2019 Project Abstract
For the Period Ending June 30, 2022

PROJECT TITLE: Development of Clean Energy Systems for Farms
PROJECT MANAGER: William Northrop
AFFILIATION: University of Minnesota
MAILING ADDRESS: 111 Church St. SE
CITY/STATE/ZIP: Minneapolis, MN 55455
PHONE: (612) 625-6854
E-MAIL: wnorthro@umn.edu
WEBSITE: www.merl.umn.edu
FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2019, First Special Session, Chp. 4, Art. 2, Sec. 2, Subd. 07a

APPROPRIATION AMOUNT: $650,000
AMOUNT SPENT: $630,191
AMOUNT REMAINING: $19,809

Sound bite of Project Outcomes and Results
This project was the first to demonstrate that anhydrous ammonia mixed with a small quantity of hydrogen can fuel on-farm grain-drying equipment. Ammonia contains no carbon molecules. Therefore, its combustion emits no carbon emissions when produced renewably from wind or solar power, reducing the carbon intensity of agriculture in Minnesota.

Overall Project Outcome and Results
Grain drying consumes over one-third of the fossil fuel energy attributed to its production. Conventional fuels used in drying include propane and natural gas. Combustion of green anhydrous ammonia reduces carbon dioxide and soot emissions because it is a carbon-free molecule. Ammonia has not been considered a suitable replacement for petroleum for farm operations due to its low flame speed and poor combustion efficiency, resulting in unburned ammonia emissions and low efficiency. Hydrogen supplementation enhances ammonia combustion. Green hydrogen is an intermediate product of green ammonia production and can also be obtained through partial cracking of ammonia. In this project, fundamental research was performed to develop ammonia-hydrogen combustion technology. That technology was applied to small-scale turbulent burner testing through eventual full-scale demonstration on a commercial grain dryer. At the end of the project, a 240-kW ammonia/H_2 burner was retrofitted into a trailer-mounted grain dryer at the West Central Research and Outreach Center (WCROC) in Morris, MN. The dryer dried grain at a similar rate to when the propane burner was installed. The demonstration was completed using green ammonia and green hydrogen produced at the WCROC. This project resulted in the first functional grain dryer operating on ammonia. Emissions of nitrogen oxides (NOx) and unburned fuel was like emissions from fossil fuel burner systems. With additional engineering refinement, a pathway to a 100% ammonia (0% hydrogen) burner is possible that could be marketed to farmers and other industrial customers. The project also included engine research that showed spark-ignited engines used for electricity generation can operate on only 5% hydrogen and 95% ammonia, much less than previously thought. Given the potential for renewable ammonia production using solar and wind power in Minnesota, its use in grain drying can lower the carbon intensity of agriculture and save fuel costs for farmers.

Project Results Use and Dissemination
Research results from the project were published at the American Society of Mechanical Engineers Fall Technical Conference in Indianapolis, IN in October of 2022, and at the prestigious International Symposium on Combustion in August of 2022, along with other local section meetings of the Combustion Institute. Additional research results are being prepared for submission to a peer-reviewed journals. The grain dryer remains at the WCROC and will be demonstrated to interested parties upon request. Results from the research has also been used in project proposals to the US Department of Energy, and other federal and state entities.

Environment and Natural Resources Trust Fund (ENRTF)
M.L. 2019 ENRTF Work Plan Final Report

Date of Report: February 14, 2023

Final Report

Date of Work Plan Approval: June 5, 2019

Does this submission include an amendment request? YES

PROJECT TITLE: Development of Clean Energy Systems for Farms

Project Manager: William Northrop

Organization: University of Minnesota

Mailing Address: 111 Church Street SE

City/State/Zip Code: Minneapolis, MN 55455

Telephone Number: (612) 625-6854

Email Address: wnorthro@umn.edu

Web Address: www.merl.umn.edu

Location: Minneapolis (Hennepin County), Morris (Stevens County)

Total ENRTF Project Budget:	**ENRTF Appropriation:**	**$650,000**
	Amount Spent:	**$630,191**
	Balance:	**$19,809**

Legal Citation: M.L. 2019, First Special Session, Chp. 4, Art. 2, Sec. 2, Subd. 07a

Appropriation Language: $650,000 the first year is from the trust fund to the Board of Regents of the University of Minnesota for the West Central Research and Outreach Center at Morris to develop and test novel clean energy storage systems for farms using wind-generated ammonia to displace fossil fuels and reduce greenhouse gas emissions. This appropriation is subject to Minnesota Statutes, section 116P.10.

PROJECT TITLE: **Development of Clean Energy Systems for Farms**

I. PROJECT STATEMENT:

The goal of this project is to develop and test a clean energy storage system for farms using anhydrous ammonia produced from wind energy. Currently, the West Central Research and Outreach Center (WCROC) is operating a pilot plant that uses wind energy to drive an ammonia production process. Further, the University of Minnesota's Thomas E. Murphy Engine Research Laboratory (MERL) has developed a unique method for combusting ammonia that can efficiently utilize renewable ammonia as a fuel for on-farm purposes like grain drying burners or engines. In this project, ammonia will be tested as fuel for grain drying and for on-farm engines using this technology. Successful development of an ammonia-based farm energy storage system will have a dramatic impact on reducing fossil energy consumption and greenhouse gas emissions in grain, feed, meat, milk, and biofuel production.

In studying the energy and carbon footprint of crop production at the WCROC, results indicated that grain drying made up 41.6% of the fossil energy attributed to grain production. Nitrogen fertilizer was the second highest fossil energy consumer at 36.4% while tractor field work was at 13.9% and transportation at 1.18% (Tallaksen et al, 2016). Conventional fuels used in these processes include propane and natural gas for grain drying, natural gas steam methane reforming for nitrogen fertilizer production, gasoline and diesel for on-site electricity generation, and diesel fuel for field work and transportation. We currently are testing the near-zero carbon ammonia as nitrogen fertilizer and for displacing diesel fuel in tractors. If this same ammonia can displace propane and natural gas for grain drying and power generation, we have a system that can eliminate over 90% of the fossil energy use of corn production using renewable sources! This impact has a significant ripple effect, substantially lowering the energy and carbon footprint of meat and dairy products as well as ethanol production.

