Figure 11: Distribution of Agricultural Residues 2017, $70/DM Ton.

Figure 12 shows the expected distribution of energy crop production. This is a projected production, and is dependent on the development of industries to consume this biomass. Such industries could be the production of bio-derived heating oil described in this report. These are, however, projections based on expected demand.

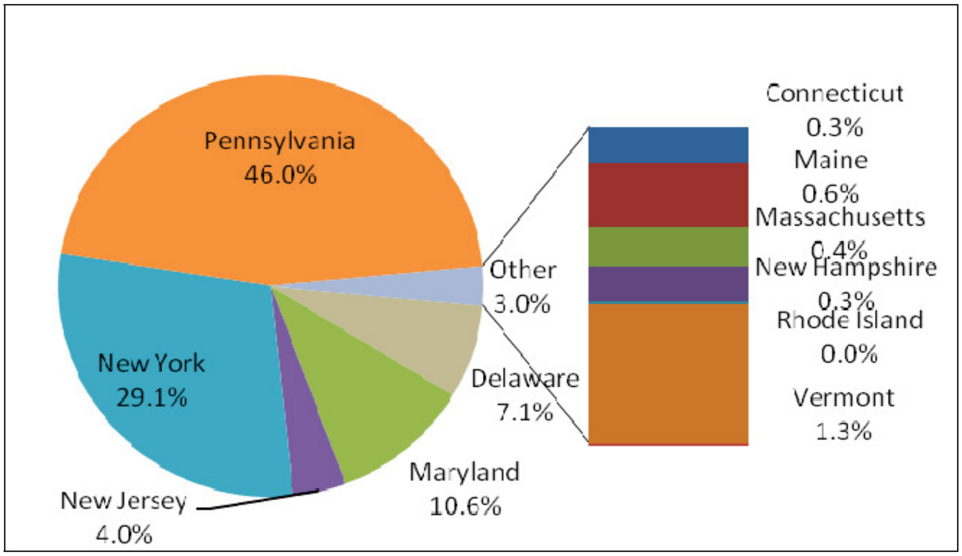

Figure 12: Distribution of Energy Crops 2017, $70/DM Ton.

Based on information collected by INL, and reported above, clean woody biomass typically has low ash quantities. As reported in Table 3, the typical ash quantity for clean woody biomass is expected to be less than 1%, while bark, slash, and bark containing ash can push the ash content to upwards of 5% or higher. Agricultural residues have been shown to have higher ash content, typically around 10%.

It is expected that woody biomass derived from waste streams, including mill residue, MSW, and C&D waste may have moderate levels of contamination, and are expected to fall into the range of other wood waste such as slash. It may be possible to improve sorting, and produce a more selective, lower ash biomass stream, but a conservative approximation is used for the purpose of this report.

Based on this information, and the information presented in Figure 6 and Figure 7, it is expected that roughly two thirds of the biomass available at $50/DM ton in 2022 will contain ash in the range of 5% ash (from logging residue, and wood waste), roughly one quarter will be purpose grown energy crops such as willow, and will have an ash content on the order of 1-2%, and a small fraction of available biomass will be an agricultural residue with ash content on the order of 10%. To meet the production goals of replacing 20% of heating oil, roughly two thirds of this biomass will be consumed, resulting in some choice in what biomass will best optimize the production of heating oil.

This analysis shows that the biomass that would be utilized in this analysis from forest residues is concentrated largely in Maine, New York and Pennsylvania. The wood waste stream is fairly evenly distributed throughout the region. This suggests that the location of any proposed pyrolysis oil production facilities would be well situated in these three states, but also indicates that the distribution of biomass is fairly general. Referring back to the preliminary analysis, the situation where production facilities are small, and distributed throughout the region will result in the lowest cost for oil production, and the best integration with existing heating oil distribution networks. Figure 13 shows the supply infrastructure for distillate heating oil for the Northeast region. This figure reinforces that there exist large distribution points distributed throughout the northeastern U.S., and that placing bio-oil production infrastructure in these states will enable the co-location of these facilities with existing oil distribution infrastructure.

