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A cost-benefit analysis of a pellet boiler with electrostatic precipitator versus conventional biomass technology: A case study of an institutional boiler in Syracuse, New York

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Abstract

Background: Biomass facilities have received increasing attention as a strategy to increase the use of renewable fuels and decrease greenhouse gas emissions from the electric generation and heating sectors, but these facilities can potentially increase local air pollution and associated health effects. Comparing the economic costs and public health benefits of alternative biomass fuel, heating technology, and pollution control technology options provides decision-makers with the necessary information to make optimal choices in a given location.

Methods: For a case study of a combined heat and power biomass facility in Syracuse, New York, we used stack testing to estimate emissions of fine particulate matter ($PM_{2.5}$) for both the deployed technology (staged combustion pellet boiler with an electrostatic precipitator) and a conventional alternative (wood chip stoker boiler with a multicyclone). We used the atmospheric dispersion model AERMOD to calculate the contribution of either fuel-technology configuration to ambient primary $PM_{2.5}$ in a 10 km x 10 km region surrounding the facility, and we quantified the incremental contribution to population mortality and morbidity. We assigned economic values to health outcomes and compared the health benefits of the lower-emitting technology with the incremental costs.

Results: In total, the incremental annualized cost of the lower-emitting pellet boiler was $190,000 greater, driven by a greater cost of the pellet fuel and pollution control technology, offset in part by reduced fuel storage costs. $PM_{2.5}$ emissions were a factor of 23 lower with the pellet boiler with electrostatic precipitator, with corresponding differences in contributions to ambient primary $PM_{2.5}$ concentrations. The monetary value of the public health benefits of selecting the pellet-fired boiler technology with electrostatic precipitator was $1.7 million annually, greatly exceeding the differential costs even when accounting for uncertainties. Our analyses also showed complex spatial patterns of health benefits given non-uniform age distributions and air pollution levels.

Conclusions: The incremental investment in a lower-emitting staged combustion pellet boiler with an electrostatic precipitator was well justified by the population health improvements over the conventional wood chip technology with a multicyclone, even given the focus on only primary $PM_{2.5}$ within a small spatial domain. Our analytical framework could be generalized to other settings to inform optimal strategies for proposed new facilities or populations.

Keywords: biomass; combined heat and power; cost-benefit analysis; fine particulate matter

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1. Introduction

As many states in the United States (US) seek to increase the use of renewable energy to address climate change, biomass fuels such as wood pellets and wood chips have received increasing attention. For example, in New York State, the Clean Energy Standard requires 50% of electricity generation to come from renewable resources by 2030 (New York State, 2016). While this will largely be achieved by hydro, solar, and wind, biomass combustion qualifies provided that the facilities fulfill other permitting criteria, including air permitting requirements to ensure that local air quality does not violate standards set by state and local agencies and the US Environmental Protection Agency (EPA). Additionally, several states are beginning to include the renewable heating sector as well to meet greenhouse gas targets as part of their climate change mitigation strategies. At the same time, individual businesses and institutions are making choices between biomass and competing technologies, with the choices influenced by myriad factors such as fuel costs, fuel reliability, state and federal regulations, and renewable energy incentive programs.

However, biomass has higher particulate emissions than common oil-fired heating systems and the science regarding carbon neutrality is unsettled as life cycle carbon emissions depend on future sustainable forestry practices (Cornwall, 2017; Schulze et al., 2012). Biomass is often marketed to smaller commercial facilities that do not require permitting and/or stack testing, so performance criteria are often not monitored or are captured only at commencement of operations. Concerns exist about the impact of wood combustion emissions on ambient air quality that would be reduced with gas-fired or oil-fired boilers or eliminated using renewable heating technologies such as ground- or air-sourced heat pumps powered with zero-emission electricity resources such as wind or solar energy. While combined heat and power (CHP) systems can be more efficient than stand-alone electricity generating units, in a cold-weather setting, air quality concerns may be heightened for high-emitting CHP facilities given their greater use in the winter when atmospheric conditions such as strong radiational inversions may enhance the impact of primary pollutant emissions (Ries et al., 2009).

Making decisions about using biomass is challenging given the heterogeneous biomass fuels and technologies with different combustion designs. The moisture and ash content are two important characteristics of biomass fuels. Wood pellets typically have 7% moisture content or less, and low ash content. In contrast, moisture in wood chips varies significantly, with greater than 40% moisture content being common, and wood chips may have higher levels of ash. Both of these factors inhibit optimized combustion. Boiler combustion chamber designs may be simple or multi-stage with oxygen sensors and sophisticated computerized controls for optimization. The emissions profiles can vary by orders of magnitude depending on the fuel-technology combination and whether emissions control technology is used (Chandrasekaran et al., 2011). As a result, air quality and corresponding public health implications may also be highly variable. In addition, wood chips can come with and without bark. Bole chips, which include bark and have less desirable burn characteristics, are less expensive but have fine particulate matter ($PM_{2.5}$) emissions that would substantially exceed emissions from high quality pellets and increase emissions from wood chips without bark. In either case, emissions from wood chips are higher than fuel oil and other combustion fuels. Only by matching the correct fuel with the appropriate technology and emissions controls can systems operate with high efficiency and low emissions.

