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The Externalities Associated with Various Heating Sources at Bates College

Amy Schmidt

Tom Fitzgerald

Dane Lamendola

Tyler Schleich

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Section 1: Executive Summary

The aim of this report is to determine the costs associated with the externalities of #2 fuel oil, natural gas, biomass, and renewable fuel oil. Externalities occur when a market transaction imposes costs on parties external to that transaction. These four energy sources are options Bates College is considering for heating its campus, either through the central steam plant or separate boiler systems. Evaluating the costs of these externalities will provide a picture of the true cost of energy, allowing the school to make a decision with complete information regarding the implications of using these energy sources.

The methodology for estimating the cost of externalities differs for the two groups of energy sources. The values for #2 fuel oil and natural gas largely follow the methodology of the ExternE report of the European Commission, in which empirical modeling and case studies provide for the estimates of various externalities of fuel sources used across Europe. The findings of the ExternE report are supplemented with outside literature in order to confirm that the ExternE methodology is valid, and to provide additional externality cost information lacking in the report. This study finds that there are a range of externality costs associated with the use of #2 fuel oil and natural gas, from the costs of health effects to atmospheric pollution.

Biomass and renewable fuel oil follow similar methodologies in terms of evaluating the costs of externalities. Various sources of literature are used to determine the possible mechanisms in which externalities may exist through the use of these energy types, and to determine their impact in terms of a monetary value. As these two energy sources are very recent additions to the market, reports beyond those available in the academic literature are also relied upon to provide information. One of the major contributors to externalities associated with renewable fuel oil is the Pacific Northwest National research Lab (PNNL). This report finds that the externality costs associated with biomass and renewable fuel oil are minimal compared to the other energy sources, as the primary externality costs are associated with the transportation of these materials.

The results of this study are reported as lower bounds for fossil fuel externalities and upper bounds for renewable fuel externalities. By reporting the renewable fuel externalities as

upper bounds, we can show the worst-case scenario associated with renewables. This will provide a contrasting figure to our minimum conservative values for fossil fuels that show the best-case scenario. These values are estimates due to our understanding that certain impacts cannot be valued monetarily given the complexity of the relationships among these energy markets, the economy, and the environment. The final value of all externality costs for each fuel source is presented in Table 1.

Table 1: Total Externality Costs in 2014 USD

Fuel Source	Market Cost per mmBTU[1]	Externalities Cost per mmBTU[2]	Percent Increase in Cost with Externalities Included[3]	Annualized cost of externalities[4]
#2 Fuel Oil	$14.90	$146.00	980%	$12,300,000
Natural Gas	$15.50	$44.66	288%	$3,580,000
Biomass	$13.20	$15.51	118%	$1,202,000
Renewable Fuel Oil	$7.50	$8.45	113%	$676,000

Section 2: Project Introduction and Background

Since 1855, Bates College has produced forward-thinking, global citizens committed to equality, justice and the love of learning. Students use this learning to wield knowledge as a means of change and inspire student research. In keeping with this ideology, the Bates Environmental Studies Program prepares students to address interactions between humans and the non-human in order to reveal constructive approaches for how we might better coexist as a community and as global citizens. This report applies such ideas to the study of energy sources currently available to Bates, and their associated externality costs.

Externalities from the human processes of energy production represent true costs, yet remain outside the energy producer-consumer market. Damages from extraction, processing, and

[1] This is the amount Bates College currently pays, or would pay given current market conditions.

[2] These are the externality costs calculated for this paper, which are social costs not including the aforementioned market cost.

[3] This value reflects the additional percent increase in price due to inclusion of externalities to the market cost.

[4] The annualized cost is the total externality price of using a fuel as the primary source of energy in the central steam power plant.

combustion of energy sources cause human health impairments, occupational mortality, infrastructure expenses, climate change impacts, and ecosystem damages.[5] Our study seeks to better identify the true cost of energy consumed at Bates and quantify these damages, hopefully in order to spark a productive conversation about alternative energy options on campus..

While Bates does not directly pay for all the costs of its energy production, these consequences are still borne out elsewhere within the economy: pollution-induced health care costs, cleanup and restoration of environmental damages, property repairs resulting from processing and transporting incidents, soil erosion from timber harvesting, and occupational mortality.[6] Considering these external costs of fuel consumption in decisions of what fuel to use would advance Bates College's "commitment to responsible stewardship of the wider world."[7] Changes in energy source composition are inevitable if the college is to reach its proposed goal of emissions neutrality by the year 2020.[8]

Bates energy consumption serves primarily to provide hot water and ambient heat to campus buildings throughout the year via a steam pressurized system. While the cold Maine winters make central heating systems necessary, how energy needs are met remains open to new possibilities and discussion. Our report thoroughly explores the externality costs of four fuel sources either in use or available to Bates. These include #2 fuel oil, natural gas, wood pellet biomass, and renewable fuel oil (RFO). Using data and observations available in the literature, we have estimated costs in 2014 USD/mmBTU, of the key externalities associated with each source; should the data and calculations be desired, the excel spreadsheets used in these calculations will be uploaded on SCARAB.

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[5] Cohen, Mark A, "Costs and Benefits of Oil Spill Prevention and Enforcement," Journal of Environmental Economics and Management 2 (1986), 167-188; Friedrich, Rainer, Krewitt, Wolfram, Mayerhofer, Petra, Truchenmüller, Alfred, and Greβmann, Alexander, "ExternE Externalities of Energy: VOl.4 Oil and Gas," Brussels: European Commission, 1995. Intergovernmental Panel on Climate Change "Climate Change 2014: Synthesis Report." Contribution on Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)], IPCC, Geneva, Switzerland, 2014.

[6] Friedrich et al, "ExternE Externalities of Energy, European Commission, 1995; Intergovernmental Panel on Climate Change "Climate Change 2014: Synthesis Report," 2014.

[7] Bates Mission Statement, 2015.

[8] Bates College Sustainability, Climate Statement, 2015. http://www.bates.edu/sustainability/climate/.

Section 3: Externalities Background

In determining pricing structures, energy companies use factors such as fuel costs, capital costs, and production-plant lifespans to determine the most affordable method of energy generation. This process gives limited consideration to more indirect, or external, impacts of the energy economy, including environmental damage and social costs. The failure to reflect on externality values represents a significant inefficiency in economic markets. The inclusion of externalities in our energy supply choices would allow Bates to determine the most economically efficient energy source, considering not only traditional monetary costs and benefits, but also environmental preservation, human health, and long-term stability.[9]

In the energy market, externalities refer to total fuel cycle costs not incorporated into the energy market cost structure. Our report accounts for such externalities throughout the entire fuel cycle, including as many of the physical and chemical processes and activities required to generate energy from a source--from primary resource extraction and preparation, transportation and storage of resources, processing and conversion, to disposal--as possible.[10]

Section 4: #2 Fuel Oil Externalities

4.1 Introduction

Bates uses an average of 130,000 gallons of #2 fuel oil per year, primarily to heat houses on Wood Street and Frye Street. #2 fuel oil (also known as #2 heating oil or home heating oil) is a petroleum product produced from crude oil. The extraction process normally involves some combination of underground pressure, water injections into the well, steam pressure injections, the release of various gases to form a "cap" to create pressure and draw oil to the surface, and pressurized chemical injections.[11] The crude oil itself is a mixture of liquid hydrocarbons formed within the Earth's surface, which remain viscous upon extraction.[12] The refining process from

[9] Roth, Ian F., and Lawrence L. Ambs. "Incorporating externalities into a full cost approach to electric power generation life-cycle costing." Energy 29 (2004): 2125-2144.

[10] US Energy Administration, "Glossary," 2015.

[11] American Petroleum Institute, "Exploration and Production", http://www.api.org/Oil-and-Natural-Gas-Overview/Exploration-and-Production.

[12] Energy Information Association, "Frequently Asked Questions," 2014.

crude to #2 oil involves two main steps: Separation, or the distilling process by which crude oil is separated into constituent parts for further refining; and conversion, or the chemical process by which these distillates are altered to better serve their intended use.[13]

Key externalities of #2 fuel oil consumption occur both in production and combustion. Production-related externalities include damages from oil spills and occupational hazards from extracting the resource. Combustion externalities include the effects of emissions particulates upon human health, damages to crops from chemical precipitation, and climate change impacts tied to the release of greenhouse gases such as carbon dioxide into the atmosphere. Following are the assumptions, methodology, and results of our effort to approximate these externalities in order to inform the institution of the consequences of its energy choices.

