2015 Project Abstract
For the Period Ending June 30, 2017

PROJECT TITLE: Reducing Emissions from Open Burning through Biomass Gasification
PROJECT MANAGER: William Northrop
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FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2015, Chp. 76, Sec. 2, Subd. 07b

APPROPRIATION AMOUNT: $268,000
AMOUNT SPENT: $265,122
AMOUNT REMAINING: $2,878

Overall Project Outcomes and Results

Minnesota forests produce 2.4 million tons of wood waste per year, a significant portion of which is burned in open piles or in large-scale gasification facilities to generate heat and power. However, open burning wastes energy and emits harmful pollutants while large-scale power generation facilities rely on transporting fuel long distances. This project demonstrated that a small-scale distributed gasifier-generator system could produce heat and power for remote rural areas while reducing harmful pollution. In laboratory tests conducted at the University of Minnesota, the research team found that small-scale gasification emitted fewer pollutants like nitrogen oxides (NOx), soot, and carbon monoxide per amount of wood consumed than open burning and comparable emissions to large-scale wood energy operations. Further, due to clean engine combustion and production of biochar, small-scale gasification was found to achieve the lowest lifecycle greenhouse gas emissions compared to open burning, large-scale gasification and wood decomposition.

In the second phase of the project, the gasifier generator system was packaged into a weatherproof container and installed at the Minnesota Department of Natural Resources Southern Regional Office in New Ulm, MN. There it supplemented the facility's installed photovoltaic solar array on winter mornings, offsetting 10-15 kW of utility purchased power used to operate geothermal heat pumps. The system's performance at DNR supports small-scale gasification's potential for use in remote applications like state park facilities. Although promising when operational, excessive DNR staff time was required to regularly start and maintain the system, and prepare dry fuel. Other operational deficiencies included internal clogging and equipment failures. To be viable for further deployment, additional development work must be done to realize a more reliable and automated system. Ultimately, this project proved that small-scale distributed biomass gasification, if improved, could be an environmentally and economically favorable alternative to open burning and large-scale gasification.

Project Results Use and Dissemination

To disseminate the results of the gasifier-generator emissions analysis, a graduate thesis explaining all elements of the project was completed. In addition, a paper emphasizing the applications and merits of distributed small-scale gasification using waste biomass was submitted to the journal *Biomass and Bioenergy*. Several tours were held at the DNR facility to showcase the gasifier offsetting the facility's electricity costs and to discuss the benefits and challenges of biomass gasification technology. Finally, power output data from the gasifier operating during winter months was published to the DNR's Energy Smart website http://www.dnr.state.mn.us/energysmart/.

Environment and Natural Resources Trust Fund (ENRTF)
M.L. 2015 Work Plan Final Report

Date of Report: September 15, 2017

Date of Next Status Update Report: Final Report

Date of Work Plan Approval: June 11, 2015

Project Completion Date: June 30, 2017

PROJECT TITLE: Reducing Emissions from Open Burning through Biomass Gasification

Project Manager: William Northrop

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Location: Minneapolis (Hennepin County), New Ulm (Brown County)

Total ENRTF Project Budget:		
	ENRTF Appropriation:	**$268,000**
	Amount Spent:	**$265,122**
	Balance:	**$2,878**

Legal Citation: M.L. 2015, Chp. 76, Sec. 2, Subd. 07b

Appropriation Language:
$268,000 the first year is from the trust fund to the Board of Regents of the University of Minnesota in cooperation with the Department of Natural Resources to characterize and promote distributed biomass gasification of wood waste as a means for producing renewable and sustainable energy in rural areas through a demonstration at the Department of Natural Resources regional office facility in New Ulm.

I. PROJECT TITLE: Reducing Emissions from Open Burning through Biomass Gasification

II. PROJECT STATEMENT:

Minnesota forests produce 2.4 million tons of wood waste per year. A significant fraction of that biomass is burned in open piles resulting in harmful pollution, generating unnecessary carbon dioxide emissions and wasting energy. The Minnesota DNR estimates that 35,000 tons of piled woody biomass was burned in Southwest MN this winter alone emitting approximately 128,000 tons of CO_2. ***This project proposes distributed gasification for combined heat and power as an alternative to open burning of wood waste in Minnesota.*** Large-scale, high efficiency gasification systems have been demonstrated in regions of MN with high agricultural intensity. However, large-scale gasification is too expensive for wood waste produced over a large geographic area due to collection and transportation costs. Large scale waste woody biomass heat and power systems also exist in concentrated metropolitan areas but again depend on transportation infrastructure to maintain low cost. Our hypothesis is that small-scale (less than 50 kW) gasification systems can produce energy from wood waste nearer to its source, improving the economics of gasification while reducing emissions of pollutants and reducing reliance on fossil sources of energy like propane that have high price fluctuation. State parks are ideal sites for distributed gasification due to their low energy use and remote location.

The three primary goals of our project are:

1) Quantify the pollutant emissions reduction potential of a reliable, small-scale, locally operated combined heat and power gasifier system operated on wood chips compared to open burning of the same quantity of biomass. Measured emissions will include nitrogen oxides (NOx); particulate matter (PM); light hydrocarbon emissions known as volatile organic compounds (VOCs); and aromatic hydrocarbon emissions including benzene, toluene and ethyl-benzene.

2) Estimate the carbon emissions reduction potential of small-scale gasification for distributed heat and power for remote applications like state parks and rural residences. CO_2 emissions will be measured from the gasifier system and equivalent carbon emissions avoided from fossil fuel burning will be calculated.

3) Publically promote the use of distributed gasification technology by demonstrating a 10 kW combined heat and power gasification system at a MN DNR facility and posting energy savings on the DNR's Energy Smart website (www.dnr.state.mn.us/energysmart/).

We will measure emissions from a donated gasifier-generator system from All Power Labs (APL) at the University of Minnesota (UMN) Engine Research Facility during the first year of the project. The system will then operate on dried wood chips in the DNR's Regional Office Facility in New Ulm, MN augmenting their newly installed photovoltaic array providing electricity during times of peak energy demand. These times correspond to winter heating during the day where electricity from the photovoltaic array is insufficient to power geothermal heat pumps. The gasifier-generator system will be returned to UMN at the end of the project for use in future research programs. This two-year program has the potential to have significant impact in Minnesota by illustrating the benefits of small-scale distributed gasification to avoid open burning of woody biomass while saving energy and reducing emissions.