Federal emissions standards for new wood boilers only apply to larger (greater than 10 MMBTU/hour) facilities, so smaller facilities outside of non-attainment areas do not generally have permitting or stack testing requirements. Beyond standard permitting criteria, deciding whether individual facilities are optimally configured is further complicated by the importance of population patterns for public health impacts, including both population density and vulnerability attributes of the population. A more advanced emissions control technology or lower-emitting fuel-boiler technology combination or both may be necessary and cost-justified in one setting but not in another setting. These geographic complexities are heightened when considering facilities in urban environments, where population density is higher, surrounding buildings may influence dispersion patterns, and baseline concentrations of $PM_{2.5}$ and other pollutants may be greater.

Evaluation of alternative technological options is often informed by health impact analyses and related cost-benefit analyses. While such analyses have been done for numerous federal regulations (US Environmental Protection Agency, 2011b; US Environmental Protection Agency, 2012; US Environmental Protection Agency, 2014) and other specific case examples (Driscoll et al., 2015; Fann et al., 2009; Levy et al., 2009), there have been few similarly detailed investigations of individual biomass facilities. This is largely because such analyses are either not required or require more time and effort than would typically be available, but also because of challenges in accurately characterizing emission rates, modeling pollutant fate and transport in complex urban settings where many current and potential biomass facilities are housed, and accurately quantifying incremental costs and benefits. While standard evaluation criteria for proposed new power plants rarely include a formal cost-benefit analysis to determine the plant fuel-technology-emissions control configuration, insight from specific case studies may inform future standards or criteria.

In this study, we focus on a case example of an advanced-technology CHP biomass system at the Gateway Center at the State University of New York College of Environmental

Science and Forestry (SUNY-ESF) in Syracuse, New York. As a relatively new facility funded in part by the New York State Energy Research and Development Authority (NYSERDA), significant stack testing was conducted to evaluate both efficiency and emissions performance, providing key input data for atmospheric dispersion modeling and subsequent health impact modeling. We also evaluated a counterfactual scenario, reflecting a conventional configuration that could have been deployed at SUNY-ESF. Parallel characterization of emissions for this conventional configuration was conducted, allowing for comparisons of the emissions rates and corresponding air quality and health effects, along with the incremental costs of the more advanced technologies. The Gateway Center is also located at a college campus and is immediately adjacent to a major sports arena and in close proximity to multiple university hospitals and residential dormitories, indicating the presence of multiple vulnerable populations with high population density at some points in time.

2. Methods

Cost-benefit analysis of alternative biomass technologies involves quantification of emissions for each of the fuel-boiler and emission control technologies under study, application of atmospheric dispersion models to determine the incremental contribution of modeled emissions to air pollutant concentrations, quantification of resulting changes in public health impacts given evidence from the epidemiological literature and data on population patterns, and monetization of health outcomes to compare with control costs (Figure 1). Below, we describe our approach and key assumptions for each of these analytical elements.

2.1. Biomass facility design and configuration

The CHP biomass facility was built to heat six buildings and provide electricity. It is located on the campus of SUNY-ESF, near multiple college campuses and a large indoor sports arena, with some of the sports arena air intakes in close proximity to the stack (Figure 2). SUNY-ESF designed its system to optimize efficiency and environmental performance consistent with its LEED Platinum Gateway Center building design. It includes a wood pellet-fired two-stage gasifier connected to an 8,000 lb/hour steam boiler, maximum rating of 9.6 MMBTU/hour input, with electrostatic precipitator (ESP) to control emissions of $PM_{2.5}$. While the system at SUNY-ESF is a CHP system, units such as these are more typically installed solely to meet thermal heating needs.

In addition to the wood-fired boiler, SUNY-ESF also installed two gas-fired boilers and several gas-fired microturbines with supplemental natural gas-fired boilers for peak and seasonal loads for wintertime heating. Based on discussions with operations staff at SUNY-ESF, the wood boiler units are assumed to operate on a baseload basis without diurnal or weekend/weekday fluctuations, while the gas-fired units respond to daily and hourly changes in demand over the baseload level. All emissions analyses focus exclusively on the biomass boiler; the gas-fired boilers are not included in the modeling analysis.

2.2. Emissions estimation

We modeled two different emissions scenarios. The first represented the technology as installed at the Gateway Center, using a staged combustion pellet boiler with an ESP, while the second represented a conventional configuration (a bole chip-fired stoker boiler with a multicyclone) that could have been selected at SUNY-ESF. For the installed technology, multiple stack testing campaigns were performed to characterize emissions. The emissions were measured using both an EPA Method 5/202 train and an EPA Conditional Test Method CTM-039 system. The CTM-039 permitted both on-line measurements and filter collection for off-line analysis similar to that reported elsewhere (Chandrasekaran et al., 2011).

For the installed pellet boiler system, the study team estimated an hourly $PM_{2.5}$ emission rate of 0.093 lb/hour for peak load and 0.068 lb/hour at reduced load based on a measured emission factor of 0.011 lb/MMBTU. Data from stack testing at a high school in Vermont, a similarly-sized boiler, were used as the basis for estimating wood chip-fired stoker boiler emissions (Rector et al., 2013). For the wood chip-fired boiler, the measured emission factor of 0.28 lb/MMBTU resulted in an hourly emission rate of 2.68 lb/hour during peak load and 2.04 lb/hour during reduced load. In both cases, we assumed that the unit was operating at peak load during January and February (7,000 lb/hour steam output), at reduced load during November-December and March-April (5,000 lb/hour steam output), and with no operation May-October, consistent with ambient temperatures in Syracuse.