4.2 Occupational Health Effects

Numerous studies have shown that occupations involved in the physical extraction of petroleum products have above-average injury and mortality rates.[14] Such costs are external to the market price of oil, yet have a real economic impact that we attempt to measure

In calculating these values, our primary assumption is that average increases in death per unit of energy produced are similar across different oil extraction operations. Data in the ExternE report come from records of United Kingdom and Norwegian oil operations in the North Sea; we are assuming that such incident rates are roughly similar in other extraction sites, such as the Gulf of Mexico. The method of valuing mortality used is to multiply the rate of incidence by the Value of Statistical Life (VSL). This is an economic tool estimating the value of a marginal change in the rate of death, and is used in many applications, including governmental cost-benefit analysis. For our study, we use the EPA's estimate of the VSL, which is about 7.4 million 2014 USD.[15] The ExternE report by the European Commission provides data on number of incidents per unit of oil energy produced; this fraction is multiplied by the EPA VSL, and then converted from the KwH to BTU energy unit. The resulting estimate is approximately $0.0302 2014 USD/mmBTU.

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[13] Wansbrough, Heather, "Refining Crude Oil," The New Zealand Refining Company Ltd.

[14] Bureau of Labor Statistics, "Census of Fatal Occupational Injuries." Released September 2015.

[15] Environmental Protection Agency, 2015.
http://yosemite.epa.gov/EE%5Cepa%5Ceed.nsf/webpages/MortalityRiskValuation.html#whatvalue

The extent to which occupational injuries constitute a true "externality" remains contentious. In perfectly efficient market theory, the wages paid to oil workers would fully encompass and compensate for the risks associated with the job. However, a perfectly efficient labor market is unlikely to occur in reality: companies may not present all hazard information to employees, employees may not fully understand the possible hazards, and either party may not perceive the hazards from catastrophic failures and unpredictable accidents. Thus, this study includes the costs of lost life via occupational hazards. For sensitivity analysis, these costs represent such a small portion of the total costs that omission does not alter the results in a statistically significant way.

4.3 Public Health Effects

Burning #2 fuel oil releases not only greenhouse gases (GHG) but also particulate matter (PM), sulfur dioxide, and various nitrous oxides, which can damage the human respiratory system.[16] Increases in the ambient atmospheric concentration of these types of pollutants increase the incidence rate of many respiratory conditions. The public health impacts of particulate emissions presented here include changes in the incidence rate of asthma, acute respiratory damage, COPD, and mortality. As these effects occur outside the market transaction between oil producer and oil consumer, pollution-induced ailments from combustion represent a true cost external to the market price Bates pays for #2 heating oil.

To feel confident in our calculations, we only consider the costs of public health damages from PM10, or ambient particulates with a diameter of 10 micrometers or fewer. Data on the increased incidence of eight respiratory treatments, and the population mortality rate, per percent increase in micrograms of PM10 per cubic meter of air come from studies employed by ExternE.[17] The document provides a range of possible incidence rates, and, in the interest of being conservative, we use the lowest rate estimates. Data on the release of PM10 per gallon of #2 fuel oil burned come from the 2014-2015 Bates EPA Energy Statement, an annual emissions statement.[18] The percent increase is calculated from the baseline ambient PM10 concentration per cubic meter recorded in Lewiston; while the most recent data comes from 2004, we feel that

[16] Friedrich et al, "ExternE Externalities of Energy, European Commission, 1995, 100.
[17] Ibd. 103-106
[18] Bates Energy Report 2014-2015.

this number still provides a more reasonable estimate of actual PM10 concentration near Bates than using the national 2014 average.[19] In a sensitivity test, our final results are similar regardless of which concentration we use.

Determining the *ambient* PM10 concentration per cubic meter of air that results from Bate's PM10 emissions requires meteorological modeling experience and tools beyond the scope of this report. However, assuming that all PM10 emissions follow relatively similar dispersion rates, and given the estimate that most PM10 emissions do not travel further than a 2069-meter radius,[20] the ambient increase in PM10/cubic meter of air is estimated as the total PM10 emissions divided by the volume of a hemisphere with a radius of 2069 meters. While this assumption decreases study accuracy, the number seems the best estimate available without utilizing sophisticated climate modeling.

The remainder of the procedure involves translating the percent increase in PM10/ cubic meter from 1 gallon of oil combustion to PM10/mmBTU of energy produced, multiplying this value times the negative health incidence rate per percent increase in PM10, and then by the cost of coping with that particular health impact. The average cost of treatment is based on the United States healthcare system, using data provided from the Centers for Medicare and Medicaid Services.[21] The final cost in 2014 USD/mmBTU equals $5.00.

4.4 Soils and Crops

Sulfur dioxide emissions create an array of polluting compounds in the atmosphere that can precipitate onto agricultural fields and negatively impact crop growth.[22] While the precise impact pathways are complex and not completely understood, much work has been done to suggest that there exists an observable impact of ambient sulfur dioxide air pollution on crop yields. In the United States, much work was done on this issue during the 1980s and 1990s; these studies remain the primary sources of crop dose-response functions. Key sources frequently referenced include Weigel et al. (1990), Roberts (1984), and Baker et al. (1986).

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19 Environmental Protection Agency, "Particulate Matter: Air Trends," 2015. http://www3.epa.gov/airtrends/pm.html

20 Godoy, S.M., Mores, P.I., Santa Cruz, A.S.M., and Scenna, N.J, "Assessment of impact distances for particulate matter dispersion: A Stochastic Approach," *Reliability Engineering and System Safety* 94, (2009), 1662

21 Centers for Medicare and Medicaid Services, "Visualizing Hospital Pricing," Data presented by Beehive Media. Costs as of 2013.

22 Friedrich et al, "ExternE Externalities of Energy, European Commission, 1995,138.

The dose-response function from Weigel et al. (1990), as provided in the ExternE study, is used for our calculations.[23] The formula estimates the percent decrease in wheat yields at incremental levels of sulfur above 30 μm/m^3. The average ambient sulfur concentration in Lewiston for 2003 (the most recent report available) was around 90 μm/m^3 (EPA "Sulfur").[24] Since this number is well above the baseline of 30 μm/m^3, it is appropriate to use the Weigel et al. response function equation.

The EPA emissions testing laboratories provides information on emissions of sulfur per gallon of #2 fuel oil burned.[25] As with PM10 above, the actual emissions rate is a fraction of this value and was calculated from the Bates college 2014-2015 emissions report. Again due to a lack of access to precise atmospheric modelling, the effects of #2 fuel oil emissions on ambient sulfur concentrations were estimated using an average relationship between source emissions and local concentrations.[26] Because the study in question was looking at East Asia and the West Coast of the United States, transferring these values to the Bates system represents a rough estimate of emissions impacts.

Dispersion calculations are used to estimate the relationship between emissions of sulfur dioxide per unit of fuel oil burned at Bates, in order to calculate the subsequent increase in ambient sulfur in the greater L-A area. Unit conversions are used to translate the data into ambient sulfur in μm/m^3 per BTU of #2 fuel oil energy. This increase in ambient pollution can then be plugged into the Weigel et al. equation to estimate the percent decrease in wheat yield per BTU. This percentage value of the price in 2014 USD per ton of wheat estimates the economic costs of reduced yields due to sulfur dioxide pollution, and measures approximately $2.39 2014 USD/mmBTU. While there is a fair degree of uncertainty associated with our estimate, we consider it reasonable given that wheat is a rather low-value crop compared to the vegetable and apples primarily grown in this area of the country. Even if our estimate of wheat loss is high, the cost of such yield loss is low enough that, in terms of Bates' likely impact, the overestimate in crop loss is compensated by an underestimate in crop value. Even after changing

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[23] Ibid. 180.

[24] Environmental Protection Agency, "Sulfur Dioxide: Air Trends," 2015. http://www3.epa.gov/airtrends/sulfur.html

[25] Environmental Protection Agency,"AP 42- Compilation of Air Pollutant Emissions Factors Volume 1: Stationary Point and Area Sources," Office of Air and Radiation, 1995.

[26] Liu, J. Mauzerall, D.L., and Horowitz, L.W, "Source-receptor relationships between East Asian sulfur dioxide emissions and Northern Hemisphere sulfate concentrations," *Atmospheric Chemistry and Physics* 8, (2008), 3729.

the order of magnitude plus or minus one, our estimates of the total cost of damages to all crops associated with burning #2 fuel oil at Bates are likely non-negligible.

4.5 Oil Spills

While not widely reported, every year a sizeable amount of oil spills into United States waterways via "small" accidents involving fewer than 5000 gallons.[27] This study quantifies the average annual economic costs of oil spills, both from the loss of economically valuable species and the labor, time, and resources diverted to spill cleanup. While ExternE does not calculate these types of costs, there is both data and research available to approximate this externality within the United States' jurisdiction.