III. OVERALL PROJECT STATUS UPDATES:

Project Status as of January 1, 2016: The gasifier-generator system from APL was purchased in late summer of 2015. The system was delivered to UMN in the fall of 2015 and was assembled by project staff in the TE Murphy Engine Research Laboratory. Project staff was also trained to use the gasifier system by APL employees. A life-cycle energy and emissions model for evaluating CO_2 and pollutant emissions was created. Data taken from experiments with the gasifier to be conducted in the Spring of 2016 will be used to create emissions factors for use in the model. The project team is on schedule to have all lab measurements from the gasifier taken by the end of June, 2016

Amendment Request (02/12/2016):

This request is to shift funds from the Equipment/Tools/Supplies budget category to the Capital Expenditures over $5000 category. This request is resulting from additional costs ($620) needed to ship the gasifier-generator

unit from All Power Labs in Berkeley, CA to the UMN research facility. Shipping costs were originally to be waived by APL but internal budgetary constraints required that they pass the costs onto the project. The UMN accepted these costs after the invoice was received from APL. The additional $620 can be completely covered through multiple small cost reductions in the equipment and supplies budget for the project during Activity 1. **Amendment Approved: [03/21/2016]**

Project Status as of July 1, 2016: The APL gasifier generator system was fully instrumented and calibrated with a corresponding data acquisition system developed to track temperatures, pressures, flow rates, and emissions of the exhaust. The gasifier system was run on hardwood chips, but data collection could not be completed due to several delays. First, the laser gas analyzer used for measuring gaseous emissions needed repairs unexpectedly. Second, the feedstock's moisture content was higher than anticipated and needed to be dried before stable runs can be achieved. Data collection is still on track to be completed by the end of August.

Project Status as of January 1, 2017: Three full runs of data were collected and analyzed at the UMN laboratory. CO_2, CO, H_2, H_2O, O_2, N_2, total hydrocarbons, NOx, and soot emissions were measured and verified. Estimations of the carbon emissions compared to other biomass usage paths have been made. The final paper/thesis is in progress and will be fully completed in Spring of 2017. The gasifier-generator system has been installed in a mobile shelter, a grid tie module added for electricity production, a wireless data acquisition system installed, and has been moved down to its location at the New Ulm DNR office where it will be run to produce electricity in February of 2017.

Overall Project Outcomes and Results: Minnesota forests produce 2.4 million tons of wood waste per year, a significant portion of which is burned in open piles or in large-scale gasification facilities to generate heat and power. However, open burning wastes energy and emits harmful pollutants while large-scale power generation facilities rely on transporting fuel long distances. This project demonstrated that a small-scale distributed gasifier-generator system could produce heat and power for remote rural areas while reducing harmful pollution. In laboratory tests conducted at the University of Minnesota, the research team found that small-scale gasification emitted fewer pollutants like nitrogen oxides (NOx), soot, and carbon monoxide per amount of wood consumed than open burning and comparable emissions to large-scale wood energy operations. Further, due to clean engine combustion and production of biochar, small-scale gasification was found to achieve the lowest lifecycle greenhouse gas emissions compared to open burning, large-scale gasification and wood decomposition. In the second phase of the project, the gasifier generator system was packaged into a weatherproof container and installed at the Minnesota Department of Natural Resources Southern Regional Office in New Ulm, MN. There it supplemented the facility's installed photovoltaic solar array on winter mornings, offsetting 10-15 kW of utility purchased power used to operate geothermal heat pumps. The system's performance at DNR supports small-scale gasification's potential for use in remote applications like state park facilities. Although promising when operational, excessive DNR staff time was required to regularly start and maintain the system, and prepare dry fuel. Other operational deficiencies included internal clogging and equipment failures. To be viable for further deployment, additional development work must be done to realize a more reliable and automated system. Ultimately, this project proved that small-scale distributed biomass gasification, if improved, could be an environmentally and economically favorable alternative to open burning and large-scale gasification.

Amendment Request (09/15/2017):

This request is to shift $390 from the Equipment/Tools/Supplies budget category to the Professional/Technical/Service Contracts category. Services for the gasification system installed at the New Ulm facility slightly exceed budgeted costs because additional safety features were added to meet OSHA standards including a railing, harness and stairs with proper foot grip for icy conditions. The overall project budget remained $2,878 below projected costs.

IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Characterize Pollutant Emissions from Small-Scale Gasifier System

Description: In this task we will characterize the pollutant emissions from a 20 kW-electric Power Pallet gasifier-generator system donated to UMN by All Power Labs (APL), Berkeley, CA. The most recent generation of the Power Pallet from APL has been successfully installed in remote locations worldwide. The gasifier converts woody biomass to syngas, a gas containing high concentrations of hydrogen, methane and carbon monoxide. Syngas is easily combustible in spark-ignited engines and serves as the only engine fuel. An intermediate filtration system removes tars and other impurities from the syngas before being sent to the engine. However, the filtration system does not completely remove some impurities from the syngas. This activity will fully characterize the engine's ability to reduce regulated and unregulated compounds through combustion and to determine whether engine combustion generates additional pollutant emissions. Increasingly stringent emissions regulations on stationary boilers and generators necessitate understanding of whether biomass gasification systems can operate cleanly and safely in the locations where they are installed.

As part of Activity 1, the Power Pallet gasifier-generator will be initially installed at UMN's new T.E. Murphy Engine Research Laboratory (MERL). The MERL is equipped with an outside test cell ideally suited for testing gasifiers. The laboratory also has a full suite of emissions equipment readily available for the purposes of evaluating the system. Pollutant emissions to be measured include nitrogen oxides (NOx); particulate matter (PM); light hydrocarbon emissions known as volatile organic compounds (VOCs); and aromatic hydrocarbon emissions including benzene, toluene and ethyl-benzene. Pollutant concentrations will be measured at three locations in the gasifier-engine system; at the outlet of the gasifier reactor, the outlet of the syngas filtration system and the engine exhaust. Results from the testing will help to inform APL on how to optimize their system and will provide data for proving emissions reductions compared to open burning of woody biomass. Additional benefits from this task will be a set of procedures for testing pollutant emissions that can be later applied to other wood burning appliances in future projects or collaborations.

This task will also compile existing data concerning pollutant emissions from open burning of wood waste. Input will be sought by federal and state organizations on the study to determine the amount of woody biomass burned on a yearly basis and measured emissions from such fires. The scientific literature will also be searched for emissions factors per mass burned for open burning of different types of waste biomass. These data will be compared to the experimental results from the gasifier generator to be tested in this project.

Summary Budget Information for Activity 1:

ENRTF Budget: $ 124,925
Amount Spent: $ 124,750
Balance: $ 175

Outcome	Completion Date
1. *Measured NOx, volatile hydrocarbon, and particulate matter emissions from system*	12/31/2015
2. *Efficiency of gasifier-generator system with combined heat and power unit*	12/31/2015
3. *Comparison of emissions generated by gasifier-generator to open burning*	6/1/2016

Activity Status as of January 1, 2016: Due to the late delivery of the gasifier generator, emissions could not be measured from the unit in 2015. However, the unit was delivered and assembled. Staff were trained to use the system and emissions measurement instruments were gathered and calibrated for use in the project.