2.3. Stack parameters

The stack height on the ESF system is 55 feet (17 m). Other stack parameters such as stack diameter, exit gas velocity and temperature for the installed system were based on measurements collected during stack testing at high and medium load levels in March 2015. For the wood chip-fired stoker boiler, the stack diameter, gas temperature and gas velocity were based on test results at the 60% load level (the maximum tested given the size of the installed system) from the Vermont school. The stack height was assumed to be identical to the ESF system.

2.4. Atmospheric dispersion modeling

While multiple atmospheric dispersion models were utilized in an overall evaluation of near-field pollution patterns, we focused on the use of AERMOD, a steady-state Gaussian plume model with widespread use in regulatory air dispersion modeling per EPA guidance (40 CFR 50 Appendix W), though we briefly discuss key differences and similarities with outputs from CALPUFF and SCICHEM, which are both Lagrangian puff models. The study team relied on 1-minute resolution surface meteorological data (processed to hourly resolution using AERMINUTE) from Syracuse Hancock International Airport for 2010 through 2014 and concurrent hourly upper air radiosonde data from Buffalo, New York, as processed by the New York State Department of Environmental Conservation (NYSDEC) using AERMET version 14134.

We established a dense receptor grid given interest in near-field dynamics, with a nested grid consisting of 10 m resolution on the university campus, 70 m resolution out to 500 m, 250 m resolution out to 3 km, and 500 m resolution out to 5 km. We used 1/3 arc-second (10 m) national elevation dataset (NED) terrain data available from the US Geologic Survey (USGS) to establish receptor elevations using AERMAP version 11103. We used BPIP-PRIME version 04274 to derive values for use in building downwash estimation and AERMOD version 14134 for dispersion modeling.

2.5. Health impact modeling

To quantify the health implications of the two alternative emissions profiles, we used standard health impact assessment modeling approaches (Fann et al., 2012), in which health outcomes attributable to incremental emissions are a function of the baseline incidence rate, the number of exposed individuals, the concentration-response function derived from the epidemiological literature, and the change in air quality to which the individuals are exposed. Given available atmospheric dispersion modeling outputs as well as significant interest in near-field populations, we focused on health effects from primary $PM_{2.5}$ emissions within the 10 km x 10 km grid characterized using AERMOD. While the literature shows a far greater geographic scale of impact and contribution from secondarily-formed $PM_{2.5}$ for power plant health impacts (Penn et al., 2017), this focused framework allowed us to more robustly characterize spatial patterns of health impacts and to be responsive to local population concerns about the health implications of biomass power or heating facilities within their communities. Moreover, if the lower-emitting technology had benefits exceeding the costs even when omitting secondarily-formed $PM_{2.5}$ or longer-range effects from primary $PM_{2.5}$, then it would clearly be justified when considering the total health impacts.

We used the basic platform of EPA's BenMAP-CE tool (v. 1.1), including key data inputs and the computational framework. BenMAP is an open-source program used to quantify the health impacts of changes in air quality, and it includes databases of concentration-response functions, population attributes, and economic data. We derived concentration-response functions independently and conducted all calculations external to BenMAP (using SAS and ArcGIS) given the high-resolution and small-scale modeling domain.

We considered an array of health outcomes commonly included in regulatory analyses (US Environmental Protection Agency, 2011b; US Environmental Protection Agency, 2012; US Environmental Protection Agency, 2014) and which have been shown previously to contribute significantly to monetized health impacts. This includes premature mortality, acute myocardial infarctions (heart attacks), respiratory and cardiovascular hospital admissions, minor restricted activity days, and lower respiratory symptoms. The concentration-response functions and the associated at-risk populations are described in Table 1. Age-specific population data were derived from the 2010 US Census with census block resolution. To align these data with the AERMOD concentration outputs, which had variable grid resolution not aligned with population datasets, we constructed a raster surface from AERMOD point outputs using inverse distance weighting and averaged all point estimates within a census block.

2.6. Cost-benefit analysis

To monetize the incremental health benefits of moving from the wood chip-fired stoker boiler with multicyclone to the pellet boiler with ESP technologies, we used standard approaches within BenMAP-CE to assign monetary values to health outcomes. Premature mortality was valued at \$6.3 million in year 2000 dollars based on a synthesis of 26 value-of-life studies. After adjusting for inflation and real income growth, this corresponds with a value of statistical life (VSL) of \$10 million in year 2015 dollars and income levels. As done by EPA (US Environmental Protection Agency, 2011a), we applied a discount rate of 3% and assumed a mortality lag structure of 30% reductions in the first year, 50% reductions over years 2-5, and 20% over years 6-20.

Acute myocardial infarctions have age-specific costs given differences in opportunity costs (lost earnings as a function of age). We scaled direct medical costs to year 2015 using the consumer price index for medical care, yielding a direct cost value of \$190,000, and we used age-specific opportunity costs with a 3% discount rate adjusted for inflation (\$12,000 for individuals age 25-44, \$18,000 for individuals age 45-54, and \$110,000 for individuals age 55-

65). Hospital admissions are valued based on cost of illness as well as the opportunity cost of a day spent in the hospital. Adjusting for inflation, cardiovascular hospitalizations for individuals age 65+ are valued at $43,000 in 2015 dollars, while respiratory hospitalizations for individuals age 65+ are valued at $36,000. Minor restricted activity days and lower respiratory symptoms are valued based on willingness to pay studies, with year 2015 values of $70 and $22, respectively.