The United States Coast Guard provides data on all recorded oil spills by spill size, and the annual total oil volume spilled, within US waterways from 1973 to 2011. From this dataset, we calculate a yearly average of oil spills by spill size and an average annual volume of oil spilled. A meta-analysis by Cohen[28] of the observed costs for a variety of sizes of oil spills is then used to approximate average annual economic costs. The measures for which Cohen provides the most data and the most confidence are cleanup costs, estimated by spill size and observed cleanup cost for events such as the Oakland Estuary spill of 1973 (171,000 gallons) and the Amoco Cadiz spill of 1978 (66 million gallons). Here, we are forced to make a key assumption that the costs of cleanup for oil spills have remained relatively stable over time. As justification, we assume that, over time, an increase in available oil control technologies compensates for the decrease in price of older technologies. The economic costs of commercially valuable species are used as a proxy for ecological costs. Given that certain species such as dolphins have non-observable value through tourism, existence value, etc., the estimate given here represents a highly conservative lower bound of the true ecosystem costs.

Calculating the costs of cleanup per gallon by oil spill size requires value estimation, since not all of the spill sizes classified by the US Coast Guard had cost estimates in the Cohen paper. To address this issue, we use the largest marginal decrease in cost across the Cohen spill

[27] United States Coast Guard, "Pollution Incidents in and Around U.S. Waters, A Spill/Release Compendium: 1969-2011," Released December 2012. http://homeport.uscg.mil.

[28] Cohen, Mark A, "Costs and Benefits of Oil Spill Prevention and Enforcement," Journal of Environmental Economics and Management 2 (1986), 167-188.

sizes to estimate the decreases in unit cost for the spill sizes in the Coast Guard data. These costs are then multiplied by the number of gallons of oil spilled per spill size in the US Coast Guard data set. For categories between two estimates by Cohen, an average of the two cost estimates was used. For example, Cohen estimates cleanup costs per gallon for spills of 100-1000 gallons at $19.64, and $9.92 for those between 3,000 and 5,000 gallons. The average of these two costs is used to estimate costs for spills of 1,000-3,000 gallons. Cohen's estimates for the costs of lost commodity species are adjusted to 2014 USD and multiplied by the annual average total gallons of oil spilled. These values are then converted to 2014 USD/mmBTU via conversion factor calculations, for a value of $134 USD/mmBTU. While not all crude oil ultimately becomes #2 fuel oil, general crude oil procurement accounts for a significant part of the supply chain. This leads us to believe that our final estimate does not overestimate the true externality costs of oil spills for #2 fuel oil.

4.6 Property Damage

Movement of oil on land is subject to hazards and infrastructure failures (primarily of pipelines) that impose externalities upon nearby properties.[29] In the United States, data for the total cost of property damage from pipeline accidents, and the volume of oil transported, are available on an annual basis. These costs of property damage, averaged over the years 2009-2013, are divided by the average number of gallons of oil transported over that same timespan.[30] This average cost/gallon is then translated into a cost per BTU, via unit conversions, of approximately $0.02 2014 USD/BTU.

4.7 Climate Change

Releases of greenhouse gases (GHG) from the combustion of fossil fuels have impacted, and will continue to impact, the global climate.[31] The location and frequency of extreme weather events, local average temperatures, coastline levels, species ranges, and growing seasons, among

[29] US DOT Pipeline and Hazardous Materials Safety Administration. "Pipeline Significant Incident 20 Year Trend." Data as of 9/25/2015. http://www.phmsa.dot.gov/pipeline/library/data-stats.

[30] Association of Oil Pipelines. "Barrels Delivered by Transmission Pipeline." Data as of 2013. http://www.aopl.org/pipeline-basics/about-pipelines.

[31] Intergovernmental Panel on Climate Change "Climate Change 2014: Synthesis Report," 2014, 2.

other factors, will be affected by the current and future climate shifts.[32] While the form and severity of these changes remains somewhat unclear, sophisticated climate modeling systems have been used to examine a wide range of possible outcomes and their impact upon human societies and economic activities.[33] The social cost of carbon (SCC) aggregates the costs of these various changes and provides a monetary cost per metric tonne of carbon-dioxide pollution.

The estimated emissions from #2 Fuel Oil combustion, provided by $(S+T)^2$, Inc. consultants,[34] are multiplied by the Environmental Protection Agency (EPA) SCC estimate at various times along the 5% discount rate pathway in order to provide a SCC, in 2020, of $4.44 2014 USD/mmBTU.

4.8 Conclusion

In general, the costs provided represent a lower-bound of the true externality costs, because we have only included those values in which we place a reasonable level of confidence. Numerous other considerations, such as the value of habitat loss, opportunity costs of dedicating resources to fuel production, etc., are not included due to a lack of research and literature on the potential cost ranges for these factors.

[32] Ibid. 6
[33] Environmental Protection Agency, "The Social Cost of Carbon," Data revised 2015. http://www3.epa.gov/climatechange/EPAactivities/economics/scc.html.
[34] Ensyn Energy Consultant Report, 2015, 1.

Table 2: Externality Costs for #2 Fuel Oil in 2014 USD/mmBTU

Externality	Cost
Occupational Health (Worker mortality during oil fuel cycle)	$0.03
Public Health (Respiratory issues and mortality caused by particulate matter)	$5.00
Crop loss (Value of reduced wheat output as proxy for overall costs)	$2.39
Oil Spills (Clean-up costs and fisheries damages)	$134.00
Property Damage (via pipeline transport)	$0.02
Climate Change (Social Cost of Carbon in 2020, 5% discount rate)	$4.44
Total Cost of Externalities for #2 fuel oil	**$146**

Section 5: Natural Gas

5.1 Introduction

Natural gas is a commonly used energy source whose consumption has grown considerably in recent years. Given the overall dependency on foreign imports to supply oil energy, natural gas has become a focus of many countries as they seek some form of energy independence while still maintaining access to a relatively cheap source of power.[35] In the United States, natural gas has become a major facet of energy use, as hydraulic fracturing, or "fracking," and other extraction processes have been heavily pursued. As a result, natural gas is now a major energy source in the United States, as its generally domestic nature and relatively low prices have made it an attractive option for a variety of institutions and enterprises.

Natural gas makes up a large portion of energy use at Bates College, at about 80,000 dekatherms per year.[36] The school receives natural gas from a domestic source on a contract basis. The terms of this contract are important, as natural gas is generally the primary component

[35] Yergin, Daniel. "Congratulations, America. You're (Almost) Energy Independent." POLITICO Magazine. November 1, 2013. Accessed November 14, 2015. http://www.politico.com/magazine/story/2013/11/congratulations-america-youre-almost-energy-independent-now-what-098985.

[36] Bates Energy Report 2014-2015.

of energy generation at the steam power plant used to heat the college during the winter months. Given its major impacts on both the energy plan and finances of running the college, considering the externalities associated with natural gas use is of primary concern to the Bates community.

Many of the assumptions employed in this section considering natural gas externalities come from those made in the ExternE report. Considering this is a study from the European Commission, the data and the case studies presented rely on European statistics and institutions. In this regard, the assumption must be made that the European energy system's pollution impacts and overall economic structure resemble those of the United States. This is a plausible assumption, as key countries like the United Kingdom considered in the ExternE report share many similarities to the United States in terms of energy source processing and use.[37] Given this similarity assumption, certain externalities are the result of converting the measurements from the ExternE report into 2014 United States dollars.

The ExternE study evaluates externalities of natural gas as it is used for electricity generation. Bates does not use natural gas for electricity generation, but rather for use in its steam plant generation facility. We assume that the electricity generation process is similar to the steam heat generation process in terms of externalities; the Electrical Engineering Portal supports this assumption.[38]

The following valuation aims to provide a defensible monetary value associated with the externalities of natural gas extraction and use, primarily following the methodology and basis of the European Commission ExternE report.

5.2 Occupational Health Effects

The occupational health effects of natural gas use occur at various stages of the fuel cycle, from the extraction of natural gas, the construction and operation of pipeline and power plant facilities, and various major events that occur at both these and offshore locations. The specific occupational health effects are comprised of minor and major injuries, along with associated deaths. The aggregate monetary value associated with these instances represents a significant portion of the overall externality costs; occupational risk represents an important aspect of considering the true cost of natural gas use.

[37] "Regulators' use of standards." International Association of Oil and Gas Procedures. March 2010, 45.