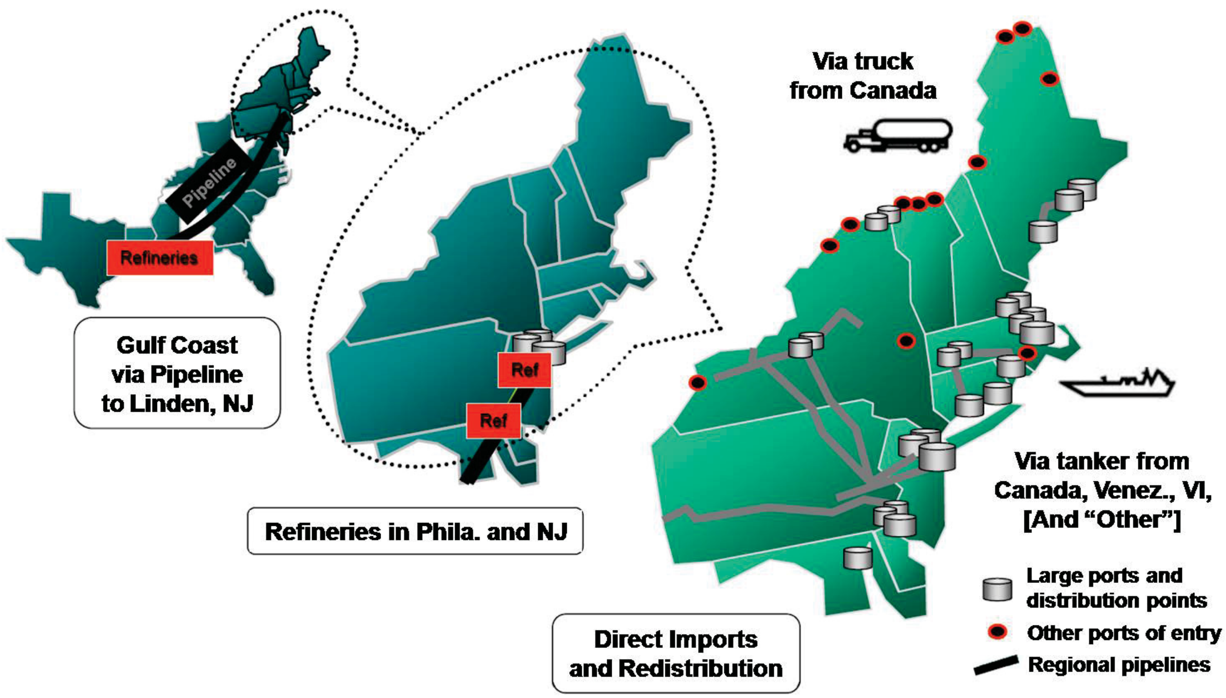

Figure 13: Northeast Distillate Supply Infrastructure. (Huber, et al.)

Modeled Logistics Scenarios

Costs for biomass at a given quantity reported above consider only the cost that must be paid to the producer of the biomass. This is represented as either a landing or farm gate price for woody or herbaceous biomass respectively, or the cost to collect wood waste. These costs do not consider any transportation logistics, or pre-processing operations in the production of biomass. A critical piece of this analysis was to then model the logistics costs to deliver an appropriately sized and processed biomass to the throat of the pyrolysis reactor. This cost was modeled using the INL Biomass Logistics model, and includes costs for unit operations necessary to process raw biomass into a form suitable for the production of pyrolysis oil.

Four base logistics scenarios were modeled, each base case included transportation, size reduction, and drying operations to produce a biomass product appropriate for pyrolysis. The specifications for this biomass were selected to meet the specifications of the 2011 Multi-Year Project Plan (MYPP-2011) for fast pyrolysis, and are as follows:

- Particle Size @ Plant Gate: < 2 inch
- Moisture Content @ Plant Gate: < 50%
- Particle Size @ Reactor Feed: 0.08 inch
- Moisture Content @ Reactor Feed: 10%

Note that the ash content listed in the MYPP has been replaced for this analysis by the calculation of expected pyrolysis process yield based on biomass feedstock ash content. This will enable a determination of the economic costs and benefits for the inclusion of ash reduction processes and the selection of lower ash content biomass for pyrolysis.

