# Environment and Natural Resources Trust Fund (ENRTF)
# M.L. 2016 Work Plan

**Date of Report:** February 1, 2016

**Date of Next Status Update Report:** January 1, 2017

**Date of Work Plan Approval:**

**Project Completion Date:** June 30, 2019

**Does this submission include an amendment request?** No

**PROJECT TITLE: Hydrogen Fuel from Wind-Produced Renewable Ammonia**


**Project Manager:** William Northrop

**Organization:** University of Minnesota

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

| | | |
|---|---|---|
| **Total ENRTF Project Budget:** | **ENRTF Appropriation:** | **$400,000** |
| | **Amount Spent:** | **$0** |
| | **Balance:** | **$400,000** |

**Legal Citation:** M.L. 2016, Chp. xx, Sec. xx, Subd. xx

**Appropriation Language:**

**I. PROJECT TITLE: Hydrogen Fuel from Wind-Produced Renewable Ammonia**

**II. PROJECT STATEMENT:**

Over 16.5M metric tons of anhydrous ammonia is transported in the US each year, 80% of which is used in the production of fertilizer for agriculture. This project builds on past and pending ENRTF investments in renewable ammonia production and utilization from wind. Expanding carbon-free ammonia production opens the possibility for its use as a clean replacement fuel for diesel engines used in ammonia transport and for agricultural equipment as its combustion results in no carbon dioxide emissions. Renewable ammonia also has long-term potential to enable efficient hydrogen ($H_2$) production for fuel cell-powered vehicles. ***This project will develop a novel technical solution to converting ammonia to hydrogen through catalytic decomposition for use in dual-fuel diesel engine applications.*** Ammonia moves within the US using diesel engine-powered barges, trains, and pipelines which could be fueled, in part, by ammonia using the developed technology. On farm diesel equipment like tractors and irrigators could also be partially fueled by ammonia.

Our proposed concept uses a catalytic reactor, thermally integrated into the exhaust manifold of a diesel engine to decompose ammonia into $H_2$, thus converting it into a useable fuel for dual-fuel diesel engine operation. The goals of the project are to:

1) Replace up to 50% of total fuel energy with renewable ammonia in a laboratory diesel engine using a thermally integrated catalytic ammonia decomposition system.
2) Reduce soot emissions from the laboratory US EPA Tier 2 certified diesel engine using the dual fuel system to 0.15 g/kW-hr over an eight-mode off-highway test cycle. This emissions level marks a 50% reduction in emissions from the original certified value.
3) Demonstrate ammonia decomposition system in a diesel tractor by installing it and using it on-farm over a six-month period.

Funding this project will have two key impacts on the environment in Minnesota and nationally:

- Existing diesel engines used in ammonia transport or agriculture can significantly reduce engine soot, meeting US EPA Tier 4 regulatory standards without expensive aftertreatment catalysts that add significant cost for small businesses.
- Renewable ammonia derived from wind will lead to significant benefits in net-$CO_2$ emissions from diesel engines. Our team has already demonstrated that ammonia can be economically produced from wind and has applied the technology to fertilizer production in Minnesota. Furthermore, primarily ammonia-powered diesel engines will reduce the carbon intensity of commercial agriculture and positively impact the lifecycle $CO_2$ emissions of biofuels like corn-based ethanol.

All design and development work of the diesel engine system will be performed at the University of Minnesota (UMN) TE Murphy Engine Research Laboratory where specialized dynamometer facilities and emissions measurement instruments will be used to develop and characterize the dual fuel system. A field-ready prototype of the system will be demonstrated at the UMN's West Central Research and Outreach Center (WCROC) in the third year of the project. In the demonstration, a diesel engine in an existing tractor at the WCROC will be retrofitted with the dual fuel system and auxiliary ammonia tank. The developed catalytic decomposition system will have a significant impact in Minnesota by raising the profile of ammonia used as a fuel. The project will generate data useful in future studies to encourage the use of ammonia as an energy carrier for zero-emissions hydrogen fuel cell-powered passenger cars in the state.