[38] Ramireddy, Vinod. "An Overview of Combined Cycle Power Plant | EEP." Electrical Engineering Portal. August 25, 2012. Accessed November 3, 2015. http://electrical-engineering-portal.com/an-overview-of-combined-cycle-power-plant.

The methodology used to valuate these effects involves multiplying the incident rate of injuries and deaths associated with the aforementioned instances by the EPA's VSL. The incident rates used from the ExternE report primarily focus on sites within the United Kingdom.[39] The report considers various facilities and locations over a considerable period of time to reach the final incident rates used in this report. It is assumed that these sites are comparable to sites in the United States, as a large portion of the infrastructure, processes and institutional codes regulating these sites are similar across the two locations.[40] Moving forward with this assumption of similarity, the externality cost associated with occupational health effects of natural gas extraction and use totals $3.96 2014 USD/mmBTUs.

5.3 Public Health Effects

A major component of the externalities associated with natural gas use are health effects associated with the release of particulate matter (PM) during the process of combustion.[41] PM byproducts play a role in the development of various respiratory infections and diseases, and thus such medical costs represent a direct externality of natural gas consumption. The ExternE methodology for this valuation is an analysis of an aggregation of literature regarding disease development and natural gas emissions.[42] This aggregation of data is used to inform how natural gas PM emissions affect populations in the United Kingdom, employing a case study technique.[43] The communities exhibited in this portion of the ExternE report are assumed to, on average closely resemble North American communities such as Lewiston, Maine.

The particular public health effects considered encompass a range of costs and disease types. The costs include the value of statistical life, which has been adjusted from the European Union value of statistical life to the EPA's value of statistical life, and various hospitalization and residual monetary costs.[44] The instances of disease considered were emergency room and hospital visits regarding asthma, COPD, respiratory infection, and childhood croup. The

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39 Holland, Mike, Paul Watkiss, and Jacquie Berry. "ExternE Externalities of Energy: VOl. 4 Oil and Gas." 307.
40 "Regulators' use of standards." International Association of Oil and Gas Procedures. March 2010, 45.
41 Holland, Mike, Paul Watkiss, and Jacquie Berry. "ExternE Externalities of Energy: VOl. 4 Oil and Gas." Brussels: European Commission, 1995; 283.
42 Ibid 285.
43 Ibid 293.
44 "Guidelines for Preparing Economic Analyses." National Center for Environmental Economics. Environmental Protection Agency. 2015. Accessed on October 7, 2015. http://yosemite.epa.gov/EE%5Cepa%5Ceed.nsf/webpages/Guidelines.html.

externality costs associated with these effects were initially given in million of euros per kilowatt hour, which was then converted into United States dollars per British thermal unit. The final monetary cost of these public health effects is $3.01 2014 USD per million BTUs.

5.4 Emission Effects

The ExternE report was not used in the calculation of the monetary costs associated with emissions from natural gas as the assumptions needed to apply those values to the United States limited the legitimacy and application of those statistics. This was due to the difference in environmental regulations, in terms of emission restrictions for power plants between the two countries, in which European countries generally exhibit stricter standards. Instead, a report that focuses on energy emissions in the United States was used to serve as the basis for this methodology. This paper from the University of Massachusetts considers a range of pollutants that are emitted from the combustion of natural gas, and follows emission guidelines set by the United States Energy Information Administration.[45]

The study uses a model of the levelized cost of expenses for various power plants to reach an external, monetary cost impact of emissions. This process involves considering the particular gases emitted from power plants, in addition to their concentrations and the impacts they have in regards to climate change and the environment directly.[46] This results in a number that provides a more complete valuation of externality costs than most studies, as it considers factors other than just the effects of greenhouse gas emissions. The final number from this study is $37.69 2014 USD/mmBTUs.

5.5 Conclusion

There are a number of notable externalities that are not included in this valuation. One of these is the impact natural gas use has on terrestrial, freshwater, and marine ecosystems. The ExternE report, in addition to the larger body of literature, struggled to valuate these impacts as the data and assumptions of causality needed for this methodology ultimately limited its

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[45] Roth, Ian F., and Lawrence L. Ambs. "Incorporating externalities into a full cost approach to electric power generation life-cycle costing." Energy 29 (2004): 2126.
[46] Ibid. 2132.

defensibility.[47] In addition to the limitations of data, it is also incredibly difficult to isolate the effects natural gas use has on the environment, when the impacts on these ecosystems are comprised of various factors and sources.

Another major facet that is left out of this report is the direct effect of fracking. Fracking has grown rapidly in use in the United States over the past years; however, there is no reliable source of information to determine the externality costs associated with this process. Rousu details in a literature review that the vast majority of studies regarding the valuation of the external costs of fracking are heavily biased, due to the nature of their source and funding.[48] As a result, this report does not include any valuation regarding the process of fracking, as the risk associated with providing a biased number would lower the quality and defensibility of this study.

Given that these aforementioned externalities certainly exist, but cannot be included in this report due to data and methodology limitations, it is assumed that the value of natural gas externalities presented here is in fact a lower bound. This value is a minimum as the most conservative estimates from the previous sections have been used in this analysis.

Table 3: Externality Costs for Natural Gas in $USD/mmBTU

Externality	Cost
Occupational health (injuries and deaths involved in the extraction process)	3.96
Public health (respiratory infection and disease)	3.01
Emission effects (cost associated with climate change and other effects of emissions)	37.69
Total cost of externalities for natural gas	**$44.66**

[47] Holland, Mike, Paul Watkiss, and Jacquie Berry. "ExternE Externalities of Energy: VOl. 4 Oil and Gas." Brussels: European Commission, 1995, 329.
[48] Rousu, Matthew C., Dave Ramsaran, and Dylan Furlano. "Guidelines for Conducting Economic Impact Studies on Fracking." International Advances in Economic Research 21, 2015, 223.

Section 6: Biomass

6.1 Introduction

While there are many different forms of biomass (or organic matter) suitable for providing energy, Bates College currently uses manufactured wood pellets in houses on Frye Street. Timber, readily available in the Maine woods, is harvested and molded into pellets under heat and pressure; natural plant lignin holds the pellets together without glues or additives. Wood pellets contain roughly 7,750 BTU per pound. The pellets are burned in boilers to generate steam for distribution within the house's heating system.[49]

Wood pellet boilers are relatively simple systems: a typical installation includes a fuel storage silo with an auger system that delivers the wood pellets from the silo to the fuel hopper of the boiler. The wood pellets are fed from the fuel hopper through the fuel feed system into the combustion chamber. The combustion fan supplies air to the combustion chamber and the exhaust is ducted to the chimney through a port at the rear of the system. A wood pellet boiler takes more time to maintain and operate than a traditional gas, oil, or electric heating system. The weekly maintenance needed includes emptying the particulate containers, and monitoring control devices to check combustion temperature, stack temperature, and fuel consumption. Boiler operation settings and alarms, such as those that alert a problem with particulate matter buildup, must be checked as well. A study done by the Massachusetts Division of Energy calculated that on average a wood pellet boiler system equates to roughly 15-30 minutes per day of physical human maintenance over the entire heating season.[50]

Bates College uses an average of 40 tons of biomass wood pellets per year to heat Chase House and 18 and 20 Frye Street. Bates College would need 5,000 tons of biomass wood pellets to power the College's central steam plant. Heutz Pellet Systems, Bates' current supplier, procures timber from logging areas in the Maine woods and transports it to various pellet manufacturing buildings in the state. Wood pellets are most cost effective when the distance by road between the manufacturer, distributor, and customer is fewer than 50 miles.[51] Presently, the

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49 Massachusetts Division of Energy Sources. "A Reference on Wood Pellet Fuels & Technology for Small Commercial & Institutional Systems" *Biomass Resource Center*, 2007.

50 Rist Frost Shumway Engineering, P.C., "Colby College Biomass Boiler Plant Feasibility Study" September 12, 2008

51 Massachusetts Division of Energy Sources. "A Reference on Wood Pellet Fuels & Technology for Small Commercial & Institutional Systems" 2007.

Bates College biomass system satisfies this criterion. The wood pellets are delivered in trucks to an outdoor silo on Frye Street; the pellets are discharged from the silo and conveyed to the boiler as needed, using automatically controlled augers to provide the right amount of fuel to meet heat demand. Some particulate matter escapes through a chimney, while some collects inside the boiler.

Key externalities of biomass occur in extraction, transportation, and combustion. Extraction related externalities include greenhouse gas emissions from the logging machinery, and soil erosion. Transportation related externalities include the impacts of greenhouse gas emissions from trucking logs from the forest to Heutz Pellet Systems and then to Bates College. The primary combustion impacts are the health effects from particulate matter emissions.