Logistics for Various Materials

Different logistics operations are necessary for the collection of different general biomass types. Four material types were modeled for this analysis, Corn Stover (representing agricultural residues), Mill Residues, Forest Thinnings (representing Logging Residues and Thinnings), and Willow (representing purpose grown energy crops). For each of these scenarios, an analysis was conducted both without any ash reduction processes, with leaching, and with a leaching and drying operation prior to feeding material into the throat of the reactor.

Models Analyzed

The model for corn stover is shown in Figure 14. The full scenario with leaching and drying is shown. The baseline scenario, which excludes both leaching and drying, excludes all operations inside the red line, and material flows directly from the grinder to the evenflow bin. For the leaching only step, the operations inside the green line are omitted, and leached, wet material flows to the evenflow bin.

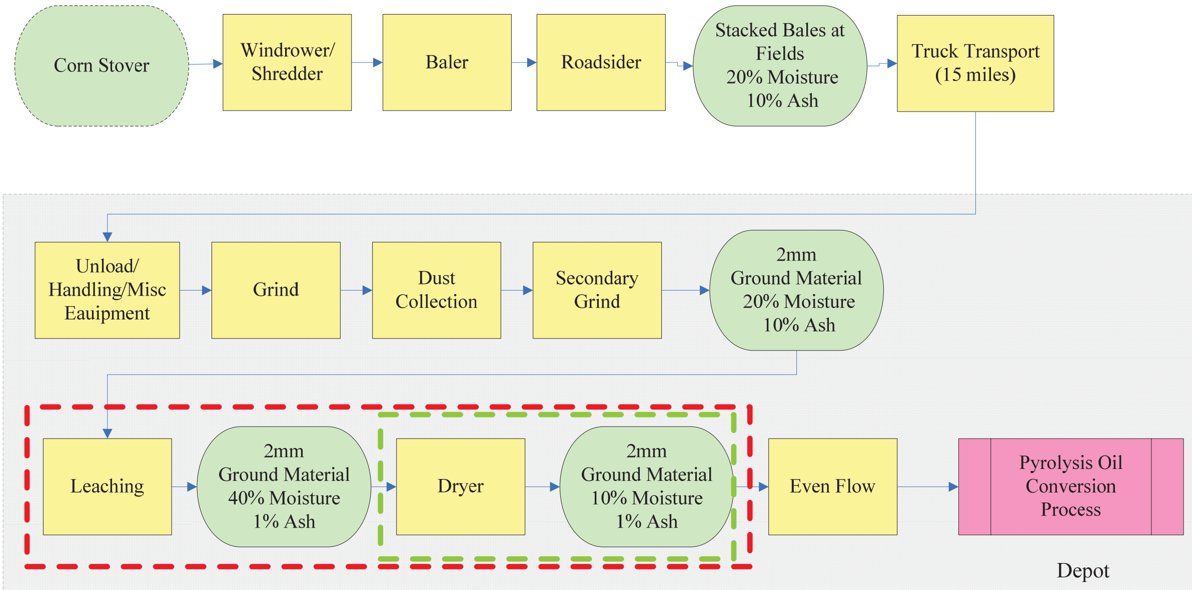

Figure 14: Corn Stover scenario.

For mill residues, the same operations were modeled at the depot, both without ash reduction, and with leaching, and then with leaching and drying. Figure 15 shows the operations for this scenario.