**III. OVERALL PROJECT STATUS UPDATES:**

**Project Status as of January 1, 2017:**

**Project Status as of July 1, 2017:**

**Project Status as of January 1, 2018:**

**Project Status as of January 1, 2019:**

**Project Status as of July 1, 2019:**

**Overall Project Outcomes and Results:**

**IV. PROJECT ACTIVITIES AND OUTCOMES:**

**ACTIVITY 1:** Design and Install Catalytic Ammonia Decomposition System on Laboratory Diesel Engine
**Description:** In part of this activity, the project team will work with Johnson Matthey, an industry partner on the project to identify promising catalyst formulations for ammonia decomposition. These formulations will be tested on a side reactor to validate their performance. This side reactor will be constructed and evaluated in a test cell at the TE Murphy Engine Research Laboratory (MERL) using a tube furnace and small pieces of catalyst using gas instruments available at the laboratory to determine performance. Performance outcomes of the bench testing will include conversion and selectivity of ammonia conversion as a function of reactor temperature. At least three different catalysts will be evaluated. A final selected catalyst material will be selected for the engine reactor prototype.

The reactor design to be used in the engine dual fuel (ammonia/diesel) system will also be designed and a prototype will be constructed during Activity 1. The reactor will be built into a custom exhaust manifold such that heat is transferred directly from the exhaust gases from the engine before the turbocharger to the catalytic decomposition reactor. Heat exchange will be optimized in the design process through finite element analysis (FEA) using commercially available codes. An ammonia flow control system will also be designed such that the proper amount is injected as a function of engine load and speed. The control system will have its own on-board microprocessor in a laboratory breadboard with the knowledge that it will be later field ruggedized for the on-farm demonstration. A design review will be held at the completion of the design that will include project personnel as well as outside advisors before the prototype reactor is fabricated.

The reactor will be installed on an available John Deere 4045 Tier 2 diesel engine located at the MERL facility. This engine will be modified appropriately to accept the dual fuel system. The engine will be operated at one speed and load point to determine that performance and safety measures are acceptable before laboratory validation testing is completed in Activity 2. A complete safety review will be also conducted for using ammonia in the MERL as part of Activity 1. This safety review will encompass the transport, storage and use of the ammonia fuel for both the laboratory-testing period and the field demonstration study.

**Summary Budget Information for Activity 1:**

**ENRTF Budget: $ 128,185**
**Amount Spent: $ 0**
**Balance: $ 128,185**

| Outcome | Completion Date |
|---|---|
| **1.** *Design review complete for dual fuel system, ready for fabrication.* | January 1, 2017 |
| **2.** *Catalyst bench tests complete, catalyst material selected for engine dual fuel system* | May 31, 2018 |
| **3.** *Developed ammonia system installed on laboratory test engine and is operational at one engine speed and load.* | July 1, 2017 |

**Activity 1 Status as of January 1, 2017:**

**Activity 1 Status as of July 1, 2017:**

**Activity 1 Status as of January 1, 2018:**

**Activity 1 Status as of July 1, 2018:**

**Activity 1 Status as of January 1, 2019:**

**Final Report Summary:**

**ACTIVITY 2:** Experimentally Validate Ammonia Decomposition Dual Fuel System

**Description:** In this activity, the prototype system installed during Activity 1 will be thoroughly tested at the MERL dynamometer facility. An eight-mode test cycle adapted from the US EPA regulations for off-highway engines will be used in the first round of testing with the dual fuel ammonia decomposition system. Instruments to be used include a Fourier Transform Infrared analyzer bench and MicroSoot photo-acoustic soot mass analyzer. These instruments are available at the MERL for use on the project and are ideally suited for evaluating the dual-fuel system's performance. It is likely that the prototype system will require design iteration during Activity 2 to optimize its performance. Outcomes of Activity 2 will include achieving project goals of 50% diesel fuel replacement with ammonia and reduced engine-out soot emissions to 0.15 g/kW-hr. The performance and emissions of the system will also be evaluated.