The externality figures calculated should not be taken as absolute values due to uncertainty in calculations, and the existence of other externalities for which no monetary values have been estimated. However, the externality results included are considered to be accurate estimations of key social and environmental costs of biomass energy generation.

6.2 Public Health Effects

A key externality associated with the burning of wood pellets is the health effects caused by the particulate matter emitted during the combustion process. Most of the particulate matter produced by burning wood pellets is accumulated in the boiler, and can be disposed of in the environment without any negative effects. However, some nitrogen oxides, carbon monoxide, organic gases, and particulate matter does escape through the chimney and has adverse human health effects. Biomass academic research focuses on the externalities from particulate matter; effects of the other pollutants are considered negligible. Particulate matter has been linked to increases in respiratory issues such as asthma, heart disease, and certain cancers.[52]

The effects of particulate matter on public health are determined by means of the dose-response functions proposed by the ExternE Project.[53] The valuation methodology is derived

[52] Vollebergh, Herman. "Environmental Externalities and Social Optimality in Biomass Markets: Waste to Energy in the Netherlands and Biofuels in France." *Department of Economics, Tilburg University* 607-672: 2009.

[53] Ribera, S. da Silva et al. "Assessment of the externalities of biomass fuel cycles in Portugal, ExternE project Externalities of fuel cycles", *Centro de Estudos em Economica da Energia, dos Transportes e do Ambiente*, 1996.

from the confidence interval of the dose-response functions, but it can not be considered as a confidence interval for the value itself, as there are other uncertainty sources which have not been accounted for. Included in the externality calculation is the value of life, as the mortality effect dominates the results. In addition, the externality calculation does not consider the externalities associated with the nitrogen oxides, carbon monoxide, and organic gases emitted. It should be noted that only particulate matter emissions from power generation have been assessed, with the rest being considered negligible or too difficult to determine. While the study provides a range for the health affect valuations, in the interest of highlighting the difference between fossil fuels and renewables we only use the upper bound estimate in our externality calculation for renewables. Therefore, the above value should be considered a "worst case" estimate for the total health damages. The externality costs associated with the human health damages calculated by Sáez et al.were initially given in euros per kilowatt hour, which was then converted into United States dollars per British thermal unit.[54] The final monetary cost of the public health effects is $.15 2014/mmBTUs.

6.3 Soil Erosion

Numerous externalities arise from the environmentally disruptive extraction of lumber via logging operations. These include loss of nutrients, erosion, alkalinization of irrigated land, changes in the landscape and ecosystems, soil compaction, and loss of biodiversity. Ultimately the nature and magnitude of these impacts will be a function of how carefully larger scale, energy-dedicated biomass extraction is implemented. The value calculated by Sáez et al. is based on the assumption that the land is bare most of the rainy season, and that erosion of the area studied is quite significant.[55] The externality costs associated with the soil erosion environmental damages were initially given in euros per kilowatt hour, which is then converted into United States dollars per British thermal unit. We used the upper bound value for the range provided in the study.[56] The final monetary cost of soil erosion effects is $6.19 2014 USD/mmBTUs.

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[54] Sáez, Rosa M., Pedro Linares, and J. Leal. "Assessment of the Externalities of Biomass Energy, and a Comparison of Its Full Costs with Coal." *Biomass and Bioenergy* : 469-78.

[55] Sáez, Rosa M., Pedro Linares, and J. Leal. "Assessment of the Externalities of Biomass Energy, and a Comparison of Its Full Costs with Coal." *Biomass and Bioenergy* : 469-78.

[56] Sáez, Rosa M., Pedro Linares, and J. Leal. "Assessment of the Externalities of Biomass Energy, and a Comparison of Its Full Costs with Coal." *Biomass and Bioenergy* : 469-78.

6.4 Climate Change

The assessment of the climate change externality requires the determination of the net CO2 emissions of the whole biomass fuel cycle. These net emissions have been estimated to be zero, or even negative. However, the negative values are still controversial, since the role of biomass crops as carbon sinks has not yet been widely recognized. Thus, the value adopted here for the whole fuel cycle will be zero, as we assume that the carbon fixed in the soil will compensate the CO2 emissions of other fuel cycle stages. Therefore, it is considered that there is no damage due to global warming from the biomass fuel cycle.

The ExternE Project claims that the Biomass fuel cycle has net emissions estimated to be zero. However, when analyzing the methodology of the ExternE study it makes sense to calculate the social cost of carbon associated with the transportation of the lumber from the woods to the generator and then to Bates College. We have not included the externality costs associated with the emissions generated by the logging machinery because of the absence of academic research in this field. Without the calculation of the externality associated with lumber machinery emissions the value calculated is a more conservative estimate. We used the 5% discount rate for the social cost of carbon emissions, which is generally considered as a larger discount rate for the social cost of carbon. This suggests that the value calculated is the largest possible estimate for the climate change externality associated with the transportation of biomass. The monetary value for the social cost of carbon was $9.16 2014 USD/mmBTUs.

6.5 Conclusion

The biomass externality figures should not be taken as absolute values, because of the uncertainties involved, and the existence of other externalities, which cannot be valued. These unevaluated externalities include the impact of climate change from the emissions of the lumber extraction operations, the human health hazards from the non-measured pollutants emitted during the combustion stage, and logging workplace fatalities. With the omission of these externality values our externality calculations can be considered underestimates.

In spite of the uncertainties underlying the analysis, it appears, when externalities are taken into account, the values associated with biomass are significantly lower than #2 fuel oil and natural gas. Biomass has a total externality cost per mmBTU of $15.51 2014 USD, while the

#2 fuel oil and natural gas externality costs per mmBTU are respectively $146 and $44.70. The internalisation of these externality costs would mean that the market price for biomass energy should be significantly lower than #2 fuel oil and natural gas. Our results would imply that the demand for biomass energy should be larger than for natural gas and #2 fuel oil. However, the initial fixed cost of roughly $6 to $11 million for the construction of the biomass system is a true barrier for the increased implementation of biomass. [57]

Table 4: Externality Costs for Biomass in $USD/mmBTU

Externality	Cost
Public Health (Respiratory issues and mortality caused by particulate matter)	$.15
Soil Erosion (Value of lost soil from lumber extraction operations)	$6.19
Climate Change(Social Cost of Carbon in 2020, 5% discount rate)	$9.16
Total Cost of Externalities for Biomass	**$15.51**

Section 7: Renewable Fuel Oil

7.1 Introduction

Renewable Fuel Oil (RFO) is a wood-based oil material that can be combusted to produce heat energy. RFO comes from the processing of Rapid Thermal Pyrolysis (RTP); for more information about RTP see Appendix A. One of the leading companies developing RTP systems is Ensyn, a 20+ year old company that has been producing RFO more commonly known as the barbecue flavoring additive"liquid smoke." Within the past 5 years, Ensyn has ventured into the market of heating and energy systems, marketing the same liquid fuel for heating instead of food based additives. The energy content of RFO stands around 64,500 BTUs/gallon.[58]

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[57] The Stone House Group. "Bates College Utility Master Plan." 2010.

[58] Lupton, Steve. "Renewable Fuel Oil - A Commercial Perspective" *Technical Information Exchange on Pyrolysis Oil: Potential Renewable Heating Oil Substitution Fuel in New England May 9-10,* 2012, Manchester, New Hampshire

Due to its many advantages, RFO is gathering traction across multiple industries for heating and electricity as the treatment system is small-scale so it can be engineered in small warehouses, and the reaction to produce the fuel is simple.[59] One of the advantages to RFO is that the feedstock can come from any otherwise-wasted biomass cellulosic material. Normally, items like palm leaves, corn husks, or scrap branch material are wasted or composted. Instead, RTP technology gives this material a new purpose. RFO has the same chemical properties as conventional fuel oil, so it is easy to implement in most conventional dual fuel oil-natural gas boiler heating systems with little mechanical change.[60] RFO is a high energy content liquid fuel that possesses similar chemical properties to conventional fuel oil #4, and can thus be transported using current liquid fuel infrastructure with minimal changes. In the long term, this fuel may be an excellent alternative to current liquid fuel technologies and can play a role in helping shift the United States infrastructure off of fossil fuels.[61]

An additional advantage to RFO comes from the RTP chemical treatment process. Within the RTP chemical treatment process, the non-condensable gas leftover at the end of the treatment is recycled to provide lift for reacting the heated sand and dried biomass. Over time, as non-condensable gas increases in the anoxic system, the gas needs to be released. Ensyn uses this to their advantage by selling this excess gas to consumers. This gas can also be run through an afterburner to a steam turbine system to generate power for nearby towns and facilities.[62] A third purpose is the gas can be burned in a steam boiler and used to heat the plant facilities or nearby buildings.[63]

7.2 Climate Change

One of the leading research groups looking into the sustainability and externalities associated with RFO is Pacific Northwest National Research Laboratory (PNNL). The current

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[59] Hill, Jason, Erik Nelson, David Tilman, Steohen Polasky, and Douglas Tiffany. "Environmental, Economic, and Energetic Costs and Benefits of Biodiesel and Ethanol Biofuels." *Pacific Northwest Academy of Sciences*, 2006. http://www.pnas.org/content/103/30/11206.full.pdf.