To estimate the incremental costs of the pellet boiler with ESP technologies relative to the wood chip-fired stoker boiler with multicyclone, we relied on figures provided by NYSERDA and SUNY-ESF. The cost differences can be related to: 1) the cost of purchasing pellets vs. chips; 2) the cost of storage for pellets vs. chips, given differences in BTU value per ton; and 3) the cost of using ESP for pellets vs. a multicyclone for chips. For purchasing cost, we estimated a cost per delivered ton of $189 for pellets versus $40 for chips. To estimate tonnage utilization of each fuel, we used the estimated fuel input power at peak and reduced load, along with monthly utilization assumptions listed above and estimated combustion efficiencies of 8,200 BTU/lb for pellets and 4,785 BTU/lb for chips. For storage costs, the SUNY-ESF pellet-type bin hardware at the Gateway Center cost approximately $60,000, including hardware and installation. The analogous storage cost would have been approximately $240,000 for chips, given the greater tonnage and related increase in storage capacity. Further building cost differentials are omitted because of the complexity in accounting. Finally, we estimated that the ESP for the pellet boiler technology cost approximately $100,200 ($60,000 in direct cost with installation cost at 67% of the direct cost), while the multicyclone associated with the chip technology would have cost approximately $20,000. Any capital costs are amortized over 30 years at 3% discount rate to arrive at an annualized cost differential of approximately $190,000

($350,000 for the pellet boiler with ESP vs. $160,000 for the wood chip-fired stoker boiler with multicyclone).

3. Results

The modeled design values (i.e., concentrations consistent with the form of the National Ambient Air Quality Standards) resulting from primary $PM_{2.5}$ emissions from the CHP biomass plant alone are presented in Table 2. As anticipated given the factor of 23 difference in emission rates between the pellet boiler with ESP and wood chip-fired stoker boiler with multicyclone, there was a correspondingly large difference in incremental concentrations. Maps of the highest modeled 1-hour average $PM_{2.5}$ concentrations within 500 m of the source for the pellet boiler with ESP and wood chip-fired stoker boiler with multicyclone are shown in Figures 3 and 4, respectively.

In total, there was a correspondingly large difference in the health impacts for the pellet boiler with ESP and wood chip-fired stoker boiler with multicyclone, albeit with small absolute impacts in both scenarios (Table 3). Given the high-resolution $PM_{2.5}$ concentration data and the location of the biomass system on a college campus, we were interested in exploring variations in spatial patterns of health impacts across health outcomes. For example, two census tracts (4301 and 4302) contain most of the college campus, with approximately 5% of the total population in the 10 km x 10 km domain. 87% of the individuals living in these census tracts are between the ages of 18 and 24. For lower respiratory symptoms, given the focus on children age 7-14, only 1% of the domain-wide health impacts are found in these two census tracts. At the other extreme, for minor restricted activity days for individuals age 18-64, 32% of the domain-wide health impacts are found in these two census tracts. For health outcomes dominated by older individuals, including mortality, acute myocardial infarctions, and hospital admissions, 5-6% of health impacts are found on campus. Although a smaller proportion of the population is age 65 or older (3% in the two census tracts on campus, versus 12% across the domain), incremental $PM_{2.5}$ exposures are correspondingly higher.

Some of the spatial complexities of the outputs are illustrated in Figure 5, which focuses on incremental impacts from the wood chip-fired stoker boiler with multicyclone (given that relative spatial patterns are nearly identical for the pellet boiler with ESP). Incremental concentrations of annual average $PM_{2.5}$ attributable to the wood chip-fired stoker boiler follow predictable spatial patterns, given prevailing winds generally from the west/northwest and some tall buildings (including a major sports arena) immediately downwind with corresponding downwash effects. For health outcomes, the incremental contribution of the power plant within a census block depends on the number of at-risk individuals, the baseline disease rates, and the incremental concentration. As a result, while for minor restricted activity days the census blocks contributing the most to health impacts are in close proximity to the power plant, the patterns for premature mortality are more complex with many of the higher total risk values occurring away from the campus (Figure 5).

In total, when economic values are assigned to the incremental health impacts in Table 3, the pellet boiler with ESP has an annual health impact approximately \$1.7 million smaller than the wood chip-fired stoker boiler with multicyclone. Over 99% of the monetized health impacts are attributable to premature mortality. Given the incremental annualized cost of the pellet boiler with ESP technologies of \$190,000, this implies that benefits greatly exceed costs (benefit-cost ratio of 9.7), even with the limited focus on primary $PM_{2.5}$ within a small spatial domain.