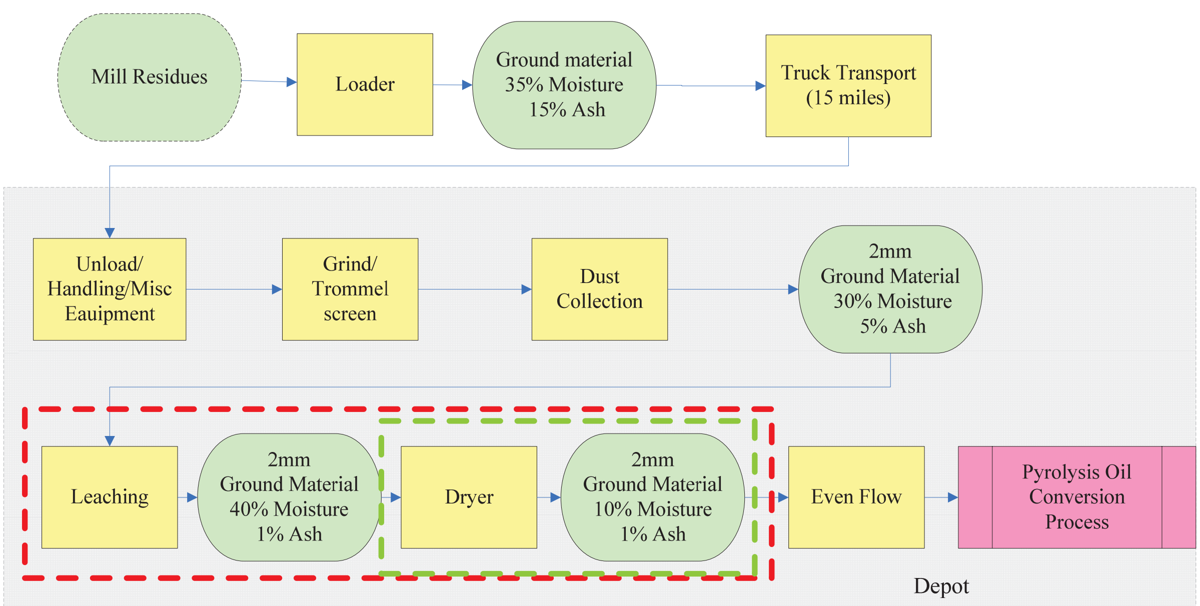

Figure 15: Mill Residue scenario.

Operations for the utilization of forest thinnings are shown in Figure 16, and Figure 17 shows the Willow scenario. Again, while not explicitly shown, the operations for pre-processing were treated in three separate cases, a base case without ash reduction and drying, a case with ash reduction, and one with both ash reduction and drying.