[60] Greaker, Mads, Hoel, Michael, and Rosendahl, Knut Einar. "Does a Renewable Fuel Standard for Biofuels Reduce Climate Costs?" *Journal of the Association of Environmental and Resource Economists* 1 (2014): 337-363 http://www.jstor.org/stable/10.1086/678189

[61] Interview with Greg Gosselin, Director of North East Sales, Ensyn Technologies. November 22nd 2015.

[62] Townsend, DT. 2015. SRS Constructs New Efficient, Clean Energy Steam Plant In Support Of Presidential Initiatives. Ebook. 1st ed. Savannah River, South Carolina: United States Department of Energy. http://www.srs.gov/general/news/releases/NR2008_SteamPlant.pdf

[63] Ensyn Technologies LLC, *Unique, Patented and Proprietary* http://www.ensyn.com/technology/application/

literature states that the only major externality associated with RFO is during the transportation of the fuel from the treatment facility to the customer.[64] When RFO is burned in a boiler system, the emission byproduct gases include CO, NO_x and SO_x. However, these byproducts are in such small concentrations (0.013, 0.25, and 0.0002 parts per million) that they can be fully diluted through global chemical reduction reactions. This is further supported by the United States EPA as Ensyn Technology's patented RFO is certified as a renewable fuel source given meets all of the requirements of the Renewable Fuel Source Standards of 2013.[65]

Currently, RFO is transported from the closest chemical treatment facility to the customer via tractor trailer similar to how gasoline and other conventional fossil fuels are transported when not by pipeline. For Bates College, RFO will be transported from Ottawa Canada to Lewiston, Maine. In order to determine the externality associated with transporting RFO, some assumptions were made to find the final cost. Assumptions were based on legislation regarding weight of tractor trailers and the fuel efficiency of the average tractor trailer. The total number of gallons of RFO an 18-wheeler can carry from Ottawa Canada to Bates College is 6000 gallons and according to the EPA, an 18-wheeler traveling approximately 100 miles produces 75.54 metric tonnes of CO_2.[66] An additional externality found to be non-existent given current academic thought involved the char/ash byproduct produced during the chemical treatment process. It was found after additional research however that this byproduct can be used as a fertilizer in gardens as it is entirely composed of carbon.[67] There was an attempt to calculate the externalities associated with the harvesting and transporting of the cellulosic material, however there was minimal literature. It was concluded that this externality would not be calculated given if there was an attempt, the amount of assumptions required would lead to tremendous inaccuracies. Our final SCC value for RFO is $8.45 2014 USD/mmBTUs.

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[64] United States Department of Energy Information Administration."Levelized Cost And Levelized Avoided Cost Of New Generation Resources In The Annual Energy Outlook 2015." 2015. http://www.eia.gov/forecasts/aeo/pdf/0383(2015).pdf

[65] United States Environmental Protection Agency. "Renewable Fuel Source Standards 2013" http://www.gpo.gov/fdsys/pkg/FR-2013-08-15/pdf/2013-19557.pdf

[66] Environmental Protection Agency. "The Social Cost of Carbon." Data revised 2015.

[67] Steele, Philip., Puettmann, E. Maureen., Penmetsa, Kanthi, Venkata., Cooper, E. Jerome. "Life-Cycle Assessment of Pyrolysis Bio-Oil Production"*Forest Products Journal* Vol. 62 (2012): 326-335.

7.3 Conclusion

The RFO figures should not be taken as absolute values because of the uncertainties involved, and the existence of other externalities, which cannot yet be valued due to lack of literature. The potential externalities not currently valued in academic literature or research labs include harvesting secondary wood materials such as branches, and human health hazards from harvesting said wood materials.[68] With these externalities not included, the final calculations in this report can be presumed to be underestimates.

From our findings the values associated with RFO are much lower than natural gas and #2 fuel oil. This implies that the prices for RFO energy should be lower than those of energy from fossil fuels when these externalities are internalized, which could cause RFO to have higher demand than natural gas and #2 fuel Oil.[69] Furthermore, a recent press release stated that the EPA has given approval pursuant to Title 40 CFR Part 79 promulgated under the Clean Air Act, required for the sale of RFGasoline into U.S. Commerce. This same approval was given to Ensyn's RFDiesel product as well. In the long term, this means that Ensyn transportation vehicles will run on renewable gasoline and diesel products. By running on this new fuel, we can hopefully see a further decrease in the transportation externalities associated with RFO.[70]

Table 5: Externality Costs for RFO in $USD/mmBTU

Externality	Cost
Climate Change (transportation emissions, 5% discount rate)	$8.45
Total cost of externalities for RFO	**$8.45**

[68] Pimentel, David., Herz, Megan., Glickstein, Michele., Zimmerman, Matthew., Allen, Richard., Becker, Katrina., Evans, Jeff., Hussain, Benita., Sarsfeld, Ryan., Grosfeld, Anat., Seidel, Thomas. "Renewable Energy: Current and Potential Issues" Bioscience, 52 (2002): 1111-11120.

[69] Anju Dahiya, *Bioenergy: Biomass to Biofuels* (New York: Elsevia, 2014)

[70] Press Release "Ensyn Receives Key Regulatory Approval for its Renewable Gasoline Approvals now in Place for Ensyn's Renewable Diesel and Gasoline" http://www.ensyn.com/wp-content/uploads/2015/11/Part-79-Gasoline-Press-Release-as-Issued-rev.pdf

Section 8: Discussion

The findings presented here suggest that the market costs Bates College pays to consume energy fail to account for all costs associated with such consumption; energy consumption, particularly our dependence on fossil fuels, is likely higher than what is socially and economically efficient under an accurate cost structure. For #2 fuel oil and natural gas, the externality costs are 980% and 233% greater than the market costs, respectively. These substantial increases in cost reflect the severity of the externalities as well as a fossil fuel market failure, where costs to consumers do not mirror the complete costs of production. Even if the numbers presented in this report carry inaccuracies up to two orders of magnitude, including these costs still significantly alters the perception that fossil fuels represent the most economically efficient energy source.

Furthermore, externalities included here reflect only those for which monetary estimation techniques exist and have been well reviewed. Even though we have not estimated economic values for externalities that lack a vetted methodology, they still exact real costs locally and globally. Internalizing the externalities calculated here within the college's energy choice decisions would provide an opportunity to modify the current fuel source allocation in a way that takes into account all the environmental, economic, and social variables in play.

Given these findings, the RFO fuel source seems a more efficient option for the central steam plant than either fossil fuel, and (due to lower conversion costs of approximately $1 million 2014 USD versus upwards of $7 million 2014 USD), also more cost-effective than a wood pellet boiler.

Acknowledging the energy externality costs calculated here, and acting upon this information, can help Bates continue to nurture a community for "coming times," with citizens who value equality and positive change. Our energy choices have global consequences, yet these consequences occur due to choices at the institutional level. Initiating an open dialogue around the effects of our energy footprint supports a "commitment to responsible stewardship of the wider world."[71] Our aim in producing this research is to provide context and knowledge to make conversation possible and productive.

[71] Bates Mission Statement, 2015.

Annotated Bibliography

Amposah, Yaw Nana., Troldborg, Mads., Kington, Bethany., Aalders, Inge., Hough, Lloyd Rupert. "Greenhouse Gas Emissions from Renewable Energy Sources: A Review of Lifecycle Considerations" *Renewable and Sustainable Energy Reviews*. Vol 39 (1) 461-475

This paper reviews current understanding and estimates of life-cycle GHG emissions from a range of renewable electricity and heat technologies identified from the Scottish Government's 2020 route map for renewable energy, and discusses potential impacts associated with these emissions. The paper continues the discussion of life-cycle sources of carbon used in rapid thermal pyrolysis (RTP) and concludes that the burning of bio-oil produced from RTP is a clean, low-risk, and inexhaustible fuel source.