The ability to store wind and solar energy is key to an efficient and effective energy system especially for farms. In general, batteries are considered to be the most logical source of energy storage. However, batteries are costly and can only store energy for short durations. The U.S. Dept. of Energy indicates that using ammonia for energy storage is much more cost effective than batteries and other forms of storage (Soloveichik, 2016). Also, if ammonia is produced from wind and solar, it can be stored and used seasonally. It can be used for nitrogen fertilizer and tractor fuel in the spring and for powering irrigation and backup generators in the summer. In fall, it can be used for grain drying, fertilizer, and tractor and transport fuel. In winter, ammonia can fuel furnaces and for electrical power generation needs. Therefore, wind and solar energy paired with ammonia production, can provide a comprehensive, dynamic, cost-effective, and year-round clean energy system for farms.

II. OVERALL PROJECT STATUS UPDATES:

First Update March 1, 2020

Work during this first period has focused on the small-scale benchtop burner used for initial ammonia combustion tests, as well as the corresponding computer model used to simulate combustion. The benchtop burner was designed, fabricated and assembled, with two identical units for parallel experiments at University of Minnesota Duluth and Twin Cities labs. Ammonia-hydrogen fuel combustion was first simulated in a 1-dimensional model, and then a 2-dimensional model corresponding to the benchtop burner.

Second Update September 1, 2020

Much of the project work during the second period involved setting up the equipment required for laboratory tests of ammonia combustion, for both the benchtop burner and larger-scale tests. The ammonia and hydrogen gas supplies were installed with required safety equipment. The exhaust gas analysis equipment was set up, connecting the burner with the FTIR analyzer for measuring ammonia and nitrogen oxides in the burner exhaust. The MERL laser diagnostic system was also configured to allow in-situ measurement of combustion radical species. Planar laser-induced fluorescence (PLIF) measurements of OH molecule concentration was obtained for an ammonia flame.

Third Update March 1, 2021

During this period, much progress has been made on the lab scale tests of Activity 1: with laboratory apparatus and test instrument set up completed, tests began on both flame stability (Duluth) and exhaust gas composition (Twin Cities). Gas composition is measured both for the exhaust gas, using a FTIR gas analyzer, as well within the flame, using planar laser-induced fluorescence (PLIF). Important groundwork has also been laid for larger-scale field testing, with: the selection of a test site in Morris, securing of a batch grain drier to be retrofitted, and discussions with commercial burner manufacturer John Zink Hamworthy about large-scale ammonia combustion strategies. With the initial experimental data available, dissemination activities have also began, with two presentations and a presentation/paper accepted for May.

Fourth Update September 1, 2021

This period saw considerable progress in Activity 1, with the completion of initial flame stability work (Duluth), as well as extinction measurements and initial laser-induced fluorescence (LIF) measurements in the counterflow diffusion burner (Twin Cities). This work is also leading to the tuning of a chemical reaction mechanism for ammonia that allow for close agreement between flame measurements and simulations. The benchtop co-flow burner was adapted to allow swirl stabilization and staged rich-lean combustion. Experiments on this adapted burner represent the first stage of a scale-up sequence for Activity 2. Dissemination activities continued with a presentation at the US National Combustion meeting and papers in preparation on the benchtop burner work.

Fifth Update March 1, 2022

Final bench flame experiments were conducted during this period leading up to the scaleup of the burner to be implemented in the grain dryer. The swirl-stabilized burner was tested at 1 kW of fuel input with different hydrogen fractions and with different swirl ratios. A design for the scaled-up burner for use in the grain dryer was started. The project team decided to implement a parallel burner design with 24 individual burners operating at 10 kW of fuel input each. This design was designed to fit in the GT grain dryer borrowed for the project demonstration.

Overall Project Outcomes and Results:

Grain drying consumes over one-third of the fossil fuel energy attributed to its production. Conventional fuels used in drying include propane and natural gas. Combustion of green anhydrous ammonia reduces carbon dioxide and soot emissions because it is a carbon-free molecule. Ammonia has not been considered a suitable replacement for petroleum for farm operations due to its low flame speed and poor combustion efficiency, resulting in unburned ammonia emissions and low efficiency. Hydrogen supplementation enhances ammonia combustion. Green hydrogen is an intermediate product of green ammonia production and can also be obtained through partial cracking of ammonia. In this project, fundamental research was performed to develop ammonia-hydrogen combustion technology. That technology was applied to small-scale turbulent burner testing through eventual full-scale demonstration on a commercial grain dryer. At the end of the project, a 240-kW ammonia/H2 burner was retrofitted into a trailer-mounted grain dryer at the West Central Research and Outreach Center (WCROC) in Morris, MN. The dryer dried grain at a similar rate to when the propane burner was installed. The demonstration was completed using green ammonia and green hydrogen produced at the WCROC. This project resulted in the first functional grain dryer operating on ammonia. Emissions of nitrogen oxides (NOx) and unburned fuel was like emissions from fossil fuel burner systems. With additional engineering refinement, a pathway to a 100% ammonia (0% hydrogen) burner is possible that could be marketed to farmers and other industrial customers. The project also included engine research that showed spark-ignited engines used for electricity generation can operate on only 5% hydrogen and 95% ammonia, much less than previously thought. Given the potential for renewable ammonia production using solar and wind power in Minnesota, its use in grain drying can lower the carbon intensity of agriculture and save fuel costs for farmers.