After the performance evaluation, a ruggedized version of the dual fuel system will be fabricated. This system will use a weatherproof controller box and sensors. The system will also be mechanically configured to match the tractor chosen at the WCROC. An ammonia sensor will be installed as part of the system to determine slip levels through the decomposition system and engine. If high levels of ammonia are present in the exhaust, an ammonia oxidation catalyst may be required. The outcome of this task will be a system ready for installation on the tractor at the WCROC facility in Activity 3.

**Summary Budget Information for Activity 2:**

**ENRTF Budget: $ 127,959**
**Amount Spent: $ 0**
**Balance: $ 127,959**

| Outcome | Completion Date |
|---|---|
| 1. *Dual fuel system can achieve 50% diesel energy replacement with ammonia over US-EPA eight-mode test cycle.* | January, 1 2018 |
| *2. Engine tests and refinement complete, dual fuel system achieves 0.15 g/kW-hr soot emissions target over eight-mode test.* | May 31, 2018 |
| *2. Ruggedized demonstration prototype constructed and ready for installation on tractor.* | July 1, 2018 |

**Activity 2 Status as of January 1, 2017:**

**Activity 2 Status as of July 1, 2017:**

**Activity 2 Status as of January 1, 2018:**

**Activity 2 Status as of July 1, 2018:**

**Activity 2 Status as of January 1, 2019:**

**Final Report Summary:**

**ACTIVITY 3:** Install Ammonia Decomposition system on tractor at WCROC and perform on-farm demonstration

**Description:** In this activity, the developed catalytic ammonia decomposition system, or a copy of the laboratory system, will be installed on a John Deere tractor at the WCROC. The installation will be complete by the end of the summer of 2018 and will be ready for use during the harvest season. The goal of the demonstration phase of the project is to prove that the ammonia system is robust and safe for operational use on-farm and that the system can achieve 50% diesel replacement by energy. During this activity, system data will be logged and

transmitted to MERL researchers for understanding in-use performance and emissions. The data will also be used to diagnose potential system malfunctions. Compiled data from the six-month demonstration period will be organized and published to complete the project. WCROC researchers will also compare fuel costs between using on-site generated renewable ammonia and the diesel fuel it displaced using the developed system.

**Summary Budget Information for Activity 3:**

**ENRTF Budget: $ 143,857**
**Amount Spent: $ 0**
**Balance: $ 143,857**

| Outcome | Completion Date |
|---|---|
| **1.** *Ammonia dual fuel system is installed on tractor and can be used operationally for the harvest in fall of 2018.* | August 31, 2018 |
| **2.** *On-farm demonstration proves that diesel fuel can be replaced at over 50% by energy using ammonia dual fuel system.* | January 1, 2019 |
| **3.** *Energy savings and soot emissions benefits area quantified and published for Sept-Feb period.* | May 21, 2019 |

**Activity 3 Status as of January 1, 2017:**

**Activity 3 Status as of July 1, 2017:**

**Activity 3 Status as of January 1, 2018:**

**Activity 3 Status as of July 1, 2018:**

**Activity 3 Status as of January 1, 2019:**

**Final Report Summary:**

**V. DISSEMINATION:**
**Description:** Results regarding the ammonia decomposition dual fuel system will be disseminated through journal papers in scientific publications and through presentations at conferences. The Program Manager will also work with the WCROC to schedule tours and activities during the demonstration phase of the project (Activity 3).