Activity Status as of July 1, 2016: A data acquisition system was created to measure emissions both after the gasifier component and after the engine exhaust. This system is capable of measuring: CO2, CO, H2, H2O, O2, N2, total hydrocarbons, NOx, and soot. Due to unexpected instrument failure and wetter than expected feedstock, data collected will not be completed until the end of the summer.

Activity Status as of January 1, 2017: Data was successfully collected the discussed emissions over a range of power levels from ~3 kW up to ~15 kW. The data was analyzed to create emission factors and system efficiency.

Practical considerations of running the system were noted. The final report is expected to be completed in Spring of 2017.

Final Report Summary: The gasifier-generator system was found to produce fewer pollutants and particulates than open burning for every kilogram of biomass consumed, but the system has low efficiency when generating power and requires extremely dry biomass to function optimally. An integrated 20kW gasifier-generator system manufactured by All Power Labs (APL) was delivered to the T.E. Murphy Engine Research Lab, where staff assembled the system and were trained in its operation. The gasifier-generator was fitted with a data acquisition system designed to collect pollutant emission information as a function of the generator's power output. The gasifier-generator was run on wood chips three separate times at four different loads and the data collected from these tests was used to characterize the system's emissions factors and efficiency.

Per kilogram of biomass consumed, 1.53 kg-CO_2, 11.3 g-CO, 8.7 g-CH_4, 2.4 g-NO_x, and 0.01 g-soot were produced on average. CO, CH_4, and NO_x concentrations generally increased with load as expected. Per kWh of electricity generated, 2.04 kg-CO_2, 30.3 g-CO, 18.6 g-CH_4, 5.0 g-NO_x, and 0.02-g soot were produced on average. The system's efficiency ranged between 4-10% with load changes. By mass, the gasifier-generator generated less CO_2, NO_x (at low loads), CO, and particulate matter than open burning. However, it did generate more CH_4 because the syngas produced by gasification and burned in the engine contained large amounts of CH_4 that was incompletely burned in the engine, especially at higher loads.

One valuable insight gained from collecting emissions data was the significant impact of the biomass' moisture content on system performance. The wood chips' moisture level ranged from 20-30%, yet even small increases in moisture decreased engine efficiency. CO levels increased with moisture because less of it was burned in the engine. Because of this incomplete combustion, engine temperatures were lower so NO_x emissions, which depend on temperature, decreased with increasing moisture. These trends suggest a tradeoff for gasifier-generators at high loads: using dryer biomass may increase efficiency but at the expense of more harmful NO_x production, illustrating a need for exhaust NO_x reduction treatment as gasifier-generator technology is improved.

Ultimately, measuring emissions from the gasifier-generator system demonstrated the potential for small-scale distributed gasification to produce heat and power while reducing harmful pollutants, although low system efficiency and susceptibility to moisture content currently inhibits the technology.

ACTIVITY 2: Quantify Carbon Emissions Reduction Potential from Biomass Gasification

Description: This task will quantify CO_2 emissions from the Power Pallet gasifier-generator system and use that data to estimate the savings possible when using the system as a replacement for propane and other fossil fuels. Biomass burning is renewable to the extent that additional fossil energy is not used in its harvesting, transport or processing. Wood waste generally is from forest thinning and logging activities and thus can be considered a byproduct of other operations. Burning wood in open piles emits CO_2 but does not use the heating value of the material to do useful work.

During this task, a complete energy balance of the Power Pallet will be completed taking into account both heat and electricity generated by the system. This information, in combination with the measured CO_2 emissions will be used to compare with both the CO_2 generated by open burning as well as the CO_2 emitted from other stationary generator fuels used in rural applications like propane or diesel fuel. From this collected information, a good estimation of carbon savings for biomass gasification compared to fossil power will be made and published in the open literature.

Summary Budget Information for Activity 2:

ENRTF Budget: $ 42,575
Amount Spent: $ 42,400
Balance: $ 175

Outcome	Completion Date
1. *Measured CO2 emissions from gasifier-generator system and energy balance*	12/31/2015
2. *Estimation of achievable carbon reductions based on fossil fuel savings*	6/1/2016

Activity Status as of January 1, 2016: Due to late delivery of the gasifier system, the CO2 emissions were not measured from the system in 2015. However, much progress was made on the lifecycle emissions model as part of Activity 2. The following is a summary of the modeling effort:

Background data on open burning and large-scale electrical generation has been researched to determine proper emissions ratios (gram of pollutant/kg of dry fuel). An in-depth estimator of emissions was created using the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model provided by Argonne National Laboratory. This model includes collection, transportation, and on site usage of the fuel to determine overall emissions. GREET also contains existing emissions factors for a steam boiler (ST), and an integrated gasifier combined cycle (IGCC) using forest residue fuel. This model was run for three separate cases: data from a real boiler, a GREET steam turbine, and a GREET integrated gasifier combined cycle. Initial results showed that the on-site NOx, PM, and CO emissions can be reduced, from the open burning case, by as much as 90%, 95%, and 99% respectively. On-site carbon dioxide emissions increased by about 6% as a result of more complete combustion (less CO and hydrocarbons remain in the combustion byproducts). Collection and transportation emissions were found to have little to no impact (0-5%) on all emissions with a maximum travel distance of 300 miles, suggesting that economic considerations are a larger issue than emissions with regards to transportation of biomass. While insufficient data on case-specific small-scale gasification could be retrieved, the emissions from the model provide a baseline that will be used for comparison as actual emissions data is collected in early 2016.

Activity Status as of July 1, 2016: Emission factors have not yet been gathered, as work has focused on creating the data acquisition system and ensuring the gasifier runs properly. Literature review was continued during this period. The model is ready to take the emissions factors gathered from the experiments.

Activity Status as of January 1, 2017: Emission factors have been created for CO2, CO, NOx, soot, and total hydrocarbons for comparison to other methods of biomass disposal for greenhouse considerations. Key results indicate small reductions in CO2 and large reductions in CO and soot emissions compared to open burning along with additional carbon sequestration potential from leftover biochar. Practical considerations of each disposal path have also been compared. The final report is expected to be completed in Spring of 2017.

Final Report Summary: The gasifier-generator produced the lowest CO_2 and soot emissions per kilogram of biomass consumed when compared to other pathways for biomass like open burning, in part because the system uniquely expels some of the consumed biomass' carbon as solid usable char instead of pollutant gas. Comparing the gasifier-generators carbon emissions to those of other biomass pathways required modeling said pathways and measuring data from the gasifier. First, the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model and other sources were used to establish baseline CO_2 emission values for common biomass usage pathways like open burning, residential usage, and decomposition. A data acquisition system fitted to the gasifier was used to collect carbon emissions data for comparison to these pathways and estimation of potential carbon reduction. The primary greenhouse gas emission from the system was carbon dioxide because it is the primary product of complete combustion.