AMMENDMENT REQUEST January 18, 2023
We are requesting that funds be shifted to reflect actual final project expenditures as follows:

- Personnel be increased by $11,112 to a total amount of $515,402 to account for increased salary for graduate research assistant at the UMN-MERL
- Professional service contracts were not needed at the WCROC. Contract budget is requested to be decreased from $24,500 to $14,392.
- Additional materials were required at the UMN-MERL to accomplish the multiple iterations of burner design and experimentation. Equipment budget is requested to be increased from $99,000 to $101,996

Amendment Approved by LCCMR 3/2/2023

III. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1 Title: Develop and test catalytic ammonia decomposition on a laboratory combustion system
Description: A combustion system using a catalytic reformer will be developed and tested in partnership between the MERL team and UMN Duluth team using a small-scale burner. Testing will include ignition, flame and heat control, emissions, fuel mixing, heat rates, residence times, and catalytic, thermal, and combustion efficiency. Emissions measurements will also be made to determine the impact of burning ammonia-derived fuels on nitrogen oxides (NOx). Experiments will be conducted at the UMD and UMN-MERL. The experimental campaign will be conducted with the benchtop burner over the range of experimental conditions shown in the table below.

Variable	Units	Range
Thermal Input	kW	1-10
Ammonia Flow Rate	SLPM	4.4-44
Eq. Natural Gas Flow Rate	SLPM	1.8-18
Equivalence Ratio	-	0.5-1.0
Decomposition Fraction*	%	10-50
Fuel Energy Fraction for Decomp.	%	1.5-7.3
Air Flow Rate	SLPM	3.3-66

* Decomposition fraction will be evaluated numerically using CFD simulations and will be as required through gas-cylinder supplied burner experiments.

Flame stability of the benchtop burner will be evaluated over the thermal input, equivalence ratio and decomposition fraction range indicated in the table. Decomposition fraction is the amount of ammonia decomposed to $H_2 + N_2$. It is the product of fuel fraction sent to the reactor and the catalyst conversion. The energy required to decompose ammonia over the decomposition fraction range shown in the table as a fraction of the thermal input. Although some energy (up to 7.3% of thermal input) is used to decompose ammonia to H_2, some of that energy is recovered in through an increase in fuel heating value.

Instrumentation to be used during the experiments will include temperature and pressure transducers and mass flow controllers for air and ammonia. Analytical instruments including Fourier Transform Infra-Red (FTIR) analyzer and Raman Laser Gas analyzer will measure emissions of hydrogen, ammonia, and nitrogen oxides from the burner. Additional diagnostics including optical instruments may be applied as needed and as available.

ACTIVITY 1 ENRTF BUDGET: $209,519

Outcome	Completion Date
1. Design review completed for an ammonia-fueled combustion system.	*1/1/2020*
2. Fabrication of an ammonia-fueled combustion system completed.	*6/30/2020*
3. Ammonia-fueled combustion system tested and refined.	*1/1/2021*

First Update March 1, 2020

The small-scale benchtop burner used for initial experiments was fabricated and assembled. Two identical burners were made for use in parallel experiments at the University of Minnesota Duluth and Twin Cities. For the initial combustion model, a 1-dimensional flame was implemented with Cantera, a thermochemistry modeling software. Work was also begun on a 2-dimensional model corresponding to the benchtop burner, implemented with OpenFOAM, an open-source computational fluid dynamics software package. Six current ammonia combustion mechanisms (sets of reaction rate equations) were tested for use in both models.

Second Update September 1, 2020

The benchtop burner was installed in the labs at both Duluth and the Twin Cities campuses. Ammonia and hydrogen fuel gas supply were installed along with the required safety and emergency shutoff equipment. The burner was also connected to gas analysis equipment (FTIR) for measuring nitrogen oxides and ammonia emissions. Initial tests showed negligible unburned ammonia, and NOx levels close to model predictions. The laser diagnostic equipment was also used to qualitatively measure the concentration of OH molecules in the ammonia flame.

Third Update March 1, 2021

The gas analysis equipment (FTIR) in the Twin Cities lab was calibrated for nitric oxide (NO) measurement, and a series of tests were performed to measure exhaust levels for a range of fuel compositions. Results showed that the exhaust composition was similar to what is predicted by two of the chemical reaction mechanisms recently published. The computer simulations were performed using Minnesota Supercomputing Institute computers for 7 of the most promising chemical reaction mechanisms. The laboratory laser system was also extended and reconfigured to allow in-flame measurement of NO concentration, the most important of the exhaust pollutants. The Duluth lab conducted a series of experiments on flame stability and blow-out, using different fuel and air flow configurations. Ammonia-hydrogen fuel with a lower hydrogen content is less reactive, and so flame stability is an important concern.

Fourth Update September 1, 2021

An existing counterflow diffusion burner in the Twin Cities lab was reconfigured for ammonia-hydrogen fuel use. The counterflow flame can be modeled as a one-dimensional system, and so represents the simplest diffusion flame, suitable for studying fundamental flame chemistry. This burner was used for a series of extinction experiments, for hydrogen fuel fraction in the range 0 – 15%. Quantitative laser induced fluorescence (LIF) measurements of the hydroxide radical (OH) have been made in the flame for use in tuning the chemical reaction mechanisms. The tuned reaction mechanisms, developed by a collaborating lab and tuned with data from this project, allows for close agreement between diffusion flame measurements and simulations. Quantitative LIF measurements of NO and NH will also be made before using the laser system for measurements on the co-flow benchtop burner. The Duluth lab also completed flame stability tests with the co-flow benchtop burner, evaluating the stability limits, including lift-off and blow-out. NO measurements were also made using the FTIR for the flame stability tests.

Fifth Update March 1, 2022

In this period, both counter-flow and co-flow burner experiments were concluded. Results of the experiments were applied to the scale-up practical burner experiments under Activity 2. The results of fundamental work were written into a two paper drafts to be submitted to journals. The main information taken from the fundamental work accomplished in Activity 1 was the amount of hydrogen required to blend with ammonia to make a flame stable. This information is critical for the grain dryer burner design and operation.

