Environment and Natural Resources Trust Fund
2016 Request for Proposals (RFP)

Project Title: **ENRTF ID: 141-E**

Clean Vehicles Fueled by Hydrogen from Renewable Ammonia

Category: E. Air Quality, Climate Change, and Renewable Energy

Total Project Budget: $ 842,849

Proposed Project Time Period for the Funding Requested: 3 years, July 2016 to June 2019

Summary:

Renewable ammonia from wind can be used to fuel vehicles. Technology will be developed to reduce emissions from diesel engines and to power fuel cell cars using hydrogen from ammonia.

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Sponsoring Organization: U of MN

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Location

Region: Metro, NW

County Name: Hennepin, Stevens

City / Township:

Alternate Text for Visual:

Figure illustrates using wind power in Minnesota to renewably produce ammonia which can be converted to hydrogen for powering diesel vehicles and for eventually refueling fuel cell passenger cars.

_____ Funding Priorities	_____ Multiple Benefits	_____ Outcomes	_____ Knowledge Base
_____ Extent of Impact	_____ Innovation	_____ Scientific/Tech Basis	_____ Urgency
_____ Capacity Readiness	_____ Leverage	_____ TOTAL	_____%

PROJECT TITLE: Clean Vehicles Fueled by Hydrogen from Renewable Ammonia

I. 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 both diesel engine applications and fuel cell vehicle refueling.*** 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. Fuel cell cars powered by H_2 produced directly from non-renewable natural gas are currently being introduced in California by most major auto manufacturers. Using renewable ammonia as a H_2 carrier could provide a pathway for their introduction in Minnesota by demonstrating a cost-effective technology for H_2 production and distribution.

Our proposed concept uses a catalytic reactor, thermally integrated into the exhaust manifold of a diesel engine or packaged in a stationary refueling unit to decompose ammonia into H_2, thus converting it into a useable fuel for dual-fuel diesel engine operation or for powering fuel cell cars. The goals of the project are to:
1) Replace up to 80% of total fuel energy in diesel engines with renewable ammonia using a thermally integrated catalytic ammonia decomposition system.
2) Generate pure compressed H_2 at a capacity of 2.5 kg/day using a custom designed compressed H_2 refueling system using pressurized ammonia decomposition.

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

- Existing diesel engines used in ammonia transport or agriculture can significantly reduce engine soot and nitrogen oxides (NO_X) emissions, 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.
- Expansion of renewable ammonia production and transport beyond fertilizer production and chemical processing can reduce costs for renewable H_2 production, paving the way for fuel cell vehicle refueling infrastructure in Minnesota and other mid-western states.

All design and development work of the diesel engine system and H_2 refueling 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 for characterizing the systems. Both technologies will be demonstrated at the UMN's West Central Research and Outreach Center (WCROC) in the third year of the project. A diesel engine in a tractor will be retrofitted for using ammonia as a fuel and the refueling system will be used to power an available small utility fuel cell electric vehicle. Demonstration of the developed technologies will have a significant impact in Minnesota by encouraging the early introduction of zero-emissions fuel cell-powered passenger cars in the state.

II. PROJECT ACTIVITIES AND OUTCOMES

Activity 1: Design, Develop and Demonstrate Ammonia Fuel System for Diesel Engines **Budget: $388,357**

In this activity, we will construct a catalytic ammonia decomposition system for integration with a diesel engine with assistance from Johnson Matthey, a global catalyst material supplier. The system will be tested on a dynamometer located at UMN. The goal will be to prove that a diesel engine can operate with up to 80% of the

fuel energy as ammonia over its full range. The technology will be demonstrated in the third year of the project on a tractor in use at the UMN WCROC facility.

Outcome	Completion Date
1. Achieve 80% diesel fuel replacement in test engine with renewable ammonia	12/31/2017
2. Show reduced pollutant emissions when operating diesel engine on ammonia	6/30/2018
3. Demonstrate emissions reduction and system feasibility on tractor at WCROC	6/30/2019

Activity 2: Design, Develop and Demonstrate Ammonia H_2 Vehicle Refueling System **Budget: $454,492**

In this task, we will develop an ammonia-based refueling system for utility fuel cell vehicles located at UMN's WCROC. The goal of this task is to design and build a refueling system that uses the same catalytic decomposition system as in Activity 1 but purposed for production of compressed H_2. Also as part of this activity, we will perform a techno-economic analysis comparing H_2 refueling infrastructure based on renewable ammonia versus natural gas.