Per kilogram of biomass consumed, 1.53 kg-CO_2 was produced on average. Per kWh of electricity generated, 2.04 kg-CO2 was produced on average. On a mass basis, CO_2 emissions did not show a clear trend with electrical load and only vary by about 15%. This observation was expected because regardless of the system's power output, the biomass it uses has a fixed carbon content that can only leave the system as exhaust gas, solid ash, or liquid tar. It was estimated that 2% of consumed biomass is converted into solid and liquid products. A decrease in CO_2 emissions at maximum load was noted, likely because incomplete combustion increased with load and caused some of the biomass carbon to be emitted as CO and CH_4 instead of CO_2. Unlike the mass basis, CO_2 emissions on an electricity basis decreased with increased power output. This trend likely occurred because at low loads, the system consumed more biomass than needed to supply the necessary power, causing excessive concentrations of CO_2.

Soot emissions were found to be more dependent on the quality of the syngas, the gas produced by the gasifier that is burned in the engine, than on power output. Low quality syngas is defined to have low concentrations of CO and H_2 and was observed at high loads. Average soot concentrations with high quality producer gas (with CO and H_2 concentrations above 10%) were typically 0.7 mg/kg of biomass. Soot emissions increased greatly when the gasifier used low quality syngas, and several spikes in soot levels were nearly 100 times higher than the standard operating soot concentration. On average, high soot levels were approximately 260 mg/kg biomass.

The gasifier-generator produced the lowest CO_2 and soot emissions by mass of all alternative pathways modeled, including decomposition and open burning, because unlike in the other pathways some of the biomass' carbon was released as solid char instead of exhaust gas. On an electricity production basis, the small-scale gasifier released more carbon emissions than its large-scale counterparts due its low efficiency. A comprehensive understanding of carbon reduction potential requires accounting for carbon emitted from processing and transportation of biomass. Large-scale plants continually require biomass from a large geographic area to maintain operation, while small-scale gasification requires less transportation because a smaller area is required to feed it. When including biomass preparation, small-scale gasifier CO_2 emissions range from 1.36-1.62 kg/kg of biomass, compared to 1.9 kg/kg biomass for large-scale systems.

Overall, small-scale biomass gasification shows promise in reducing CO_2 emissions while using biomass for heat and power, largely because of its unique capacity to convert some of the biomass' carbon into usable solid biochar rather than CO_2.

ACTIVITY 3: Demonstrate and Promote Distributed Gasification for Rural Applications

Description: In this activity, we will transport the Power Pallet gasifier-generator at the MN-DNR's Regional Office Facility in New Ulm and install the unit in an outbuilding to protect it from weather. A contractor will be hired to install the unit and perform the necessary electrical and plumbing connections to the DNR facility. The Power Pallet unit will be placed adjacent to a facilities maintenance garage and staff from the shop will run the unit during the winter of 2016/2017. Electrical energy will be used to power geothermal heat pumps during the day, supplementing the installed photovoltaic array at the facility. Heat will be provided to an adjacent building and electricity will be connected to the facility power.

The main purpose of this phase of the project is to demonstrate the feasibility of small-scale gasification systems in rural applications like state parks. A key outcome will be to understand the staffing needs for the unit in terms of refueling and maintenance required for such a system. DNR staff will operate the system and The UMN project team will monitor the unit both on-site and remotely using a data acquisition system to collect additional performance and emissions data.

Once the system is operational, the DNR will allow public access to the facility and publish energy generation data on their Energy Smart website. These outreach activities are a crucial part of the program to educate the public and government decision makers about the benefits of distributed gasification for combined heat and power.

Summary Budget Information for Activity 3:

ENRTF Budget: $ 100,500
Amount Spent: $ 97,972
Balance: $ 2,528

Outcome	Completion Date
1. *Installed gasifier-generator system and hookup at DNR*	9/1/2016
2. *Data from operating system updated on DNR Energy Smart Website*	12/31/2016
3. *Multiple tours and exhibits of installed gasifier-generator system conducted at DNR*	6/1/2017

Activity Status as of January 1, 2016: Nothing has been accomplished for Activity 3 during this period.

Activity Status as of July 1, 2016: Electrical installation for sending power back to electrical grid from installed gasifier-generator installed at the DNR New Ulm facility has been designed. The APL "grid tie" system will be

used to interface with the existing PV array. The design of the enclosure for the gasifier-generator has also been completed. The system will be installed in a purchased 10'x8' shipping container at the UMN MERL facility and shipped to New Ulm.

Activity Status as of January 1, 2017: The enclosure for the gasifier-generator system has been created through a contractor and the system has been moved to the New Ulm location. The enclosure includes a specially modified shipping container with roof access for loading wood chips. The grid tie module was installed on the gasifier-generator and all of the paperwork for connecting to the grid has been completed and approved. A new data acquisition system has been added to monitor the gasifier's status while off-site. Wiring the gasifier in New Ulm including underground boring and connections to the site grid connection have been completed. Final connections are to be completed the first week of Feb. The gasifier is expected to begin producing electricity on February 20th and will continue to do so for three months with the help of UMN staff. Power data will be collected using a special meter and reported to the DNR Energy Smart website. The key goal of the onsite testing will be to determine how the gasifier can supply power during early morning hours when the New Ulm facility's solar array cannot produce enough power for the geothermal heat pumps. This power is currently being purchased from the local power co-op. The geothermal heat pumps are expected to be running throughout the month of March, allowing adequate demonstration of the gasifier's capability to supplement the photovoltaic array.

Final Report Summary: While operating at the DNR facility in New Ulm, the gasifier-generator decreased the amount of purchased electricity by 10-15 kW, saving up to 30 kg CO_2 emissions per day and demonstrating a potential for gasification to help power remotely located buildings. The gasifier-generator system was installed in a 10'x8' shipping container modified for convenient refueling, electrical connection, and maintenance access. The contained system was transported to the DNR facility in New Ulm, where it was electrically tied to the facility's photovoltaic array and geothermal pumps. The data collection system used for emissions measurement at the UMN TE Murphy Engine Research Laboratory was modified for remote access. For three months, UMN and DNR staff operated the system as it powered geothermal pumps during morning hours when the photovoltaics alone could not do so. The DNR facility would normally purchase local power for the pumps, but the gasifier reduced the amount of purchased power by 10-15 kW each day. This reduction translated to a daily CO_2 emission reduction of 15 or 30 kg, depending on whether the purchased power was generated by a natural gas or coal plant, respectively.

On sunny days, the photovoltaic array could provide necessary power more quickly so the gasifier only had to be run for five hours. However, the gasifier could run for longer time periods, implying its benefit to local facilities on cloudy days. The gasifier-generator's power output data during these three months was reported to the DNR's Energy Smart website for public access and promotion of the gasifier system. In addition, multiple tours of the system were held to show the gasifier's operation firsthand.