Final Report between project end (June 30) and August 15, 2022

No work on Activity 1 was completed in the final period as all effort was placed on the Activity 2 demonstration portion of the project.

ACTIVITY 2 Title: Field testing of a catalytic ammonia decomposition fuel system on a farm-scale grain dryer
Description: A prototype catalytic reformer and combustion system will be developed at the UMN Duluth and UMN MERL and then retrofitted to a grain dryer for field testing at the WCROC research farm. Industry representatives from grain dryer manufacturers will be invited to discuss and provide feedback to the design process. Ammonia produced using wind energy will fuel the prototype combustion system. The system will first be tested in an empty grain dryer. Once the system has been fully commissioned, several batches of corn grain will be dried. In addition to flame stability and efficiency characteristics, grain residence time and moisture levels into and out of the grain dryer will be measured as well as unburned ammonia emissions. The experiments will be conducted at the WCROC. Experiments using the grain dryer burner will be conducted over the range of operating conditions shown in the table below.

Variable	Units	Range
Thermal Input	kW	500-1,000
Ammonia Flow Rate	SLPM	2,200-4,400
Eq. Natural Gas Flow Rate	SLPM	910-1,830
Equivalence Ratio	-	0.7-1
Decomposition Fraction	%	10-50
Fuel Energy Fraction for Decomp.	%	1.5-7.3
Air Flow Rate	SLPM	1,650-4,720

When demonstrating the farm-scale burner only one of two burners installed in the currently installed grain dryer at the WCROC will be converted to operate on ammonia. The other will remain fueled by LPG. The relative performance of each burner will be evaluated during the final demonstration phase. In addition to flame stability and efficiency characteristics, grain residence time and moisture levels into and out of the grain dryer will be measured as well as unburned ammonia emissions from the integrated farm-scale burner.

ACTIVITY 2 ENRTF BUDGET: $244,494

Outcome	**Completion Date**
1. *Design and fabricate prototype ammonia-fueled combustion system for a grain dryer.*	*6/30/2021*
2. *Prototype ammonia combustion system installed and commissioned on a grain dryer.*	*9/30/2021*
3. *Grain dried and field-testing completed within the ammonia-fueled grain dryer.*	*12/31/2021*
4. Perform a life-cycle assessment to determine impact on GHG emissions.	*6/30/2022*

First Update March 1, 2020
Initial work on the farm-scale dryer consisted of background research on the design of large-scale burners relevant a crop-drier retrofit.

Second Update September 1, 2020
Continued survey of current research related to the design of the large-scale crop drier, including scaling of NOx emissions in industrial burners, and combustion strategies for NOx reduction. Industrial burner manufacturer John Zink Hamworthy Combustion was identified as a contact to provide input on the farm-scale burner design. Future work will select a grain dryer for demonstration and begin the process of retrofit design for ammonia/hydrogen mixtures.

Third Update March 1, 2021
During a team visit to the demonstration site at Morris, the final location for the demonstration was selected. This involved deciding on the fuel gas supply strategy and demonstration dryer. Following this meeting, the Morris team secured the use of a portable batch grain dryer: a GT XL245, which has a capacity of 2.2 MBtu/hr

when operated with propane fuel. The dryer has a single large burner unit will would be retrofit to burn ammonia-hydrogen fuel. The contact with John Zink Hamworthy (JZH) led to a series of conversations with JZH engineers: first about their experience in burning ammonia in waste incineration, and then about design of large-scale burners for ammonia. As a result of these conversations, we confirmed two promising strategies for reducing NOx emissions in ammonia combustion: (1) swirl stabilization of the flame, and (2) staged rich/lean combustion. The lab scale burner was modified to allow for swirl and partial premixing of the fuel with air.

Fourth Update September 1, 2021
The lab scale swirl burner has been tested under a number of different conditions. Fuel flow, stoichiometry, and staging have been examined. Experiments have revealed operating conditions which result in stable flame quality and minimized NO_x production. Staged rich/lean combustion and swirl have been shown as useful approaches in maintaining stable flame at low (15-35%) hydrogen fuel supplementation rates. Optimal NO_x conditions found in experiments will inform upcoming secondary scale-up process from 3.4kW to 10kW heat output. 10kW scale-up burner will then be patterned to create burner ring for demonstration in spring.
A comprehensive burner study on the 3.4kW lab-scale burner is underway with the addition of optical measurements and variable rates of swirl. This study aims to better understand which variables are significant influences of combustion quality and emissions in ammonia-fired burners. Conditions which minimize emissions will be candidates for later scale-up process. Results of burner study are to be published in an academic journal.

Fifth Update March 1, 2022
The 10-kW scale-up burner was designed and built based on the 3.4 kW design, building on the experience gained from earlier fundamental research activities. This burner was tested in an outdoor burner stand at the UMN MERL. Similar hydrogen and ammonia percentages as in the laboratory tests were used with the same airflow as the chosen grain dryer provided by a large electric fan. Experiments showed that the single burner could achieve 10 kW and maintain low emissions of unburned ammonia and NOx. Three swirl tip and burner length iterations were tried, until an optimal design was found that resulted in stable operation.

Final Report between project end (June 30) and August 15, 2022
In this final period, the 10-kW burner design was patterned 24 times and mounted on a central ring fuel manifold such that each burner received the same fuel flow rate. The burner and fan section of a GT XL245 trailer-mounted grain dryer was disassembled, and a new fuel vaporizer and burner ring section was added. A new control panel for ammonia-hydrogen operation was constructed and leak tested. Each burner received airflow from the main dryer fan through 3-D printed induction cups. The burner was operated in two demonstration campaigns at the WCROC in Morris, MN. The first set of tests proved that the burner could operate at the desired 240 kW thermal input (0.8 MBtu/hr), albeit at less than half of the design thermal capacity of the dryer on propane. In the second demonstration experiment, the ammonia-hydrogen burner dried corn over a slightly longer period than it would have on propane. However, since the stock grain dryer generally does not operate at its full thermal input when running on propane to not overtemperature the grain, the drying time with the retrofitted burner was not twice as long, even with the lower rated thermal rating. Emissions of the full-scale grain dryer was tested at the exit of the grain bin. Unburned ammonia emissions were negligible during normal operation, and NOx was the same, or slightly lower than the 10 kW outside laboratory experiments.