4. Discussion

Our modeling indicates that the near-field primary $PM_{2.5}$ health impacts for a CHP biomass plant are small in this geographic setting under two different configurations, but that the relative differences in emissions are substantial and that the incremental investment in a lower-emitting configuration is justified by the incremental health benefits. This is predominantly because of the significant contribution of $PM_{2.5}$-related premature mortality to monetized health impacts, raising the question of the degree of uncertainty in that value, for which we only reported a central estimate given the challenges in formally quantifying and propagating all sources of uncertainty. Although there are numerous sources of parametric uncertainty, there are three broad sources of uncertainty that could be large enough to influence our benefit-cost conclusions – whether health effects are observed at ambient concentrations typically found in the geographic domain of interest, whether the effects of ambient $PM_{2.5}$ are identical to the effects of biomass-related primary $PM_{2.5}$, and whether the economic value assigned to premature mortality is robust.

On the first question, at an ambient air quality monitoring station in East Syracuse (approximately 5 miles from the biomass CHP plant), design value concentrations of $PM_{2.5}$ were 6.8 $\mu g/m^3$ (annual) and 18 $\mu g/m^3$ (24-hour) in 2015 (US Environmental Protection Agency, 2016). While this is well below the NAAQS (annual average of 12 $\mu g/m^3$, 98th percentile of 24-hour average 35 $\mu g/m^3$), recent epidemiological evidence indicates health effects at the level of exposure associated with current background levels in Syracuse (Crouse et al., 2012; Shi et al., 2016). On the second question, while there has been little direct research on health impacts of biomass plants, evidence indicates that wood smoke may have greater inflammatory potential than other $PM_{2.5}$ sources (Kocbach et al., 2008; Naeher et al., 2007). A review article concluded that there is no evidence that exposure to wood smoke is less harmful than exposure to fossil fuel combustion (Sigsgaard et al., 2015). Economic valuation is clearly uncertain, but our estimate of VSL is in the middle of the range of values reported in literature reviews (approximately between \$2 million and \$20 million) (Viscusi, 1992), and the incremental benefits of the pellet boiler with ESP technologies relative to the wood chip-fired stoker boiler with multicyclone exceed the incremental costs for any VSL in that range, even with the exclusion of regional impacts and secondarily-formed $PM_{2.5}$. Thus, while uncertain, our assumptions are reasonable and consistent with standard health impact assessment practice, and our conclusions are robust.

Although uncertainty in emissions estimation or atmospheric modeling outputs would not likely be sufficient in magnitude to influence our benefit-cost conclusions, multiple sources of uncertainty should be acknowledged. There was some uncertainty for the pellet boiler emissions given indications that the system was not optimized when stack testing was conducted (i.e., an incorrectly calibrated induction fan that led to higher emissions than designed). For the wood chip-fired stoker boiler, a database of testing results demonstrates that emissions can be highly variable between similar units in different locations, indicating that the results from the Vermont school boiler may not perfectly match a hypothetical installation at SUNY-ESF. For atmospheric dispersion modeling, we applied the models CALPUFF and SCICHEM to the identical sources using the same basic assumptions. While we did not conduct analogous health impact modeling with the CALPUFF and SCICHEM outputs, a comparison of concentration surfaces illustrates that AERMOD had lower 24-hour and annual $PM_{2.5}$ impacts than CALPUFF or SCICHEM. Thus, although AERMOD is typically considered to be a conservative atmospheric dispersion model, there is no evidence that the use of AERMOD led to a systematic upward bias in $PM_{2.5}$ concentrations and resulting health impacts.

Our modeling was focused on a very small geographic domain relative to standard practice in health impact assessment, with consideration only of primarily emitted $PM_{2.5}$. We selected the small modeling domain to focus on near-field impacts given a relatively small facility with a relatively short stack. This clearly led to a systematic underestimate of the differential health implications of the two alternative power plant configurations. The geographic focus leads to other limitations and uncertainties, although it also provides some novel insights. For example, standard health impact assessments rely on the assumption that the ambient concentration at the residence is a good surrogate for exposure to pollution of ambient origin, with a focus on air pollutants with more limited small-scale spatial variation and on populations in larger geographic aggregates. For a pollutant varying significantly over space and time, these assumptions may be called into question, especially for a near-field collegiate population that may have distinctive diurnal and seasonal activity patterns. The presence of a large sports arena with a capacity of nearly 50,000 implies short-term increases in population that could appreciably influence population exposure patterns if sporting events were aligned in time with short-term concentration peaks, although indoor concentrations attributable to the CHP biomass plant would be anticipated to be less than ambient given ventilation systems for the sports arena. Relatedly, the AERMOD outputs indicate that the CHP biomass plant contributes to a number of 1-hour peaks that are more modest on a daily or annual average basis, but there is no robust epidemiology of sub-daily exposures to $PM_{2.5}$ that would indicate health effects differential from longer-term averages. Finally, in terms of the economic analysis, we only included a subset of the potential costs that may differ between the two configurations. For example, pellet boilers could have higher maintenance costs over time, as some of the component parts are more expensive to replace. That said, we included the typical drivers of incremental costs, and our model could be updated easily to accommodate new economic insights.