**Status as of January 1, 2017:**

**Status as of July 1, 2017:**

**Status as of January 1, 2018:**

**Status as of July 1, 2018:**

**Status as of January 1, 2019:**

**Final Report Summary:**

**VI. PROJECT BUDGET SUMMARY:**

**A. ENRTF Budget Overview:**

| Budget Category | $ Amount | Overview Explanation |
|---|---|---|
| Personnel: | $ 321,000 | 1 project manager at 8% FTE ($41,691); 1 Co-PI researcher at 6% FTE ($24,084), 1 research scientist at 25% FTE ($75,780); 1 undergraduate student researcher at 25% FTE ($20,152); one WCROC Technician at 50% FTE (20,471); and 1 graduate research assistant at 50% FTE ($138,822) |
| Professional/Technical/Service Contracts: | $15,000 | Diesel engine mechanic for rebuilding, configuring and installing system on tractor engine at WCROC facility (est. $10,000). Emissions instrument calibration at MERL (est. $5,000). Contractor selection to be made using university procedures. |
| Equipment/Tools/Supplies: | $60,500 | Laboratory system plumbing, electrical supplies, consumables, test cell parts and other consumables (est. $20,000). Parts for constructing catalytic laboratory decomposition system(s) including metal parts, fittings, control hardware, wiring, and catalysts (est. $30,000). Tractor and engine parts and consumables for WCROC facility experiments (est. $10,500) |
| Travel Expenses in MN: | $ 3,500 | Mileage and travel expenses for field site visits and meetings at Morris, MN. Lodging and expenses for a 2-month student visit for system installation and commissioning in third summer of project. |
| **TOTAL ENRTF BUDGET:** | **$ 400,000** | |

**Explanation of Use of Classified Staff:** NA

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

**Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation:** 1.45

**Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation:** 0.25

**B. Other Funds:**

| Source of Funds | $ Amount Proposed | $ Amount Spent | Use of Other Funds |
|---|---|---|---|
| **Non-state** | | | |
| Johnson Matthey Inc. | $25,000 | $ 0 | Some materials may be available before July 1, 2017 Although not offered as cost share, engineering services and catalytic material support will be provided by JM. Materials will be supplied to UMN through University Material Transfer Agreement signed by both parties. |

| State | | | |
|---|---|---|---|
| Regents of the University of Minnesota | $170,622 | $ 0 | The foregone federally negotiated ICR funding constitutes the University's cost share to the project. The cost share is been determined using the federal IDC rate of 52% with appropriate exclusions for equipment and academic year tuition and benefits. |
| **TOTAL OTHER FUNDS:** | **$195,622** | **$ 0** | |

**VII. PROJECT STRATEGY:**

**A. Project Partners:**

This project involves collaboration between two colleges a UMN, the College of Science and Engineering and the College of Food, Agricultural and Natural Resource Sciences (CFANS). The CSE project team is at the MERL within the Department of Mechanical Engineering. The recently commissioned MERL is ideally equipped for the research project as it contains four engine test cells equipped with engines, dynamometers and advanced emissions measurement systems. The laboratory also contains all the necessary software for designing and modeling the prototype system.

The CFANS project team is located at the WCROC is an agricultural experiment station in Morris, MN. It consists of approximately 1,100 acres of crop and pasture lands, horticulture gardens, dairy and swine production facilities, and several renewable energy systems. The Renewable Energy Program has five research scientists / engineers and has a five year strategy to reduce fossil energy consumption in production agricultural through the adoption of renewable and efficient energy systems. The UMN WCROC built and now operates a Renewable H2 and ammonia Pilot Plant powered with a co-located utility-scale 1.65 MW wind turbine. The WCROC also has agreed to retrofit an existing diesel engine-powered tractor with the developed ammonia dual fuel system.

Johnson Matthey (JM) is a global manufacturer of sustainable technologies including catalytic materials for a large number of industrial sectors including petrochemical and automotive areas. JM has a corporate focus on clean air, clean energy and low carbon technologies and are experts in the application and recycling of precious metals. JM will provide in-kind engineering assistance and catalytic materials for the ammonia decomposition systems to be developed in this project.