ACTIVITY 3 Title: A catalytic reformer developed and tested on a spark-ignition engine: A catalytic ammonia decomposition fuel system for a spark-ignition engine will be designed, fabricated, and tested at the UMN MERL. The experiments will be conducted on a flexible research spark-ignition engine to determine the acceptable range of operation when used in electricity generator applications. The engine will be tested for performance and emissions characteristics using instruments available at the laboratory. The goal of the activity will be to demonstrate that an exhaust-heated ammonia decomposition system is superior to operating the engine on ammonia alone. Emissions will be measured in the experimental campaign to determine whether species like nitrogen oxides (NOx) are reduced using the developed fuel system. Experiments will be conducted at the UMN MERL.

ACTIVITY 3 ENRTF BUDGET: $195,897

Outcome	Completion Date
1. Design review completed for an ammonia-fueled single-cylinder engine.	*1/1/2020*
2. Fabricate reactor and test an ammonia catalytic composition system on engine.	*1/31/2021*
3. Complete emissions and performance testing on the engine at the MERL	*6/20/2021*

First Update March 1, 2020
Single cylinder engine commissioned at the University of Minnesota Thomas E Murphy Engine Research Laboratory. The engine is capable of variable compression ratio and spark-ignition engine operation. The engine was tested on natural gas-like fuels over a range of operating speed and load.

Second Update September 1, 2020
Catalytic reactor design competed. However, the catalyst needed for the reactor module was delayed due to a switch in manufacturer. The original manufacturer underwent corporate restructuring, which necessitated the switch. It is expected that engine testing with the ammonia reactor will take place in the summer of 2021.

Third Update March 1, 2021
The catalyst needed for the engine testing portion was constructed and sent to the catalyst coating company. Once the coating is applied, the reactor can be assembled and tested on the single cylinder engine.

Fourth Update September 1, 2021
The reactor is complete and ready for testing on the single cylinder engine. In the third quarter of 2021, the single cylinder engine was relocated and recommissioned in a laboratory equipped with ammonia fueling. Testing will commence in early 2022 per the original project schedule.

Fifth Update March 1, 2022
Engine testing has been completed with hydrogen and ammonia mixtures and with ammonia alone. Results show 5% hydrogen mixed with ammonia is optimal for operation of engine generator systems, much less than previously thought, and less than reported in most peer-reviewed literature. This finding is significant because it shows that only a small amount of ammonia can be cracked using the develop catalyst to enable steady spark-ignition operation. Emissions of unburned ammonia and NOx were high, but simulations show that a three-way catalyst (like technology on most passenger cars) could reduce emissions to sufficiently low levels. Research also showed that nitrous oxide emissions are a potential concern for ammonia combustion in engines. N_2O, while not acutely harmful at low concentrations, is a significant greenhouse gas (GHG) with almost 300 times the GHG potential as carbon dioxide. Future work will look to reduce N_2O from the engine emissions when operating on ammonia-hydrogen blends.

Final Report between project end (June 30) and August 15, 2022
The engine research portion of the project concluded by showing that 95% ammonia/5% hydrogen is the optimal blend for spark-ignition engines. The research also concluded that N_2O emissions are lowest when the engine is operated with a fuel-to-air ratio slightly rich of stoichiometric, the perfect ratio resulting in no excess oxygen or fuel in the exhaust. Emissions of N_2O at stoichiometric were shown to be lower than that when ammonia is used as a supplemental fuel in diesel engines because diesel engines operate in the lean fuel-to-air ratio regime. In general, the engine experiments lead to a pathway for green ammonia to be used a reliable fuel for spark-ignited engines. Future work should further advance ammonia engine technology for use in on-farm applications like power generation, irrigation pumps, or tractors. Ammonia use in engines also has promise for use in marine or rail transportation applications, as well as for back-up power generation.

IV. DISSEMINATION:

Description: Results regarding the ammonia decomposition system used in grain drying will be disseminated through journal papers in scientific publications and through presentations at conferences. The Program Manager Northrop will also work with the WCROC and UMD partners to schedule tours and activities during the grain dryer demonstration phase of the project (Activity 2).

The Minnesota Environment and Natural Resources Trust Fund (ENRTF) will be acknowledged through use of the trust fund logo or attribution language on project print and electronic media, publications, signage, and other communications per the ENRTF Acknowledgement Guidelines.

First Update March 1, 2020
No dissemination activities for the project to report in this period.

Second Update September 1, 2020
No dissemination activities for the project to report in this period. Initial work from Activity 1 will be presented in winter/fall of this year.

Third Update March 1, 2021
The three presentations of project work during this period were: (1) The project was presented to the University and public at the annual 3-Minute Thesis competition, where Daniel Thomas, a project PhD student at the Twin Cities lab, won first place in the Mechanical Engineering department competition, and advanced to present again at the College level competition. (2) A poster on the project was presented at the 38th International Symposium on Combustion, the most important international combustion conference. The poster showed initial exhaust gas composition data together with the results of the simulations of the lab-scale jet flame. (3) A presentation has been accepted for the US National Combustion Meeting on May 24, and the associated paper is due April 5. This presentation will present experimental and simulation results for the simplest lab-scale flame: a counterflow diffusion flame, which can be modeled with a 1-dimensional domain.

Fourth Update September 1, 2021
Initial results for the counterflow diffusion flame study were presented at the US National Combustion Meeting as scheduled in May. Complete results for this study are being written up for a paper to be submitted to the International Symposium on Combustion (2022). Work on the benchtop co-flow burner and swirl burner will also be prepared for publication.