While demonstration of the gasifier in New Ulm showcased its potential for energy production in rural areas and state park facilities, it also revealed significant issues with the system's daily operation and long-term reliability. Daily startup of the system required 20-30 minutes depending on the moisture level of the biomass. After shutdown each day, accumulated ash, biochar, and water needed to be removed from the system. Every two weeks, the syngas filter media required replacement and tar buildup needed to be removed from all components leading up to the filter. Also, if not regularly cleaned the heat exchanger entirely clogged and prevented operation. In total, maintenance could take more than four hours, whereas similarly sized gas or diesel generators require minimal maintenance. Unexpected issues arose such as the woodchip feeder auger shearing off, the engine air intake hose collapsing, a gas blower shorting out, and ice buildup freezing crucial components. These problems can be addressed through component redesign to ensure proper operation over a wider range of conditions, but they currently pose significant questions regarding the system's reliability and ease of use. A complete re-design of the system is recommended as future work to follow up on the potential of small-scale gasification discovered in this project.

V. DISSEMINATION:

Description: Results regarding emissions and CO_2 from the gasifier generator system will be disseminated through journal papers in scientific publications and through presentations at conferences. The Program Manager will also work with DNR to schedule tours and activities once the gasifier system is operational in New Ulm. Instantaneous energy production from the system will be published on the DNR's Energy Smart website: (http://www.dnr.state.mn.us/energysmart/).

Status as of January 1, 2016: No dissemination of results has occurred as of this status date.

Status as of July 1, 2016: No dissemination of results has occurred as of this status date.

Status as of January 1, 2017: Work has begun on a thesis and a paper, both of which will be completed early in 2017. The paper will be published in either 'Energy and Fuels' or 'Biomass and Bioenergy' (as we are awaiting a response on the paper's eligibility for *Biomass and Bioenergy*). Tours of the gasifier system installed at the New Ulm facility will be scheduled for March and April of 2017.

Final Report Summary: To disseminate the results of the gasifier-generator emissions analysis, a graduate Master's thesis explaining all elements of the project was completed. In addition, a paper emphasizing the applications and merits of distributed small-scale gasification using waste biomass was submitted for publication in the journal *Biomass and Bioenergy*. Several tours were held at the New Ulm facility to showcase the gasifier powering the facility's geothermal pumps and to discuss the benefits and challenges of biomass gasification technology. One tour included five engineers and managers from Cummins Power Generation (June 9, 2017) and another group of three staff from Deep Portage Learning Center (June 27, 2017) were also hosted. Power output data from the gasifier operating during winter months was also published to the DNR's Energy Smart website. The project as publicized within the MN-DNR in an online article. All documents associated with the project are provided as attachments to this report with exception to the journal paper, which is available upon request. The Master's thesis will be available after publication of the article in accordance with university and journal policies.

VI. PROJECT BUDGET SUMMARY:

A. ENRTF Budget Overview:

Budget Category	$ Amount	Overview Explanation
Personnel:	$ 204,114	1 project manager at 8% FTE; 1 laboratory director at 2% FTE; 1 research scientist at 25% FTE; 1 undergraduate student researcher at 50% FTE; and 1 graduate research assistant at 50% FTE
Professional/Technical/Service Contracts:	~~$30,000~~ $30,390	Contract to Zinniel Electric for installing electrical service at DNR New Ulm facility. Contract to Booth Welding and Fabricating for installing proper railings and safety features to meet OSHA standards for installation at DNR.
Equipment/Tools/Supplies:	~~$13,430~~ $13,040	Consumables, wiring, plumbing and maintaining emissions and performance instruments for gasifier emissions testing. Also includes communications hardware for sending data back to UMN from New Ulm installation.
Capital Expenditures over $5,000:	$15,620	All Power Labs Power Pallet 20 kW gasifier generator system
Travel Expenses in MN:	$1,958	Mileage and travel expenses for field site visits and meetings at New Ulm. Lodging and expenses for student visits to install and

		commission gasifier in second year of project.
TOTAL ENRTF BUDGET:	**$ 265,122**	

Explanation of Capital Expenditures Greater Than $5,000: A 20 kW Power Pallet gasifier generator system manufactured by All Power Labs (APL), Berkeley, CA will be purchased using project funds. Due to the close and longstanding relationship between UMN and APL, the purchase price has been reduced from $40,000 to $15,620 including shipping with the promise that UMN will provide operating data to APL and help them with improving their product. The outreach component of the proposed project is also valuable to APL in marketing its gasifier technology to customers in the US. The system has a useful life of approximately 15 years and will be used primarily for research and demonstration purposes. Upon completion of the project, the system will be returned to the TE Engine Research Laboratory at UMN for continued research, education and outreach.

Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation: 1.35

Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation: 1.5

B. Other Funds:

Source of Funds	$ Amount Proposed	$ Amount Spent	Use of Other Funds
State			
	$ 10,680	$ 10,680	150 hours DNR staff time to coordinate installation, procure wood fuel, and operate the gasifier equipment. Wood chips will also be produced by DNR assuming 6 tons at $30 per ton
TOTAL OTHER FUNDS:	**$ 10,680**	**$ 10,680**	

