



Environment and Natural Resources Trust Fund

M.L. 2025 Approved Work Plan

General Information

ID Number: 2025-290

Staff Lead: Lisa Bigaouette

Date this document submitted to LCCMR: June 8, 2025

Project Title: Renewable Energy Conversion for Farm Diesel and Ammonia

Project Budget: \$726,000

Project Manager Information

Name: Paul Dauenhauer

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Project Reporting

Date Work Plan Approved by LCCMR: June 24, 2025

Reporting Schedule: March 1 / September 1 of each year.

Project Completion: June 30, 2028

Final Report Due Date: August 14, 2028

Legal Information

Legal Citation: M.L. 2025, First Special Session, Chp. 1, Art. 2, Sec. 2, Subd. 07e

Appropriation Language: \$726,000 the first year is from the trust fund to the Board of Regents of the University of Minnesota to develop a novel charge-swing catalytic condenser that will enable the low-cost production of hydrogen from water using rural electricity for on-the-farm energy storage or renewable diesel and ammonia fertilizer.

Appropriation End Date: June 30, 2028

Narrative

Project Summary: To develop a novel charge-swing reactor that can convert water to hydrogen at lower cost ($< \$1 / \text{kg-H}_2$) for on-the-farm energy storage or as reductant for diesel or ammonia fertilizer.

Describe the opportunity or problem your proposal seeks to address. Include any relevant background information.

Rural Minnesota has the opportunity for extensive renewable energy from wind and solar power at low cost ($< 3\text{¢/kWhr}$) with limited utility other than sale to the existing electrical grid. However, substantial economic potential only exists for individual farmers or large agricultural collectives to install wind and solar power generation if they can find alternative uses for power. The largest barrier to storing distributed electrical power remains its conversion to chemical energy; electrical power once converted to a reductant such as H_2 gas can be stored or transported within a global energy market or be used onsite for the manufacturing of fuels such as conventional (diesel) or alternative (dimethyl ether) liquids. Additionally, conversion of wind or solar power to H_2 is the largest economic barrier to on-site manufacturing of fertilizers such as ammonia that are critical to agriculture. H_2 production via electrolysis has remained costly, at prices in excess of $\$6/\text{kg-H}_2$, primarily due to the conventional manufacturing process utilized, which employs expensive membrane materials and precious metals (e.g., Pt and Ir). We are pursuing entirely new H_2 -generation technology that uses low-cost materials and operates at high efficiency, to enable the on-site production of H_2 from renewable power in

What is your proposed solution to the problem or opportunity discussed above? Introduce us to the work you are seeking funding to do. You will be asked to expand on this proposed solution in Activities & Milestones.

We propose the development of a catalytic device called a 'charge-swing catalytic condenser' that will enable the low-cost production of hydrogen from water using rural electricity for renewable diesel and ammonia fertilizer. While the conventional method of electrolysis uses exotic membrane materials combined with precious metals to continuously separate and diffuse protons, the new charge-swing condenser will be designed and fabricated with low-cost Earth-abundant materials. The condenser will operate in two modes in simple operation to first produce H_2 from water, followed by a second function to regenerate and release oxygen. The condenser is designed as a series of layers that have independent functions to control the distribution of electrons, to split water to form hydrogen, and to store oxygen during operation. These condenser devices can be fabricated with large surface areas and integrated into simple form factors that allow for use in existing wind and solar facilities, generating H_2 onsite that can store electrical power. The simple construction and operational modes allow for mass production of these devices that will drive down capital costs required to achieve costs below $\$1/\text{kg-H}_2$, which will enable rural cost-competitive diesel and ammonia fertilizer production.

What are the specific project outcomes as they relate to the public purpose of protection, conservation, preservation, and enhancement of the state's natural resources?

A charge-swing catalytic condenser device will be designed that demonstrates carbon-free sustainable H_2 generation from water to offset CO_2 in small devices with a projected production cost below conventional electrolysis. In addition, carbon-free H_2 generation reduces the emissions of CO_2 into the atmosphere and increases the overall sustainability of the fertilizer, ammonia, used in Minnesota agriculture. Hydrogen is also the key ingredient necessary for producing sustainable clean-burning fuels and the removal of heteroatoms from liquids that leach into the soil; lower-cost hydrogen increases the cost-effectiveness of abatement for preservation and conservation of public lands through more viable pollution cleanup.

Project Location

What is the best scale for describing where your work will take place?

Region(s): Metro

What is the best scale to describe the area impacted by your work?

Statewide

When will the work impact occur?