Fifth Update March 1, 2022
Results of the burner experiments were accepted for publication in the International Symposium on Combustion for presentation (2022). Two additional journal publications are in preparation on the use of ammonia in burner applications.

Final Report between project end (June 30) and August 15, 2022
Research results from the project were published at the American Society of Mechanical Engineers Fall Technical Conference in Indianapolis, IN in October of 2022, and at the prestigious International Symposium on Combustion in August of 2022, along with other local section meetings of the Combustion Institute. Additional research results are being prepared for submission to a peer-reviewed journals. The grain dryer remains at the WCROC and will be demonstrated to interested parties upon request. Results from the research has also been used in project proposals to the US Department of Energy, and other federal and state entities.

V. ADDITIONAL BUDGET INFORMATION:

A. Personnel and Capital Expenditures

See attached budget

Explanation of Capital Expenditures Greater Than $5,000:
NA

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

Enter Total Estimated Personnel Hours for entire duration of project: 4794	Divide total personnel hours by 2,080 hours in 1 yr = TOTAL FTE: 2.30

B. Other Funds

SOURCE OF AND USE OF OTHER FUNDS	Amount Proposed	Amount Spent	Status and Timeframe
Other Non-State $ To Be Applied to Project During Project Period:			
Other State $ To Be Applied To Project During Project Period:	$326,347	$205,097	Ongoing
In-kind Services To Be Applied To Project During Project Period:			
Past and Current ENRTF Appropriation: Appropriations related to this project includes: 1. A 2006 ENRTF project to produce hydrogen from wind energy ($800k). 2. A 2015 ENRTF project to research new renewable nitrogen fertilizer production technologies ($1 million - in progress), and 3. A 2016 ENRTF project 'Hydrogen fuel from Wind-Produced Ammonia" to displace diesel fuel in tractors ($250K - in progress).	$2,050,000	$2,050,000	Secured
Other Funding History: $2.95 million was provided by the University and State to complete the renewable hydrogen and ammonia pilot plant at WCROC. $500k and $400k was provided by UMN MnDRIVE and UMN IREE respectively to refine ammonia production technologies, develop policy, and evaluate economics. $180K was provided by Mn Corn to evaluate a novel production technology and evaluate initial economics. $2.9 million was awarded by the US Dept of Energy ARPA-E REFUEL program to develop and test a pilot-scale production unit of a novel ammonia production technology developed within the U (in progress).	$6,930,000	$6,930,000	Secured
TOTAL OTHER FUNDS:	**$9,306,347**	**$ 8,980,000**	

VI. PROJECT PARTNERS:

A. Partners outside of project manager's organization receiving ENRTF funding

Name	Title	Affiliation	Role
Dr. Will Northrop	Assoc. Prof., MERL Director	UMN Dept of Mech Eng.	PI
Mr. Eric Buchanan	Scientist, Renewable Energy	UMN WCROC	Co-PI

Name	Title	Affiliation	Role
Dr. Alison Hoxie	Associate Professor	UM-Duluth Dept of Mech & Industrial Eng.	Co-PI

B. Partners outside of project manager's organization NOT receiving ENRTF funding

Name	Title	Affiliation	Role
NA			

VII. LONG-TERM- IMPLEMENTATION AND FUNDING:

The main goal of this project is to show that ammonia can be effectively used within a farm energy storage system. The long-term goal is to develop commercially viable near zero carbon technologies that can be implemented on farms.

VIII. REPORTING REQUIREMENTS:

- Project status update reports will be submitted March 1 and September 1 each year of the project
- A final report and associated products will be submitted between June 30 and August 15, 2022

IX. SEE ADDITIONAL WORK PLAN COMPONENTS:

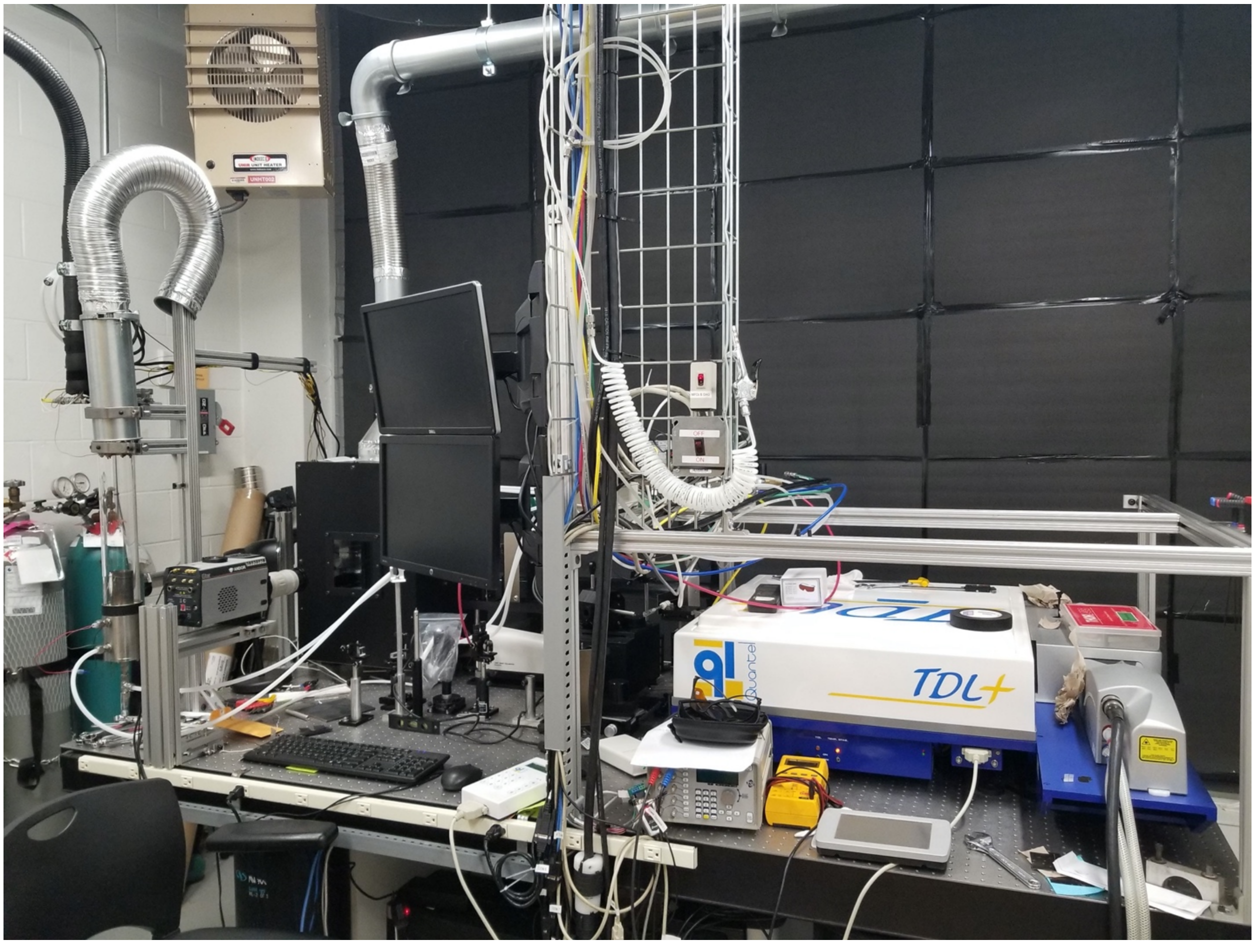
A. Budget Spreadsheet
B. Visual Component or Map
C. Parcel List Spreadsheet
D. Acquisition, Easements, and Restoration Requirements
E. Research Addendum