VII. PROJECT STRATEGY:

A. Project Partners:

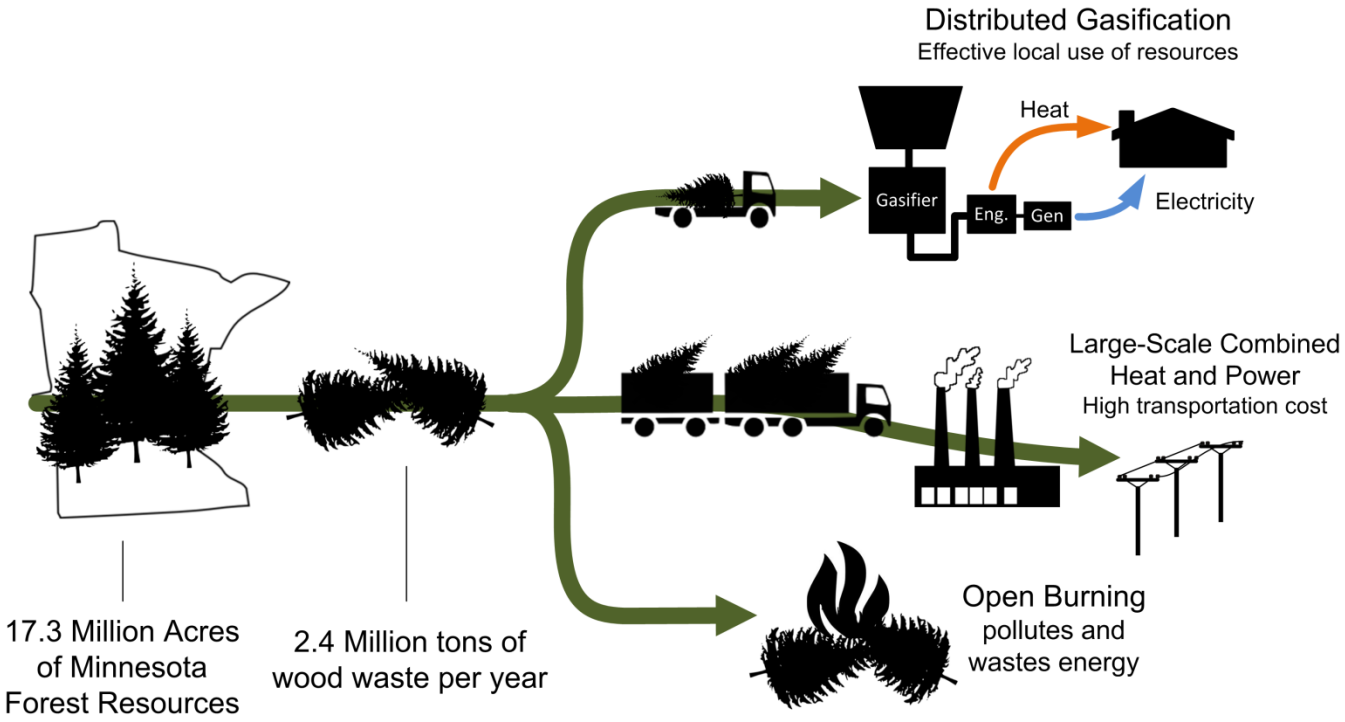
The UMN will work with the MN-DNR on this project. The Power Pallet will be installed at the MN-DNR's Regional Office Facility in New Ulm in the second year of the project. Mark Lindquist is the main technical contact at DNR responsible for interfacing with UMN to complete this project. Mark will work closely with the UMN team throughout the project. No DNR salary will be paid from this grant. The DNR has committed 150 hours of in-kind staff time to coordinate installation of the gasifier, procure wood fuel, and operate the equipment. DNR staff will also contribute time in putting gasifier energy production on the Energy Smart website.

B. Project Impact and Long-term Strategy:

The main goal of this project is to prove that distributed gasification is a clean, renewable and cost-effective option for reclaiming energy that is otherwise lost when open burning waste woody biomass. The disseminated results from the project will provide information about how small-gasifiers might be installed more widely in rural Minnesota as an alternative to small propane or diesel-fueled generator systems. One immediate result of a successful demonstration of the technology with the DNR could be the installation of more small gasification systems in state parks to meet their goals in renewable energy and environmental stewardship.

Long term, the UMN team hopes to leverage this project to secure new funding to develop new gasifier technologies and perhaps foster the manufacture of such systems in the State of Minnesota.

IX. VISUAL COMPONENT or MAP(S):



XI. REPORTING REQUIREMENTS:

Periodic work plan status update reports will be submitted no later than January 1 2016, July 1 2016, and January 1 2017. A final report and associated products will be submitted between June 30 and August 15, 2017.

Environment and Natural Resources Trust Fund
M.L. 2015 Project Budget

Project Title: Reducing Emissions from Open Burning through Biomass Gasification
Legal Citation: M.L. 2015, Chp. 76, Sec. 2, Subd. 07b
Project Manager: Will Northrop
Organization: University of Minnesota
M.L. 2015 ENRTF Appropriation: **$** 268,000
Project Length and Completion Date: June 30, 2017
Date of Report: September 15, 2017

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Activity 1 Budget	Amount Spent	Activity 1 Balance	Activity 2 Budget	Amount Spent	Activity 2 Balance	Activity 3 Budget	Revised Activity 3 Budget	Amount Spent	Activity 3 Balance	TOTAL BUDGET	TOTAL BALANCE
BUDGET ITEM	***Characterize Pollutant Emissions from Small-Scale Gasifier System***			***Quantify Carbon Emissions Reduction Potential from Biomass Gasification***			***Demonstrate and Promote Distributed Gasification for Rural Applications***					
Personnel (Wages and Benefits) Overall	*$102,250*	*$102,250*	*$0*	*$40,900*	*$40,900*	*$0*	*$61,350*	*$61,350*	*$60,964*	$386	*$204,500*	*$386*
Prof. Will Northrop, Project Manager (75% salary, 25% benefits); 8% FTE for 2 years ($26,955)												
Prof. David Kittelson, Lab Director (75% salary, 25% benefits); 2% FTE for 2 years ($11,931)												
Darrick Zarling, Research Scientist (75% salary, 25% benefits); 25% FTE for 2 years ($65,181)												
1 Undergraduate Research Assistant (100% salary); 50% FTE for 2 years ($12,139)												
1 Graduate Research Assistant (60% salary, 40% benefits); 50% FTE for 2 years ($88,294)												
Professional/Technical/Service Contracts												
Construction serviced firm TBD; installing outbuilding and electrical service at DNR New Ulm facility.							~~$30,000~~	$30,390	$30,390	$0	*$30,390*	$0
Equipment/Tools/Supplies												
Consumables, wiring, plumbing and maintaining emissions and performance instruments for gasifier emissions testing. Also includes communications hardware for sending data back to UofM from New Ulm installation.	$6,880	$6,880	$0	$1,500	$1,500	$0	~~$6,000~~	$5,610	$4,660	$950	*$13,990*	*$950*
Capital Expenditures Over $5,000												
All Power Labs Gasifier Generator System	$15,620	$15,620	$0								*$15,620*	*$0*
Travel expenses in Minnesota												
Mileage and travel expenses for field site visits and meetings at New Ulm. Lodging and expenses for a 3 month student visit for gasifier installation and commissioning in second year	$175	$0	$175	$175	$0	$175	$3,150	$3,150	$1,958	$1,192	*$3,500*	*$1,542*
COLUMN TOTAL	**$124,925**	**$124,750**	**$175**	**$42,575**	**$42,400**	**$175**	**$100,500**	**$100,500**	**$97,972**	**$2,528**	**$268,000**	**$2,878**

Biomass Gasification: The Power Pallet

Funding provided by:
ENVIRONMENT AND NATURAL RESOURCES TRUST FUND

DEPARTMENT OF NATURAL RESOURCES

Fuel	Power Rating	Efficiency	Full Hopper
Woodchips	18 kW	≈10%	4-5 hours

Why Gasification?

Renewable Energy Source:
Biomass is both abundant and renewable around the globe that is often left unused. Additionally, waste biomass from forestry, agriculture, and lumber production is commonly left to rot or burned on site.

Carbon Neutral:
Despite the large amounts of CO_2 emitted during operation, the same amount of CO_2 is removed from the atmosphere during biomass growth leading to a net zero impact on carbon emissions. This is valid provided that harvested biomass is always allowed to regrow.