Outcome	Completion Date
1. Achieve 2.5 kg-H2/day production rate with laboratory refueling system	6/30/2018
3. Demonstrate refueling of a small utility vehicle at the WCROC facility from ammonia	1/1/2019
4. Show techno-economic viability of H2 for passenger vehicles from renewable ammonia	6/30/2019

III. PROJECT STRATEGY

A. Project Team/Partners

Will Northrop is an Assistant Professor at the UMN in the Department of Mechanical Engineering. He is the project's principal investigator and UMN will be the recipient of all funding. Prof. Northrop will lead a team of research staff at the UMN TE Murphy Engine Research Laboratory to accomplish the stated project goals including one Graduate Research Assistant for each of the two activities, a Research Associate and a part-time Undergraduate Research Assistant. Prof. Northrop is partnering with Michael Reese of the UMN's WCROC facility outside Morris, MN. Mr. Reese will manage a technician at the WCROC to implement the refueling and tractor demonstration phase of the project. He will also be involved in design aspects of the ammonia decomposition units given his extensive experience with ammonia-based systems. Dr. Andrew York is a Senior Principal Scientist at Johnson Matthey and is experienced in a wide array of catalyst material development and catalytic systems. He currently works closely with university researchers on many projects investigating the effect of different fuels and catalytic systems on internal combustion engine performance and emissions. Dr. York will aid the design and testing of the catalytic ammonia decomposition systems to be developed in this project and provide catalytic materials as in-kind support for the effort. JM will not be receiving any funds from the project and will participate in exchange for early access to generated data.

B. Project Impact and Long-Term Strategy

Thus far, investment in H_2 fueling infrastructure has been limited to California and New England based on state-funded initiatives. Fuel cell vehicles are being introduced into the marketplace by a number of auto manufacturers and installed infrastructure for H_2 refueling is an enormous challenge to ensure widespread market penetration of this promising technology. ***The long term goal for this project is to encourage at least 4 renewable ammonia-fueled fuel cell car refueling systems for passenger vehicles along the corridor between the Twin Cities and Duluth within the next five years***. With this infrastructure, it is hoped that automotive manufacturers like Toyota will be attracted to introduce their first commercial fuel cell cars in Minnesota, greatly enhancing the profile of the state in encouraging the next generation of zero emissions vehicles. This project is also likely to result in patentable inventions regarding integrated ammonia decomposition systems.

C. Timeline Requirements

This project will be conducted over a 36 month time period. The first two years of the project will be dedicated to design development and testing of both ammonia decomposition systems. The third year of the project will be devoted to demonstration of developed technology and to techno-economic analyses to motivate the expanded development of ammonia-based H_2 infrastructure.