In spite of these limitations, our modeling offers some important insight about strategic directions for evaluation of biomass CHP facilities. First, our study reinforced the large differences in emissions across alternative biomass fuels and boiler-emission control configurations. While this is well established, there are often appreciable differences between emissions factors and site-specific performance, and our detailed stack testing helped to develop robust emissions characterizations. Our modeling also emphasized that even relatively small absolute public health benefits of emissions controls or lower-emitting fuel-boiler technology combinations may be cost-justified, reinforcing the value of the cost-benefit analytic framework. While geographically focused health risk modeling limited our ability to fully characterize health benefits, highly spatially resolved modeling can also allow for targeted interventions beyond emissions control strategies, such as improved filtration/ventilation in specific buildings that may experience higher direct impacts from facility emissions. For example, a computational fluid dynamics (CFD) model applied at this site determined elevated $PM_{2.5}$ concentrations at the rooftops and windward façades near the CHP facility, even though the concentrations at the ground level were very low (Tong et al., 2017).

In general, individual facilities are rarely evaluated in terms of either their health impacts or the costs and benefits of alternative configurations. Larger power plants are subjected to rigorous dispersion modeling requirements to ensure that ambient air meets national and state standards, but companion health analyses are rarely conducted, and comparable analyses are not done for smaller facilities. While it would be impractical to conduct extensive emissions characterization, atmospheric dispersion modeling, and health risk assessment for all individual proposed biomass facilities, screening-level evaluations are viable. Studies have shown that health risks per unit emissions can be approximated based on a subset of simple population and source covariates; for example, variability in mortality risk per ton of primary $PM_{2.5}$ emissions from power plants in the mid-Atlantic US was readily explained by downwind population patterns (Buonocore et al., 2014). Life cycle analyses frequently use health damage functions that depend only on stack height and urban/rural setting (Humbert et al., 2011). Atmospheric dispersion modeling and health risk modeling for a selected number of biomass facilities in areas of differing population density, with varying stack heights and technologies, would provide the foundation for first-order estimates of mortality risk per ton from prototypical biomass facilities. These values could be used to either choose among technological alternatives or to determine the necessity of more refined modeling.

5. Conclusions

When making decisions among alternative electricity-generating, CHP or commercial heating system biomass facilities, the public health implications related to ambient air quality should be considered alongside greenhouse gas emissions, economics, and other factors. For a small-scale institutional biomass facility, our results indicated that the incremental benefits of moving to a lower-emitting biomass technology greatly outweighed the incremental costs. These findings would likely generalize to comparable biomass facilities located in urban areas, especially where near-field population density is high and includes a significant number of vulnerable individuals.

List of abbreviations

CHP = combined heat and power; EPA = Environmental Protection Agency; ESP = electrostatic precipitator; NYSERDA = New York State Energy Research and Development Authority; $PM_{2.5}$ = fine particulate matter; SUNY-ESF = State University of New York College of Environmental Science and Forestry; VSL = value of statistical life

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Figure 1: Analytical framework for cost-benefit analysis of alternative CHP biomass emissions scenarios.

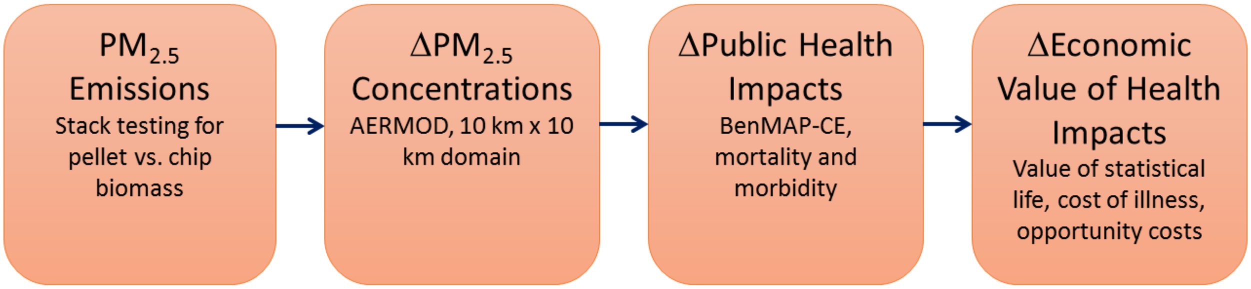

Figure 2: Location of the CHP biomass facility in Syracuse, New York.