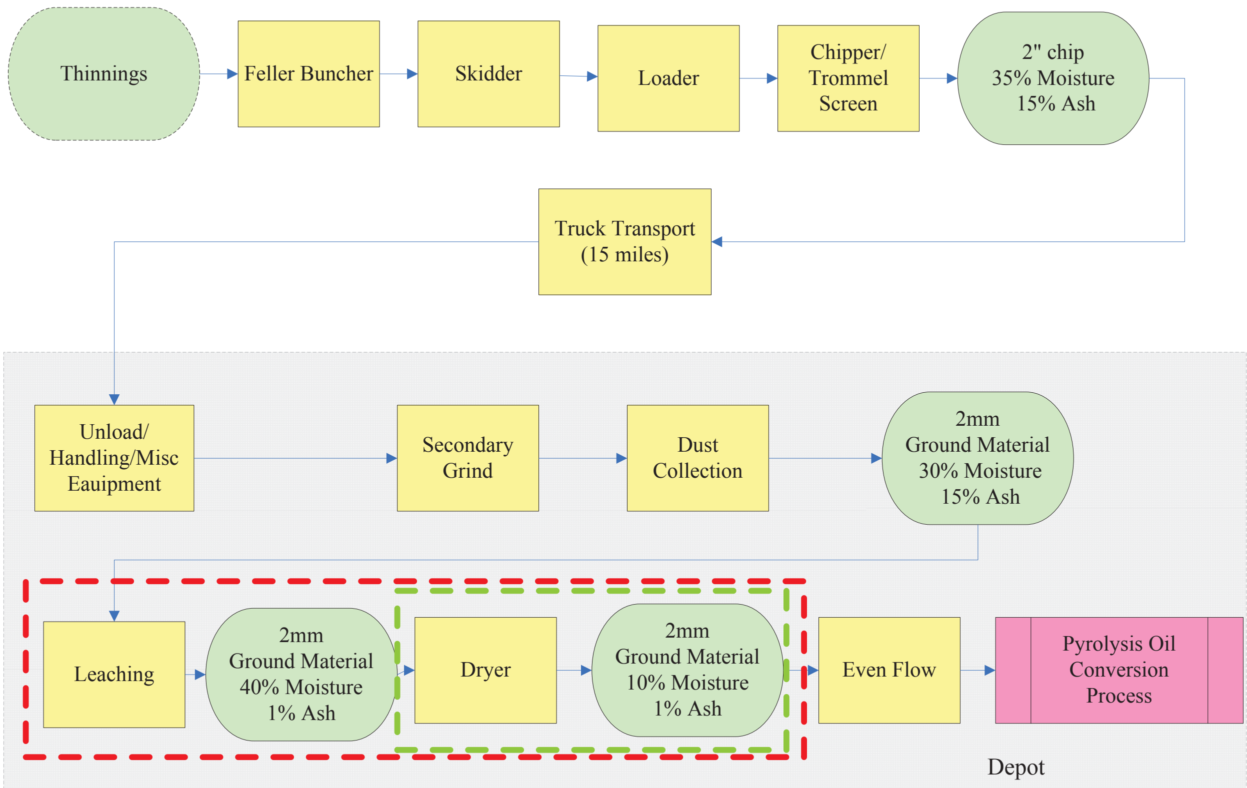

Figure 16: Forest thinnings scenario.

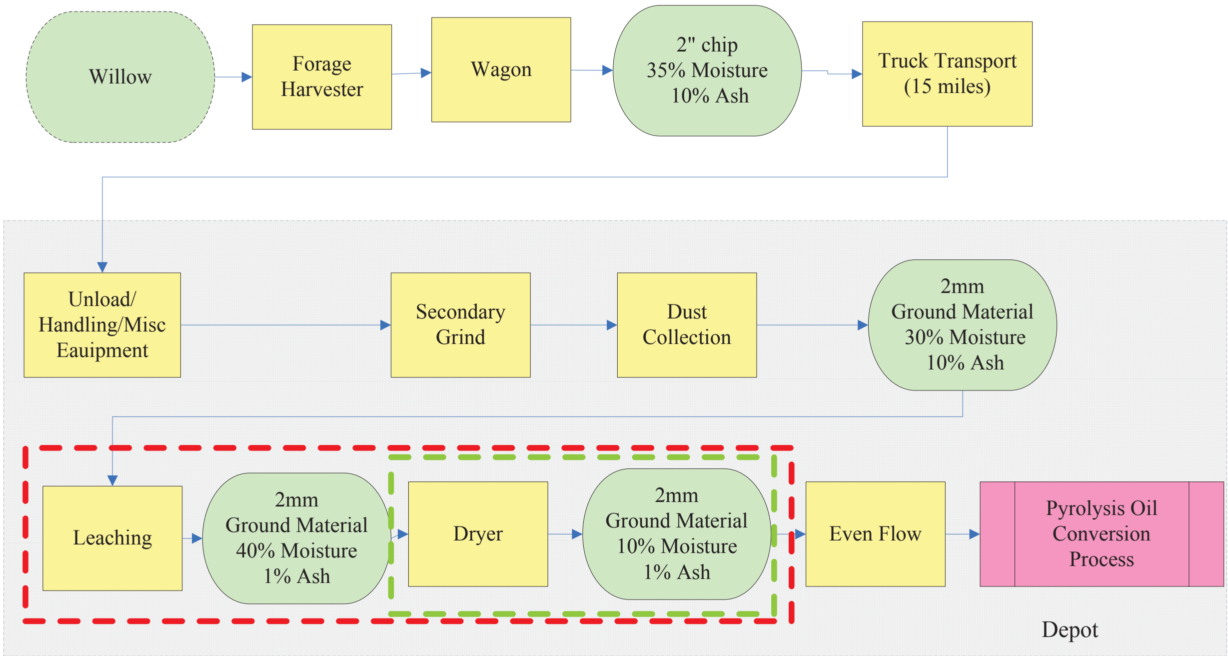

Figure 17: Willow collection scenario.

The results of each of these scenarios and modeling operations were collected in Table 6. These costs were grouped according to the harvest and collection costs, the transportation costs to the processing depot, and the depot processing and storage costs at the depot. In this case, a distributed model of pyrolysis processing is used, assuming small pyrolysis production operations distributed throughout the northeastern U.S.

The costs are grouped according to the biomass under consideration, with case 1 representing no ash reduction, case 2 representing leaching, and case 3 representing leaching and drying, as described above.

Table 6: Logistics Costs.