Association of Oil Pipelines. "Barrels Delivered by Transmission Pipeline." Data as of 2013. http://www.aopl.org/pipeline-basics/about-pipelines/

This information was used in conjunction with US DOT data on total accident costs to estimate the cost of damages per unit of crude oil transported through United States pipelines.

Bureau of Labor Statistics. "CPI Inflation Calculator." http://data.bls.gov/cgi-bin/cpicalc.pl

This tool was used to convert cost estimates from different reference years into 2014 $USD.

Centers for Disease Control Asthma Control Program. "Asthma's Impact on the Nation." National Center for Environmental Health.

This informational pamphlet from the CDC provides asthma-related summary statistics for the United States. Included is an estimate of the average yearly cost of care for asthmatic children, a value employed in calculating the externality costs of pollution-related public health impacts.

Centers for Medicare and Medicaid Services. "Visualizing Hospital Pricing." Data presented by Beehive Media. 2013. http://www.beehivemedia.com/dataviz/hospitalpricing/

This tool provides user-friendly results for the average cost of various medical services in the United States. The data were used to estimate the costs of different public health impacts, identified in the ExternE study, of energy production air pollution.

Cohen, Mark A. "Costs and Benefits of Oil Spill Prevention and Enforcement." *Journal of Environmental Economics and Management* 2 (1986): 167-188.

Cohen calculates the average cost per gallon of oil spills in excess of 100 barrels. He analyzes data on the costs of cleanup efforts provided by both oil companies and government regulatory agencies in order to estimate the average cost of cleanup per gallon of oil for different sizes of spills. He also reviews *literature estimating the cost of environmental damages from oil spills. Due to a lack of sources for other types of costs such as non-use or losses in tourism, Cohen uses the losses of commercially valuable species, or those with a direct market price, as a proxy for environmental costs. In a decision to be as subjective as possible given our abilities as undergraduate students, we also only use the cost of cleanup and the cost of loss in commercially marketed species as our proxy of the annual, per-unit cost of oil spills within the oceanic boundaries of the United States.*

Environmental Protection Agency. "AP 42- Compilation of Air Pollutant Emission Factors Volume 1: Stationary Point and Area Sources." Office of Air and Radiation, 1995.
This EPA study lists the emissions factors of pollutants from various fuel types, and also discusses the relative effectiveness of common pollution control mechanisms. These data were used to estimate the emissions of particulate matter and sulfur dioxide resulting from the combustion of #2 fuel oil.

Environmental Protection Agency. "The Social Cost of Carbon." Data revised 2015. http://www3.epa.gov/climatechange/EPAactivities/economics/scc.html
EPA calculations of the Social Cost of Carbon, used to produce climate change-related externality costs of greenhouse gas emissions for the four fuel sources considered in this report.

Environmental Protection Agency. "Sulfur Dioxide." http://www3.epa.gov/airtrends/sulfur.html
Data from sulfur dioxide monitoring sites throughout the country. The most recent values recorded in Lewiston, Maine were used to calculate percentage increases in ambient sulfur dioxide air pollution as a result of the Bates central steam plant.

Friedrich, Rainer, Krewitt, Wolfram, Mayerhofer, Petra, Truchenmüller, Alfred, and Greβmann, Alexander. "ExternE Externalities of Energy: VOl.4 Oil and Gas." Brussels: European Commission, 1995. http://www.externe.info/externe_d7/?q=node/43
A wide-ranging and detailed study of externalities associated with the complete life cycle of oil-produced energy. This document has been widely referenced by academic scholars seeking to calculate the context-specific externality costs of many types of fuel sources. This study also provides the general externality categories which we include in our analysis of the externality costs for our four energy sources. In particular, the formulas provided for measuring pollution's impact upon agricultural production were used to estimate the costs of agricultural losses in the United States (with wheat as a proxy crop) from #2 fuel oil combustion pollution.

Fritsche, Uwe, Rausch, Lothar."Life Cycle Analysis of GHG and Air Pollutant Emissions from Renewable and Conventional Electricity, Heating, and Transporting Fuel Options in the EU until 2030" *European Topic Centre on Air and Climate Change*. 2009.

This paper continues to look at life cycle analysis of GHG and air pollutant emissions from renewable and conventional electricity, heating and transporting the available fuel sources in Europe. The LCA of this paper identifies the environmental impacts of entire networks of activity from start to end of the generation process.

Godoy, S.M., Mores, P.I., Santa Cruz, A.S.M., and Scenna, N.J. "Assessment of impact distances for particulate matter dispersion: A Stochastic Approach." *Reliability Engineering and System Safety* 94, (2009): 1658-1665.

This article provides results from a Gaussian Model of particulate matter (P) dispersion, run using a Monte Carlo simulation methodology to address uncertainty/differences in atmospheric conditions. This study supports the continued use of Gaussian-style models to estimate atmospheric dispersion of pollutants, particularly P and P. The estimate of the dispersion radius of P provided in this study was used to approximate the effect of P emissions from the Bates central heating plant on ambient air quality. The use of this study's findings is defensible because the Monte Carlo repeated simulations help produce an estimate more insensitive to changes in atmospheric variation.

Greaker, Mads, Hoel, Michael, and Rosendahl, Knut Einar. "Does a Renewable Fuel Standard for Biofuels Reduce Climate Costs?" *Journal of the Association of Environmental and Resource Economists* 1 (2014): 337-363 http://www.jstor.org/stable/10.1086/678189

This article addresses how renewable fuel emissions compare to emissions from fossil fuels. The research suggests that, even if renewable fuel oils produce non-negligible emissions, the amount is still much less than with fossil sources. As such, any level of transition to biofuels would reduce total GHG emissions. This article is helpful in addressing what the carbon emissions might be for renewable sources; they must be addressed in order to create consistent externality accounts for each energy source.

Hill, Jason, Erik Nelson, David Tilman, Steohen Polasky, and Douglas Tiffany. "Environmental, Economic, and Energetic Costs and Benefits of Biodiesel and Ethanol Biofuels." *Pacific Northwest Academy of Sciences*, 2006. http://www.pnas.org/content/103/30/11206.full.pdf.

This study measures the life-cycle environmental impacts of biofuels and expands the industry model to include total net emissions from biofuel combustion as well as production.

Holland, Mike, Paul Watkiss, and Jacquie Berry. "ExternE Externalities of Energy: VOl. 4 Oil and Gas." Brussels: European Commission, 1995.

http://www.externe.info/externe_d7/?q=node/43
The natural gas section of the ExternE report serves as the basis for the methodological process and numbers used for valuation in regards to this energy source. This study provides information regarding the various forms of externalities of natural gas use, covering a wide range of external market factors. The assumptions and scope of this paper require some fitting to the United States market, but overall the similarities amongst these instances are comparable and allow for defensible analysis.

Intergovernmental Panel on Climate Change "Climate Change 2014: Synthesis Report." Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 2014. 151 pp.
Basic data from the Intergovernmental panel on Climate Change regarding human causes of climate change and the impacts of greenhouse gas emissions. This source provides the background for our discussion of the social cost of carbon emissions.

Jedynska, Aleksandra, Tromp, Peter C., Houtzager, Marc M.G., and Kooter Ingeborg. "Chemical characterization of biofuel exhaust emissions" *Atmospheric Environment* 116 (2015):172-182.
A scientific analysis of the composition of exhaust from burning biofuels. Worthwhile for calculating pollution/health costs.

Liu, J. Mauzerall, D.L., and Horowitz, L.W. "Source-receptor relationships between East Asian sulfur dioxide emissions and Northern Hemisphere sulfate concentrations." *Atmospheric Chemistry and Physics* 8, (2008): 3721-3733.
While primarily a case study of pollution emissions in East Asia, this study uses the MOZART-2 oxidant-aerosol model and provides some general conclusions on sulfur dioxide emissions pathways. Due to our lack of access to EPA and other professional pollution modeling tools, the estimate for the impact of emissions upon ambient sulfur dioxide concentrations in the atmosphere provided by this study served as our best estimate of the marginal increases in sulfur dioxide caused by emissions at Bates College.

Lupton, Steve. "Renewable Fuel Oil - A Commercial Perspective" *Technical Information Exchange on Pyrolysis Oil: Potential Renewable Heating Oil Substitution Fuel in New England* May 9-10, 2012, Manchester, New Hampshire
This presentation was given at the Technical Information Exchange on Pyrolysis Oil as part of the discussion to bring renewable fuel oil to steam boiler systems throughout New England. The goal of the exchange was to present the creation of a new LLC called Envergent Technologies which was a combination of Ensyn Renewables (Renewable Fuel Oil company) and UOP (a Honeywell Technologies company).