2016 Detailed Project Budget

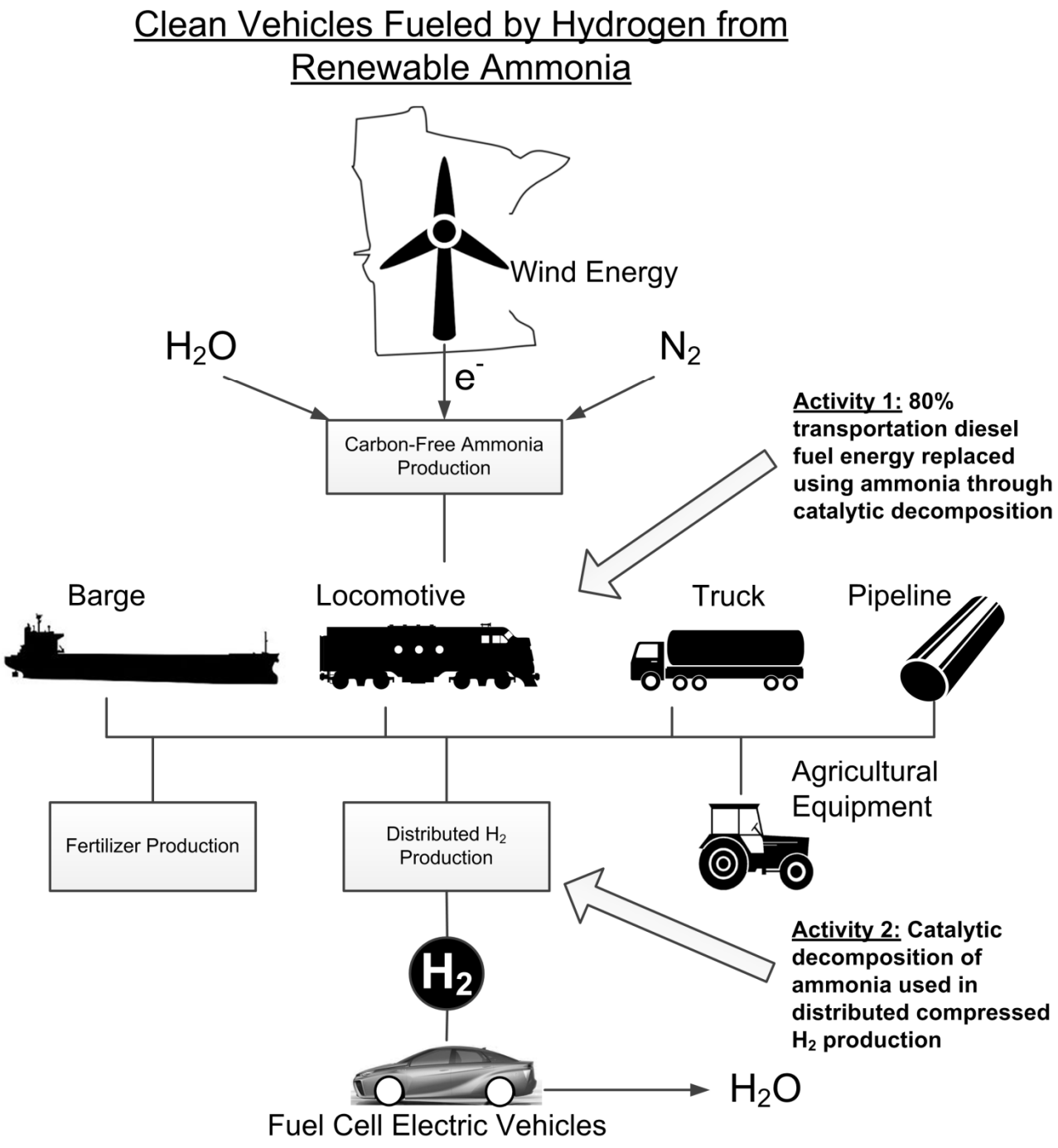
Project Title: Clean Vehicles Fueled by Hydrogen from Renewable Ammonia

IV. TOTAL ENRTF REQUEST BUDGET: 3 years

BUDGET ITEM	AMOUNT
Personnel:	**$ 551,349**
Prof. Will Northrop, Project Manager (66.2% salary, 33.8% benefits); 8% FTE for 3 years	$ 41,691
Michael Reese, Co-Manager, (66.2% salary, 33.8% benefits); 10% FTE for 3 years	$ 41,356
1 WCROC Technician, (66.2% salary, 33.8% benefits); 50% FTE for 2 years	$ 40,943
Darrick Zarling, Research Associate (66.2% salary, 33.8% benefits); 25% FTE for 3 years	$ 75,780
2 Undergraduate Research Assistants (100% salary); 50% FTE for 3 years	$ 73,934
2 Graduate Research Assistants (60% salary, 40% benefits); 50% FTE for 3 years	$ 277,644
Equipment/Tools/Supplies:	**$ 253,000**
Equipment and Supplies for construction of engine-mounted ammonia decomposition system (estimate): Test engine (*equipment*) ($20,000), reactor fabrication (*equipment*) ($20,000), plumbing ($5,000), instrumentation parts including pressure and temperature sensors, transmitters and data acquisition ($20,000), consumables like diesel fuel, test ammonia, engine oil and calibration gases ($15,000), laboratory supplies for dynamometer test cell ($5,000)	$ 85,000
Equipment and Supplies for construction of fuel cell electric vehicle refueling system (estimate): refueling system skid fabrication including reactor and associated parts ($60,000), transmitters and data acquisition ($10,000), consumables like ammonia and calibration gases ($5,000), laboratory supplies like safety equipment and installation parts ($5,000), associated plumbing and wiring parts ($5,000)	$ 85,000
WCROC tractor installation parts and supplies (estimate): Second engine reactor fabrication (equipment) ($20,000), associated engine parts ($5,000), diesel fuel ($1000)	$ 36,000
WCROC hydrogen refuelling system installation parts and supplies (estimate): associated plumbing and refueling nozzle ($10,000), safety and signage ($2,000), Wiring and additional instrumentation ($10,000)	$ 22,000
WCROC utility FCEV upgrade parts (estimate): Replacement battery pack ($15,000), electric drivetrain parts ($5,000), hydrogen system parts ($5,000)	$ 25,000
Contracts/Services:	**$ 35,000**
WCROC Services: Tractor technician services ($10,000), utility fuel cell vehicle technician services ($15,000), Permitting for refueling system installation ($10,000)	$ 35,000
Travel:	**$ 3,500**
Project team vehicle travel and lodging from WCROC to East Bank Campus for project work: university rental vehicles ($1200), fuel ($500), lodging (15 nights at $120/night = $1,800)	$ 3,500
TOTAL ENVIRONMENT AND NATURAL RESOURCES TRUST FUND $ REQUEST =	**$ 842,849**