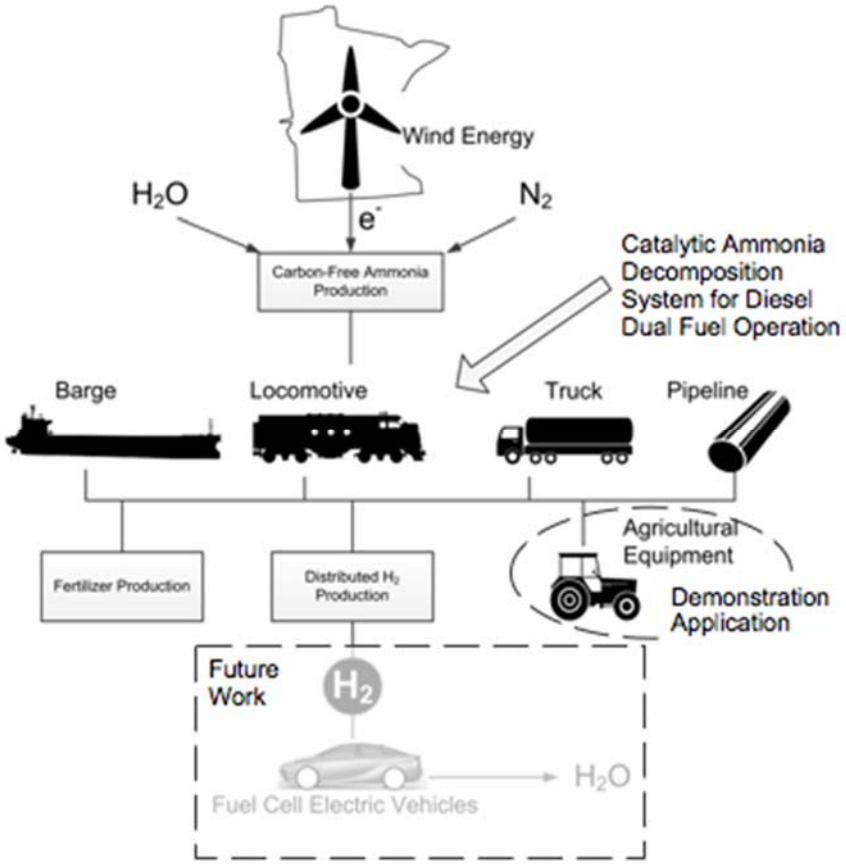
**B. Project Impact and Long-term Strategy:**

The main goal of this project is to show that ammonia can be effectively used as a replacement for diesel fuel in off-highway equipment. The project team will accomplish this by proving a new technology that will allow ammonia to burn better by partially decomposing it to hydrogen. One long term goal of the project is to develop a commercially viable dual fuel system for diesel engines used in transporting ammonia (e.g., rail and barge) and for on-farm applications. Another goal of the project is to raise public awareness of ammonia as a carbon-free fuel in the Minnesota and the nation. Extensions of this project could use similar catalytic decomposition technology to convert ammonia to compressed gaseous hydrogen for fueling fuel cell vehicles.

**C. Funding History:**

| Funding Source and Use of Funds | Funding Timeframe | $ Amount |
|---|---|---|
| The U of MN Renewable Hydrogen Pilot Plant was funded partially through an $800k 2006 ENRTF project. The University and the State provided an additional $2.95 million to complete the hydrogen pilot plant and add the ammonia production process. Research funded by U of MN MnDRIVE ($500K) and U of MN IREE ($400K) is in progress to evaluate novel production methods for renewable nitrogen (ammonia) fertilizer. A 2015 ENRTF project (101E - $1 million) is also pending legislative approval to further expand renewable nitrogen fertilizer research at the University. This proposal will evaluate the use of ammonia as a fuel. Both fuel and fertilizer production will use ammonia generated using wind power at the U of MN pilot plant. | The funds have been secured | $5,650,000 |

**IX. VISUAL COMPONENT:**




**X. RESEARCH ADDENDUM:** Research addendum under internal UMN peer review

**XI. REPORTING REQUIREMENTS:**

Periodic work plan status update reports will be submitted no later than January 1 2017 and 2018, and July 1 2017, 2018 and 2019. A final report and associated products will be submitted between June 30 and August 15, 2019.