Massachusetts Division of Energy Sources. "A Reference on Wood Pellet Fuels & Technology for Small Commercial & Institutional Systems" *Biomass Resource Center*, 2007.

This report provided a summary of how a biomass wood pellet boiler is operated. The report also provided pertinent data to understanding the externalities associated with the biomass energy life cycle.

Nelson, Thomas P. "An Examination of Historical Air Pollutant Emissions from US Petroleum Refineries." *Wiley Online Library,* 2012. DOI 10.1002/ep.11713.

Nelson documents levels of air pollution from oil refineries within the United States at an aggregate level. While the data is not specific enough to convert into estimates of pollution per unit of #2 fuel oil produced, this article substantiates our claim that there are other externalities beyond those that we calculate in this report.

Pierce, Mark. "Comparing Values of Various Heating Fuels." Cornell University, 1998.

This Cornell Extension resource provides the conversion factor for BTUs per gallon of #2 fuel oil, as estimated by the US Department of Energy. This conversion factor was used throughout the analysis of the externalities of #2 fuel oil to calculate costs in $USD/BTU.

Pimentel, David., Herz, Megan., Glickstein, Michele., Zimmerman, Matthew., Allen, Richard., Becker, Katrina., Evans, Jeff., Hussain, Benita., Sarsfeld, Ryan., Grosfeld, Anat., Seidel, Thomas. "Renewable Energy: Current and Potential Issues" Bioscience, 52 (2002): 1111-11120.

This paper looks at renewable energy technologies as well as the potential issues with running renewable energy systems. It concludes that if developed and implemented correctly, renewable energy could provide nearly 50% of US energy needs; this would require about 17% of US land resources. The paper also discusses land resource requirements and total energy inputs for construction of facilities that produce 1 billion kilowatt-hours of electricity per year.

Ribera, S. da Silva et al. "Assessment of the externalities of biomass fuel cycles in Portugal, ExternE project Externalities of fuel cycles", *Centro de Estudos em Economica da Energia, dos Transportes e do Ambiente*, 1996.

The study performed by ExternE provides further depth of knowledge into the externalities associated with Biomass. The study also provides the biomass externality values for human health hazards and soil erosion.

Rist Frost Shumway Engineering, P.C., "Colby College Biomass Boiler Plant Feasibility Study" September 12, 2008

The study provides insight into Colby College's new wood fired biomass boiler plant. Rist Frost Shumway Engineering, P.C. was the the hired engineering consultant by Colby College to provide a final cost *benefit feasibility study. This report will allow us to apply the possible costs and benefits of adding a potential fired biomass boiler plant at Bates College.*

Roth, Ian F., and Lawrence L. Ambs. “Incorporating externalities into a full cost approach to electric power generation life-cycle costing.” Energy 29 (2004): 2125-2144.
This article provides a strong methodological approach to calculating the life-cycle costs of natural gas emissions from energy production. Accounting for the complete range of relevant greenhouse gases and encompassing a scope that fits the assumptions of this project, this article provides information that is critical to the natural gas externality valuation.

Rousu, Matthew C., Dave Ramsaran, and Dylan Furlano. “Guidelines for Conducting Economic Impact Studies on Fracking.” International Advances in Economic Research 21 (2015): 213-225.
This studies provides an analysis of the economic impact of fracking literature. The study concludes that the majority of these papers are generally “consulting” type papers that have some form of bias, and as a result there are few if any resources available that provide an accurate valuation of the externalities associated with fracking.

Sáez, Rosa M., Pedro Linares, and J. Leal. "Assessment of the Externalities of Biomass Energy, and a Comparison of Its Full Costs with Coal." *Biomass and Bioenergy* : 469-78.
This study provides a biomass specific externality valuation, and follows the methodology of the ExternE project. It can almost be regarded as an extension of the ExternE project.

Steele, Philip., Puettmann, E. Maureen., Penmetsa, Kanthi, Venkata., Cooper, E. Jerome. “Life-Cycle Assessment of Pyrolysis Bio-Oil Production”*Forest Products Journal* Vol. 62 (2012): 326-335.
This report accounts for a significant amount of the externalities associated with the processing and treatment of bio-oil. This report has been produced as part of the Consortium for Research on Renewable Industrial Materials (CORRIM) Phase I reports on the life-cycle inventory and life-cycle impact assessment (LCIA) studies of biofuels.

The Stone House Group. “Bates College Utility Master Plan.” 2010.
This agreement summarizes the Bates call to action for carbon neutrality.

Townsend, DT. 2015. SRS Constructs New Efficient, Clean Energy Steam Plant In Support Of Presidential Initiatives. Ebook. 1st ed. Savannah River, South Carolina: United States Department of Energy. http://www.srs.gov/general/news/releases/NR2008_SteamPlant.pdf.

This is a specific case-study where a steam energy plant was converted from coal-powered combustion to renewable energy. This is a great article about installing a biomass powered steam plant in order to go clean/renewable. The project goals were to (1) improve energy efficiency and reduce greenhouse gases and, (2) implement renewable energy generation projects on agency property for agency use. As a result of the success of this project, the arrangement doesn't increase the SRS budget or annual cost of operating the facilities included in the project scope.

United States Coast Guard. "Pollution Incidents in and Around U.S. Waters, A Spill/Release Compendium: 1969-2011. Released December 2012. http://homeport.uscg.mil

These data on oil spills were used to calculate the average annual cost, per BTU of energy, of oil spill impacts within the United States.

United States Department of Energy Information Administration. "Glossary." 2015. https://www.eia.gov/tools/glossary/index.cfm?id=F.

Provides the official definitions used in governmental analysis or legislation regarding energy issues, such as what constitutes a complete "fuel cycle."

United States Department of Energy Information Administration."Levelized Cost And Levelized Avoided Cost Of New Generation Resources In The Annual Energy Outlook 2015." 2015 http://www.eia.gov/forecasts/aeo/pdf/0383(2015).pdf

This source discusses the levelized costs of energy from coal, oil, biofuels, solar and wind. Levelized costs function as a combination of O&M costs with construction costs. This is very relevant as we can look at the cost of building and maintaining a biofuel powered steam plant, or RFO powered steam plant. Additionally, we can examine the benefits and costs associated with other renewable energy options for reducing Bates' operational costs, such as solar and wind.

US DOT Pipeline and Hazardous Materials Safety Administration. "Pipeline Significant Incident 20 Year Trend." Data as of 9/25/2015. http://www.phmsa.dot.gov/pipeline/library/data-stats

This 20-year data series on pipeline accident-related property damage costs was used to calculate the average cost of property damage per BTU of crude oil transported. Since any source of crude oil can be refined into #2 fuel oil, this value was equals our externality cost for #2 fuel oil.

Vollebergh, Herman. "Environmental Externalities and Social Optimality in Biomass Markets: Waste to Energy in the Netherlands and Biofuels in France." *Department of Economics, Tilburg University* 607-672: 2009.

This paper provides the social cost benefit analysis that estimates both the private and environmental costs of a biomass market in Netherlands and France. The study will be used to cross reference the externalities found in the Netherlands to the current Bates College Biomass energy system.

Appendix A:

An In-Depth Description of the Chemical Process of RTP to Produce RFO:

The RTP reaction begins with wet biomass being fed into the treatment system from a large vat. As the material enters the first transport pipe, hot flue gas from the continuous RTP reaction is used to dry the wet biomass and pushes it down into a second vat. When the biomass enters the conversion vat, hot sand at approximately 900 to 1000 degrees Fahrenheit is released from the bottom of a sand reheater, pushes the biomass up a vent, and reacts with the biomass to make pyrolytic vapor. Unconverted biomass becomes a powder-like charcoal. It is important to distinguish this event as a reaction and not combustion as there is no oxygen present to combust the biomass. The sand and charcoal are separated from vapor stream in a cyclonic separator. The solid material is transferred back to the sand reheater. In the sand reheater, the charcoal is combusted in a bubbling bed to reheat the sand. Flue gas carries ash overhead to a collection system. After depositing the ash, the flue gas is reused to dry out more wet biomass. Clean, hot sand is transferred from the sand reheater back to the biomass converter. The pyrolytic vapors are then sent down a pipe fed into a condenser. In this vat, there is a copper coil pipe with cold water inside. When the hot pyrolytic vapors come into contact with the cool copper pipe, the heat is drawn out of the vapors and is liquefied. The water in the coil absorbs the heat and is piped out to a coolant system. The leftover condensed pyrolytic liquid is the final bio-oil product to be loaded and transported to the customer and used for various purposes.