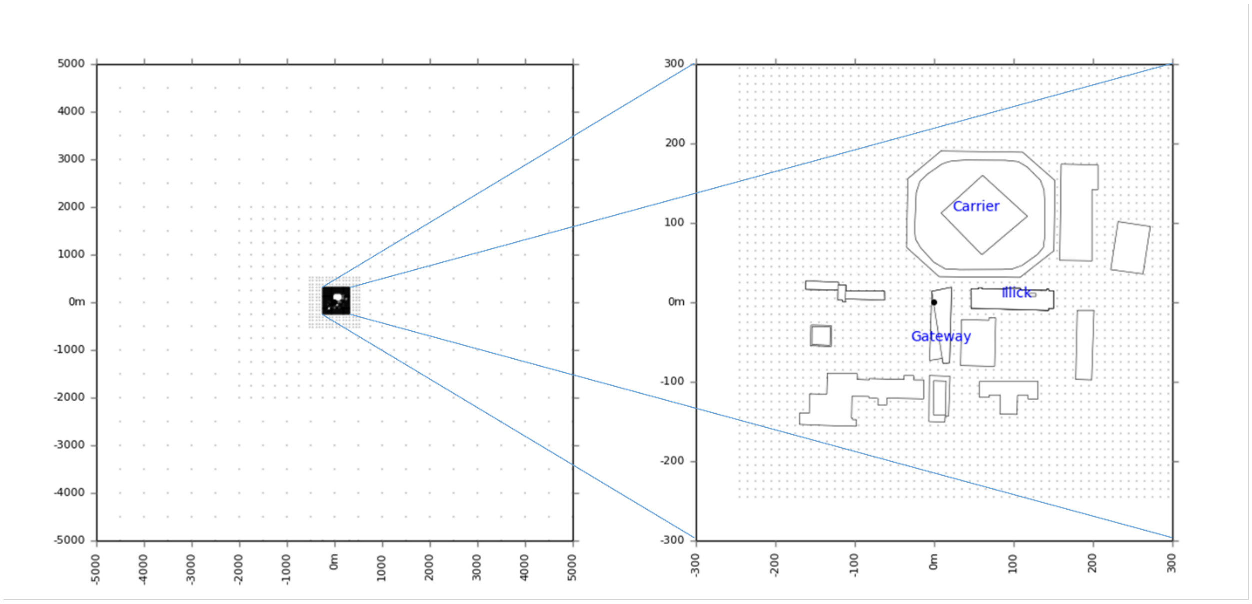

Figure 3: Modeled highest 1-hour average primary $PM_{2.5}$ concentrations associated with emissions from pellet boiler with ESP. Note: there is no National Ambient Air Quality Standard for 1-hour $PM_{2.5}$. Modeled buildings are identified by the outlined white areas. The location of the maximum concentration is marked with the + sign.

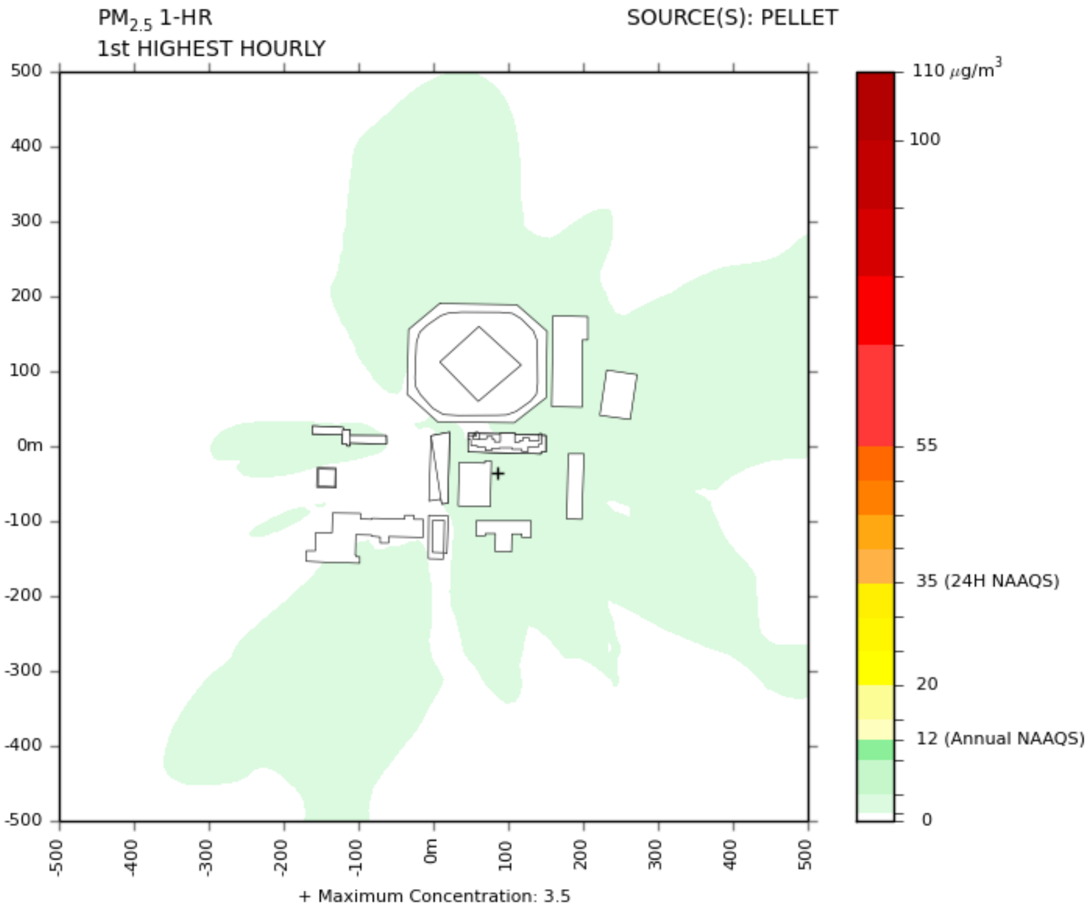

Figure 4: Modeled highest 1-hour average primary $PM_{2.5}$ concentrations associated with emissions from chip-fired stoker boiler with multicyclone. Note: there is no National Ambient Air Quality Standard for 1-hour $PM_{2.5}$. Modeled buildings are identified by the outlined white areas. The location of the maximum concentration is marked with the + sign.