V. OTHER FUNDS *(This entire section must be filled out. Do not delete rows. Indicate "N/A" if row is not applicable.)*

SOURCE OF FUNDS	AMOUNT	Status
Other Non-State $ To Be Applied To Project During Project Period:	N/A	
Other State $ To Be Applied To Project During Project Period:	N/A	
In-kind Services To Be Applied To Project During Project Period: The foregone federally negotiated ICR funding constitutes the University's cost share to the project. The total cost share is $321,924 and has been determined using the federal IDC rate of 52% with appropriate exclusions for equipment and academic year tuition and benefits. Although not offered as cost share, engineering services and catalytic material support from Johnson Matthey for development of custom systems will total $25,000.	$ 321,924	*pending*
Funding History: The U of MN Renewable Hydrogen Pilot Plant was funded partially through a $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.	$ 5,650,000	Secured
Remaining $ From Current ENRTF Appropriation:	N/A	


Clean Vehicles Fueled by Hydrogen from Renewable Ammonia
Wind Energy
H_2O
N_2
e^-
Carbon-Free Ammonia Production
Activity 1: 80% transportation diesel fuel energy replaced using ammonia through catalytic decomposition
Barge
Locomotive
Truck
Pipeline
Agricultural Equipment
Fertilizer Production
Distributed H_2 Production
Activity 2: Catalytic decomposition of ammonia used in distributed compressed H_2 production
H_2
H_2O
Fuel Cell Electric Vehicles

PROJECT TITLE: Clean Vehicles Fueled by Hydrogen from Renewable Ammonia

I. PROJECT MANAGER QUALIFICATIONS

Will Northrop, Assistant Professor, University of Minnesota, Department of Mechanical Engineering will be the project manager of the proposed work. Prof. Northrop received his M.S. and Ph.D. in mechanical engineering from University of Michigan-Ann Arbor in 2003 and 2009 respectively. Prior to coming to University of Minnesota (UMN), he worked as a Senior Researcher at General Motors Research and Development as a member of the Propulsion Systems Research Laboratory. At UMN he is a principal investigator on projects in the areas of advanced combustion, alternative fuels, emissions control for internal combustion engines, and hydrogen/syngas production and utilization. He is the recent recipient of UMN's McKnight Land Grant Professorship for non-tenured faculty. Prof. Northrop is currently advising nine graduate students and four undergraduate research assistants working on funded research projects. He has published over twenty peer reviewed articles and three US patents. A previous experimental study led by Prof. Northrop and sponsored by the MN Corn Growers Association and Agricultural Utilization Research Institute compared H_2, gasoline and ethanol as fumigants for diesel engines operating in an advanced dual-fuel combustion mode. The research using a laboratory diesel engine found that H_2 could replace diesel fuel up to 80% on an energy basis and result in extremely low emissions of NO_X, soot, CO and total unburned hydrocarbons compared to diesel-only operation. Prof. Northrop also has considerable industry experience in H_2 production from alternative fuels. The current project builds on this previous work and is well within the scope of current research projects he manages.

II. ORGANIZATIONAL DESCRIPTION

University of Minnesota Mechanical Engineering Department: The Department of Mechanical Engineering, part of the College of Science and Engineering at the University of Minnesota Twin Cities Campus, serves the state and nation as a leading center of education, research, and innovation. The Department has 42 active faculty, 30 staff members, 300 graduate students, 50 postdoctoral associates, research associates and visitors, and about 550 undergraduate students. In 2013, the Department invested over $5M into a new laboratory facility for engines fuels and emissions research. Recently named the T.E. Murphy Engines Research Laboratory, the facility is ideally equipped for the proposed 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 two systems to be developed in the proposed activities.

University of Minnesota-WCROC: The UMN WCROC is an agricultural experiment station. 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 H_2 and ammonia Pilot Plant powered with a co-located utility-scale 1.65 MW wind turbine. This plant will be used for demonstrating the refueling system and providing data for techno-economic analyses to be conducted in the proposed research program. The WCROC also has demonstration vehicles necessary to conduct the research study including a small utility fuel cell vehicle and a diesel engine-powered tractor.

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.