	Harvesting	Transport	Preprocessing	Storage	Total	Total w/o Harvesting
Stover 1	$57.78	$6.66	$20.71	$7.27	$92.42	**$34.64**
Stover 2	$57.78	$6.66	$29.35	$7.27	$101.03	**$43.28**
Stover 3	$57.78	$6.66	$62.12	$7.27	$133.83	**$76.05**
Thinnings 1	$29.15	$4.42	$47.69	$1.18	$82.44	**$53.29**
Thinnings 2	$29.15	$4.42	$63.51	$1.18	$98.26	**$69.11**
Thinnings 3	$29.15	$4.42	$77.47	$1.18	$112.22	**$83.07**
Mill Residues 1	$0.00	$4.10	$32.89	$0.0.72	$37.71	**$37.71**
Mill Residues 2	$0.00	$4.10	$45.50	$0.72	$50.32	**$50.32**
Mill Residues 3	$0.00	$4.10	$56.42	$0.72	$61.24	**$61.24**
Willow 1	$16.94	$6.38	$69.17	$0.60	$93.08	**$76.15**
Willow 2	$16.94	$6.38	$100.86	$0.60	$124.77	**$107.84**
Willow 3	$16.94	$6.38	$127.70	$0.60	$151.61	**$134.68**

Because the ORNL BTS2 Data includes the cost of harvesting, the totals are included both with and without this cost. For a total cost of each scenario, the total without harvesting must be added to the total cost of the biomass reported from the BTS2 data.

Comparing Table 6and the information in Figure 6 and Figure 7, it is clear that mill residues and forest thinnings produce the lowest cost feedstock , due to the low access fee. Purpose grown energy crops (willow) are too expensive both in the production costs, and the logistics costs while there limited qunatities of crop residues available in the study area.

Total biomass - cost at reactor throat

Based on the information presented, the goal to verify a feedstock cost (e.g., <$65/dry ton) for >5% replacement of petroleum-based heating oil within 5 years (2017) and >20% replacement of petroleum heating oil within 10 years (by 2022) can be achieved using the first mill residue scenario. Mill residues assume an already ground material available for use. Leaching and drying are too expensive to reach the <$65 target and must be excluded, but it is assumed that a trommel screen attached to a grinder process can remove ash to acceptable levels. With the exception of woody thinnings all other feedstocks evaluated in this analysis were too expensive to reach the cost target.

Using mill residues, to achieve >5% replacement Table 4 shows a requirement of about 2.1 million tons of dry biomass. To obtain that quantity of material, Figure 6 shows an average access fee of $18.06/dry ton. Combining the logistics cost and access fee gives an overall cost of $55.77/dry ton. To achieve >10% replacement, Table 4 shows a requirement of 8.4 million tons of biomass with an average access cost of about $37.71/dry ton giving an overall cost of $67.04/dry ton.

These represent conservative values, given expected yields for a given quantity of biomass. If expected values are used, Table 7 can be generated. This table contains expected ash content, the effect of the ash content on pyrolysis process yield, the resulting change in required biomass, and the attendant change in raw biomass cost, resulting in the total cost of biomass feedstock to meet the goals of the program.

Table 7: Expected Total Cost based on Expected Ash and Process Yield.

Year	Repl.%	Preproc. Op.	Feedstock Ash	Expected Yield	Required Biomass dt/yr	Feedstock Cost $/dt	Preprocessing Cost $/dt	Total Cost: $/dt
2017	5%	Leached	1%	45%	2.9M	$14.99	$61.24	$76.23
2017	5%	Raw	5%	30%	4.3M	$18.06	$37.71	$55.77
2022	20%	Leached	1%	55%	9.4M	$27.71	$61.24	$88.95
2022	20%	Raw	5%	50%	10.4M	$29.33	$37.71	$67.04

This analysis is restricted to the granularity of the information available from the ORNL BTS2 data, and is further restricted by the availability of information on the effect of ash content and ash composition on the pyrolysis process. Some recent studies have suggested that some ash species may act as process catalysts, improving the yield of a pyrolysis operation. This is beyond the scope of this work.

Finally, future work could focus on blending the feedstocks in order to also reach the specified goals.

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