Reduced Emissions:
The Power Pallet includes basic combustion controls, which lead to reduced CO and particulate emissions compared to other sources of biomass combustion such as wood stoves and open fires.

Off-Grid Electricity:
While it can be attached to the electrical grid to export power, the attached generator allows the gasifier to easily produce its own microgrid if no grid connection is available making it ideal for remote locations. The portability of the system also allows it to be moved around as a temporary power source.

Stable Production:
Gasification can produce power as long as there is feedstock in the hopper. Unlike solar and wind power, this is largely unaffected by weather conditions.

How it Works - Five Processes of Gasification:

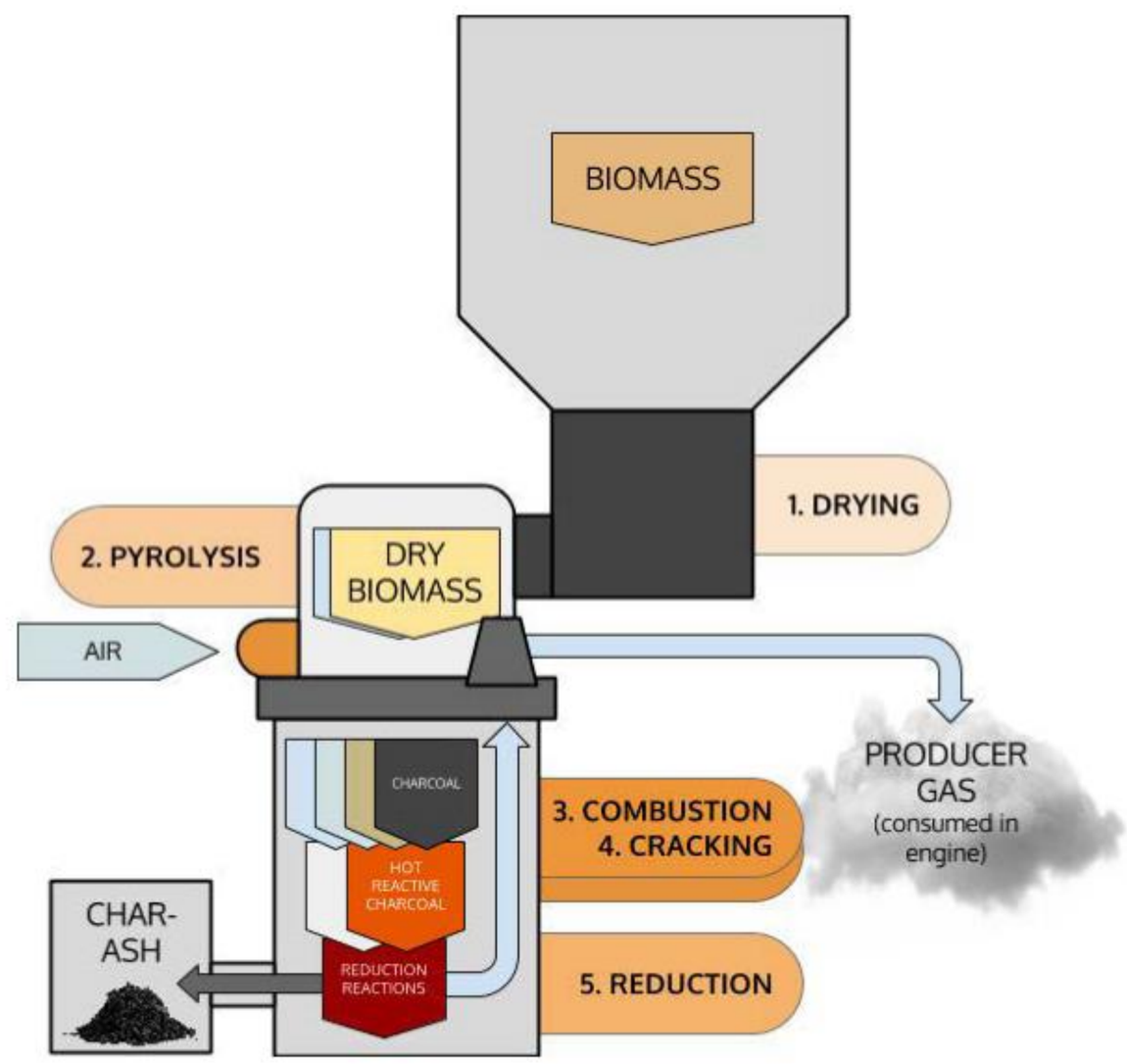
1) Drying:
Evaporates excess water present in the feedstock prior to entering the reaction chamber. Too much water will quench the necessary reactions.

2) Pyrolysis:
At high temperatures (400 – 600 °C), the feedstock begins to break down into gaseous tars (high order hydrocarbons) and solid charcoal. While some systems collect these pyrolysis tars to create biofuels such as biodiesel, this system breaks down these tars to create combustible gases.

3) Combustion + Tar Cracking:
A restricted amount of oxygen is let into the gasifier that reacts with the hot charcoal and tars to create gaseous CO_2, CO, H_2O, H_2, and CH_4. These reactions are largely exothermic, and produce the heat that sustains the rest of the gasification process.

4) Reduction:
At temperatures above 600 °C in low oxygen environments, some of the CO_2 and H_2O will break down into additional CO and H_2. Normal producer gas concentrations are around 15-20% CO and H_2. This gas is sufficient to fuel a natural gas internal combustion engine.

5) Ash Collection:
The charcoal remaining at the bottom of the gasifier is periodically removed to allow fresh feedstock to move into the chamber. Charcoal created in this manner is often referred to as biochar, which has many uses including a nutrient rich soil amendment, combustion fuel, and filter bed material. Biochar is also an effective method of carbon storage, as it is resistant to decomposition.