Attachment A:
Environment and Natural Resources Trust Fund
M.L. 2019 Budget Spreadsheet

Legal Citation: M.L. 2019, First Special Session, Chp. 4, Art. 2, Sec. 2, Subd. 07a
Project Manager: William Northrop
Project Title: Development of Clean Energy Storage Systems for Farms
Organization: University of Minnesota
Project Budget: $650,000
Project Length and Completion Date: 36 months, June 30, 2022
Today's Date: Feb 14, 2023

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	**Revised budget 1/24/23**	**Amount Spent**
BUDGET ITEM		
Personnel (Salary)	**$515,402**	**$515,402**
PI Northrop $50,324 (75% salary, 25% benefits) 0.08 FTEx3 yrs		
Lab Manager MERL $51,968 (75% salary, 25% benefits) 0.19 FTEx3 yrs		
Undergrad Intern - Engines $17,804 (100% salary, 0% benefits) 0.25 FTEx3 yrs		
Co-PI Allison Hoxie $20,000 (75% salary, 25% benefits) 0.04 FTEx3 yrs		
UMD Graduate Student $80,000 (60% salary, 40% benefits) 0.04 FTEx3 yrs		
Joel Tallaksen $44,852 (75% salary, 25% benefits) 0.25 FTEx2 yrs		
Cory Marquart $31,464 (75% salary, 25% benefits) 0.25 FTEx2 yrs		
Co-PI Eric Buchanan $33,888 (75% salary, 25% benefits) 0.1 FTEx3 yrs		
Farm Technician $18,661 (75% salary, 25% benefits) 0.25 FTEx2 yrs		
Undergrad Intern $6,000 (100% salary, 0% benefits) 0.1 FTEx3 yrs		
MERL Grad Research Assistant ~~$149,331~~ $160,443 (60% salary, 40% benefits) 0.5 FTEx3 yrs		
Professional/Technical/Service Contracts	**$14,392**	**$10,458**
Mechanic for grain dryer install at WCROC		$0
Hydrogen and Ammonia Safety Trainer for Team		$0
Emissions calibration at MERL (1/4 yearly PM on emissions equipment)		$10,458
PHA Engineering 3rd Party Review for grain dryer at WCROC		$0
Equipment/Tools/Supplies	**$101,996**	**$101,996**
Plumbing, electrical supplies, consumables, test cell parts at MERL		$24,996
Parts for lab decomposition system including metal parts		$4,000
Consumables and saftey equipment for ammonia at MERL		$6,000
Maintenance and repair parts for ammonia production at WCROC		$8,000
Lab consumables at UMD		$15,000
Catalysts from Johnson Matthey and Metal Substrates		$23,000
Sensors, meters, and vented container at WCROC		$5,000
Mass flow controllers and control equipment at MERL		$6,000
Sensors, meters for ammonia safety at UMD		$4,000
Grain Drying Burners for Modification in Activity 2		$6,000
Capital Expenditures Over $5,000		**$0**
Travel expenses in Minnesota	**$18,210**	**$2,334**
Northrop and staff - Travel to Morris 3 trips/year		$2,178
Hoxie and staff - Travel to Morris and Minneapolis 3 trips/year		$0
Buchanan and staff - Travel to Minneapolis and Duluth 3 trips/year		$156
Other		**$0**
		$0
COLUMN TOTAL	$650,000	$630,191