**Environment and Natural Resources Trust Fund**
**M.L. 2016 Project Budget**

**Project Title:** Hydrogen Fuel from Wind Produced from Renewable Ammonia
**Legal Citation:**
**Project Manager:** Will Northrop
**Organization:** University of Minnesota
**M.L. 2016 ENRTF Appropriation:** **$** 400,000
**Project Length and Completion Date:** 3 Years, June 30, 2019
**Date of Report:** February 1, 2016

| 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 | Amount Spent | Activity 3 Balance | TOTAL BUDGET | TOTAL BALANCE |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **BUDGET ITEM** | **Design and Install Catalytic Ammonia Decomposition System on Laboratory Diesel Engine** | | | **Experimentally Validate Ammonia Decomposition Dual Fuel System** | | | **Install Ammonia Decomposition system on Tractor at WCROC and Perform On-Farm Demonstration** | | | | |
| **Personnel (Wages and Benefits) - Overall** | $87,685 | $0 | $87,685 | $106,959 | $0 | $106,959 | $126,357 | $0 | $126,357 | $321,000 | $321,000 |
| Prof. Will Northrop, Project Manager (75% salary, 25% benefits); 8% FTE for 3 years ($41,691) | | | | | | | | | | | |
| Michael Reese, Key Personnel (75% salary, 25% benefits); 6% FTE for 2 years ($24,084) | | | | | | | | | | | |
| Research Technician at WCROC,(75% salary, 25% benefits), 25% FTE for 2 years ($20,471) | | | | | | | | | | | |
| Darrick Zarling, Research Scientist (75% salary, 25% benefits); 25% FTE for 3 years ($75,780) | | | | | | | | | | | |
| 1 Undergraduate Research Assistant (100% salary); 50% FTE for 3 years ($20,152) | | | | | | | | | | | |
| 1 Graduate Research Assistant (60% salary, 40% benefits); 50% FTE for 3 years ($138,822) | | | | | | | | | | | |
| **Professional/Technical/Service Contracts** | | | | | | | | | | | |
| Diesel engine mechanic for rebuilding, configuring and installing system on tractor engine at WCROC facility. To be competitively selected following University of Minnesota | | | | | | | $10,000 | $0 | $10,000 | $10,000 | $10,000 |
| Emissions instrument calibration at MERL for FTIR analyzer and micro-soot analyzer. To be competitively selected following University of Minnesota procedures. | | | | $5,000 | $0 | $5,000 | | | | $5,000 | $5,000 |
| **Equipment/Tools/Supplies** | | | | | | | | | | | |
| Laboratory system plumbing, electrical supplies, consumables, test cell parts and other consumables. Parts for constructing catalytic laboratory decomposition system(s) including metal parts, fittings, control hardware, wiring, and catalysts. Tractor and engine parts and consumables for WCROC facility experiments. | $40,000 | $0 | $40,000 | $15,000 | $0 | $15,000 | $5,500 | $0 | $5,500 | $60,500 | $60,500 |
| **Travel expenses in Minnesota** | | | | | | | | | | | |
| Mileage and travel expenses for field site visits and meetings at Morris, MN. Lodging and expenses for a 2-month student visit for system installation and commissioning in third summer of project. | $500 | $0 | $500 | $1,000 | $0 | $1,000 | $2,000 | $0 | $2,000 | $3,500 | $3,500 |
| **COLUMN TOTAL** | **$128,185** | **$0** | **$128,185** | **$127,959** | **$0** | **$127,959** | **$143,857** | **$0** | **$143,857** | **$400,000** | **$400,000** |