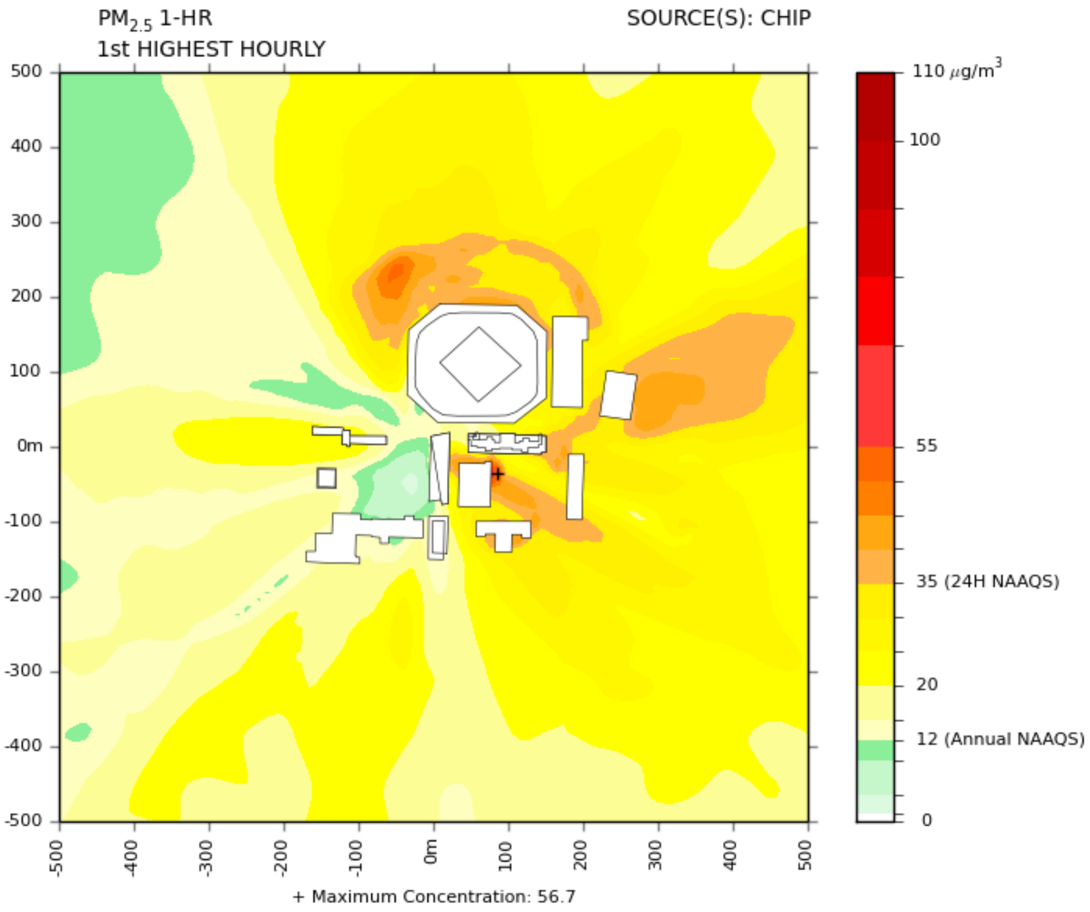

Figure 5: Spatial patterns of (a) total population, (b) incremental $PM_{2.5}$ concentrations, (c) minor restricted activity days/year, and (d) premature deaths/year associated with emissions from chip-fired stoker boiler with multicyclone.

Table 1: Concentration-response functions and population data for mortality and morbidity outcomes associated with $PM_{2.5}$ exposure

Outcome and supporting references	**Concentration-response function [a]**	**At-risk population**	**Baseline rate database**
Premature mortality (Krewski et al., 2009; Laden et al., 2006; Pope et al., 2002; Roman et al., 2008; Schwartz et al., 2008)	1%	Age 25+	BenMAP 2010, Onondaga County
Acute myocardial infarctions (Mustafic et al., 2012)	0.25%	Age 18+	BenMAP 2007, Onondaga County
Cardiovascular hospital admissions (Levy et al., 2012; Zanobetti et al., 2009)	0.1%	Age 65+	BenMAP 2007, Onondaga County
Respiratory hospital admissions (Levy et al., 2012; Zanobetti et al., 2009)	0.1%	Age 65+	BenMAP 2007, Onondaga County
Minor restricted activity days (Ostro and Rothschild, 1989)	0.7%	Age 18-64	Ostro and Rothschild, 1989
Lower respiratory symptoms (Schwartz and Neas, 2000)	2%	Age 7-14	Schwartz et al., 1994

[a] Percent increase in health outcome per μg/m^3 increase in $PM_{2.5}$ concentrations; central estimate derived from synthesis of cited references

Table 2: Modeled primary $PM_{2.5}$ concentrations ($\mu g/m^3$) from the CHP biomass plant

Averaging time	National Ambient Air Quality Standard	Chip-Fired Stoker Boiler with Multicyclone	Pellet Boiler with ESP
24-hour	35	11.0	0.5
Annual	12	2.2	0.1

Table 3: Annual health impacts attributable to primary $PM_{2.5}$ emissions from the CHP biomass plant within the 10 km x 10 km AERMOD receptor region.

	Pellet boiler with ESP	Chip-fired stoker boiler with multicyclone
Premature mortality	0.0085	0.20
Acute myocardial infarctions	0.00043	0.010
Cardiovascular hospital admissions	0.00057	0.013
Respiratory hospital admissions	0.00052	0.012
Minor restricted activity days	7.6	170
Lower respiratory symptoms	0.10	2.3