Biomass Gasification: The Power Pallet

Funding provided by:
ENVIRONMENT AND NATURAL RESOURCES TRUST FUND

DEPARTMENT OF NATURAL RESOURCES

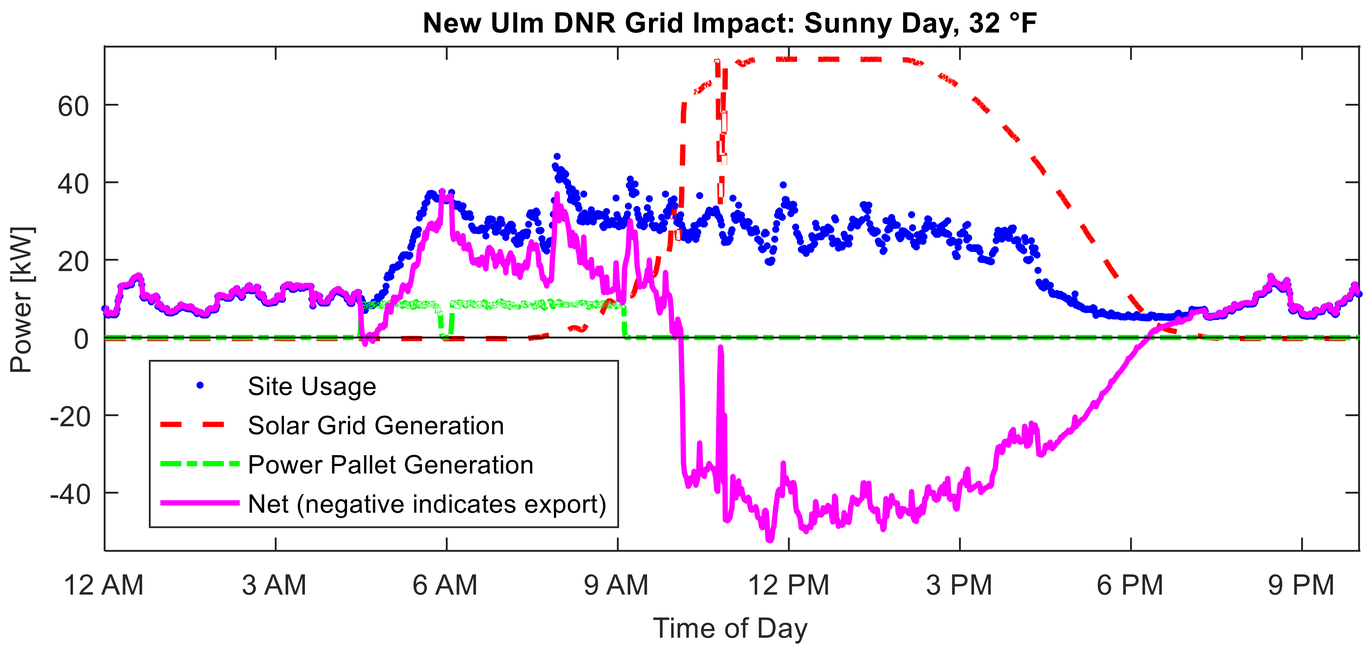
New Ulm DNR Gasifier

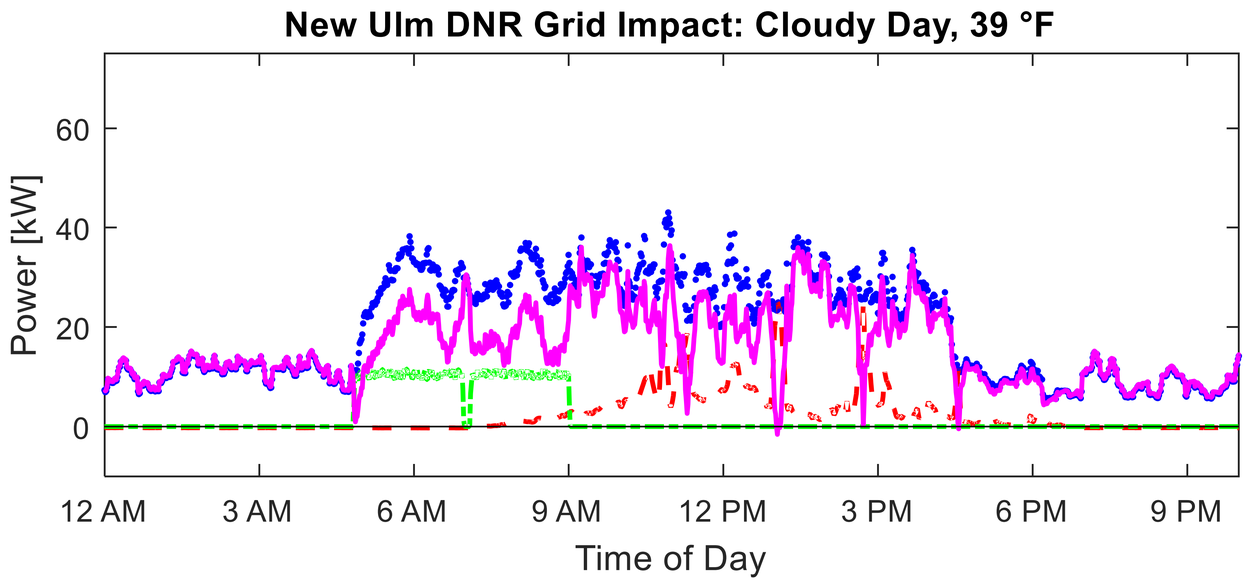
The DNR has a 70 kW solar grid installed on site that can produce all of the needed power on a sunny day. This project seeks to determine the effectiveness of using a gasifier to supplement the 70 kW solar array present at this facility to and knock down peak electrical demand during hours that the solar array is inactive, therefore reduce the operating costs and carbon footprint of the DNR facility.

Solar Array Supplementation in Action

Sunny Days

- Solar array does not begin producing peak power until late in the morning
- Building has a base power load overnight, as well as increased load in the early morning to preheat for the work day
- In this case, the gasifier is used as a bridge between when power demand rises for the day and the solar array begins producing power





Cloudy Days

- Solar array produces greatly reduced power, even during peak hours
- Gasifier output is unaffected
- The operating hours of the gasifier could be extended as needed – this system can be run for long periods uninterrupted – to further reduce purchased electricity

Gasification Emission Factors

Note: Emission factors indicate mass of emission per mass of biomass burned (on a dry basis)

	CO_2 (kg/kg)	NO_x (g/kg)	CO (g/kg)	CH_4 (g/kg)	Soot/PM (g/kg)	Total CO_2e* (g/kg)
Open Burning	1.62	2.9	97.2	4.6	15.5	1888
Residential	1.56-1.62	0.05-2.7	19-154	6-10	1.2-10	1740-2112
Decomposition	1.74	--	--	33.3	--	2584
Steam Turbine	1.83	1.13	5.82	0.60	2.57	1854
Power Pallet	**1.34 – 1.60**	**1.6 – 3.6**	**9.6 – 21.6**	**8.6 – 13.3**	**0 – 0.26**	**1570 – 1966**

*: CO_2e indicates total greenhouse effect based on 100-year global warming potentials of CO_2, CO, and CH_4

Conclusions

- Because some of the carbon is stored in biochar, gasification has reduced CO_2 emission compared to more complete combustion sources
- Controlled combustion leads to less CO and PM emission compared to open burning and simple household furnaces
- Adding further emission reductions such as a catalytic converter could further reduce emissions to be more in line with a typical steam turbine power plant
- Even unused biomass can have high CO_2 and CH_4 emissions during the decomposition stages
- At high load (10 kW+), where the gasifier is most efficient, the overall greenhouse effect is less than that even of largescale power plants