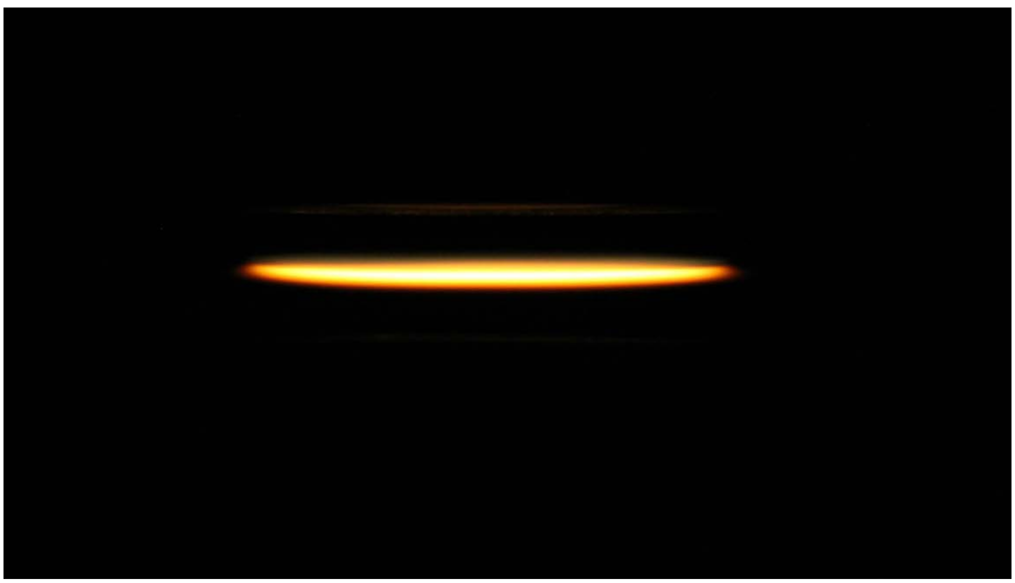
Visual Attachment
Development of a Clean Energy System for Farms
M.L. 2019, First Special Session, Chp. 4, Art. 2, Sec. 2, Subd. 07a



Experimental setup for fundamental ammonia flame experiments


1 kW swirl burner in the lab operating on ammonia/H2 mixture

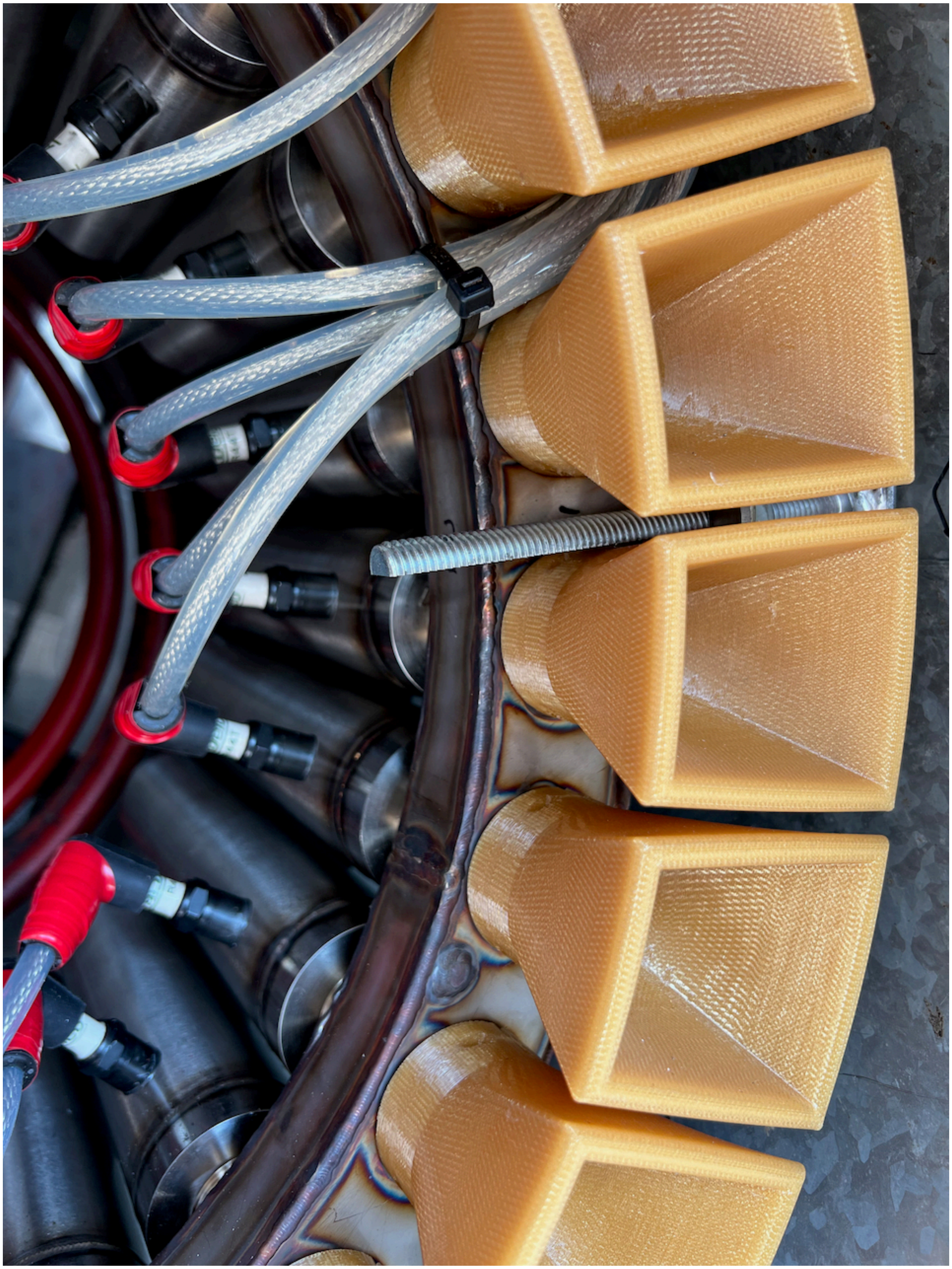
Opposed flow flame in the lab operating on ammonia/H2 mixture



Opposed flow flame in the lab operating on ammonia/H2 mixture


10 kW laboratory burner experiment at night

24-burner can assembly for grain dryer


Closeup image of burner installed in grain dryer

Complete grain dryer installation

Full installation with WCROC wind turbine in the background.


Burner operating in grain dryer during demonstration.