In the Future

Activities and Milestones

Activity 1: Synthesize charge-swing condenser films

Activity Budget: \$233,725

Activity Description:

Charge-swing condenser films will be prepared from layered metal and metal-oxide films on conductive silicon wafers with a top surface that can undergo reduction-oxidation in the presence of water or steam. Wafers will be prepared with varying thicknesses of dielectric and/or oxygen-accumulating films varying in thickness from 1 to 100 nanometer thickness, with varying degrees of crystallinity and grain size. Composition, crystallinity, and thickness of the composite films will be varied to optimize overall performance of the device. Task #1: Silicon-based devices are synthesized with a combined high-k dielectric oxide film and a redox active top layer of metal/metal-oxide film in sizes at or above 1 cm². Task #2: A secondary, alternative design device with oxygen-sorbent base layer is fabricated with a water-splitting O₂-conductive film capable of stabilizing a charge above 1 V on surfaces at or above 1 cm². Task #3: Both device concepts from milestones 1 and 2 are varied in film thickness over three possible length scales to reduce charge leakage through the films.

Activity Milestones:

Description	Approximate Completion Date
Silicon-based devices are synthesized with a combined high-k dielectric oxide film and redox top layer	June 30, 2026
A device designed with an oxygen-sorbent base layer is fabricated capable of 1 V stabilization	June 30, 2027
Film thicknesses are varied over three possible lengthscales to assess electronic leakage	June 30, 2028

Activity 2: Evaluate and characterize charge-swing condenser films

Activity Budget: \$241,905

Activity Description:

Accumulation of oxygen with applied potential will promote the initial release of H₂ gas in phase 1, while a second phase will reverse the applied potential and evolve O₂ gas to complete the entire regeneration cycle. The electronic device will be designed and optimized to control the flow and distribution of electrons throughout the device to accelerate the rate of water splitting to evolve H₂ and O₂ gas separately and to maximize the total amount of evolved gas. Task 1: Electronic characterization of fabricated devices identifies a design that exceeds 100 nF/cm² in total device capacitance. Task 2: Device electronic switching between applied potential phases occurs at speeds as fast as 10 Hz without a loss in device capacitance. Task 3: Three different redox active metals are evaluated as the top active layer exposed to water or steam for the water splitting mechanism to determine their ability to split and/or accumulate oxygen. Evolved gases are measured with a mass spectrometer above the detection limit.

Activity Milestones:

Description	Approximate Completion Date
Electronic characterization of devices exceeds 100 nF/cm ²	June 30, 2026
Device electronic switching exhibits speeds as fast or faster than 10 Hz	June 30, 2027
Three different redox active metals are evaluated for water splitting	June 30, 2028

Activity 3: Fabricate charge-swing condenser devices for applications

Activity Budget: \$250,370

Activity Description:

The fabricated films designed in activities 1 and 2 will be developed in parallel for application as a device that could function with higher productivity per unit volume with incorporated electrical connections and spacing for gas flow. This film design will utilize a flexible substrate that can be rolled into dense pellets that maximize the film surface area per unit volume while also permitting macropores for gas flow into and out of the reacting pellet. Task 1: Charge-swing condensers are fabricated on flexible conductive substrate films such as metal on Kapton. Task 2: Charge-swing condensers are fabricated with an oxide-based electrical contact that enables application of potential to soft substrates. Task 3: The performance of charge-swing condensers for electronic charge separation and for water splitting (i.e., measurable H₂ evolution) is evaluated for flexible devices with curvature in excess of 1 cm⁻¹.

Activity Milestones:

Description	Approximate Completion Date
Charge-swing condensers are fabricated on flexible conductive films	January 31, 2028
Charge-swing condensers are fabricated with oxide electrical contacts	March 31, 2028
Charge swing condenser performance is evaluated with curvative above 1 cm ⁻¹	June 30, 2028

Project Partners and Collaborators

Name	Organization	Role	Receiving Funds
C. Daniel Frisbie	University of Minnesota, Twin Cities	Leads the effort to fabricate devices and characterize their electronic properties	Yes
Professor Chris Leighton	University of Minnesota, Twin Cities	Synthesizes functional films and evaluates their properties and storage capacity	Yes
Professor Chris Bartel	University of Minnesota, Twin Cities	Computes the energy of reaction and diffusion films for water splitting and storage	Yes

Dissemination

Describe your plans for dissemination, presentation, documentation, or sharing of data, results, samples, physical collections, and other products and how they will follow ENRTF Acknowledgement Requirements and Guidelines.

All data generated during research tasks will be stored within the University of Minnesota electronic system including internal data drives. Research results will be shared internally via monthly meetings to discuss progress and communicate next steps. Research results will be made available upon publication via multiple methods including: peer-reviewed publications, open access preprints, and additional information via email request. Data sets will be incorporated into publications and preprints, while large data sets will be made available to the public via the Data Repository of the University of Minnesota. Results will also be communicated to the public via presentation at conferences in relevant research fields. All presentations and publications of results funded by this project will acknowledge the Environment and Natural Resources Trust Fund.

Long-Term Implementation and Funding

Describe how the results will be implemented and how any ongoing effort will be funded. If not already addressed as part of the project, how will findings, results, and products developed be implemented after project completion? If additional work is needed, how will this work be funded?

The goal of the project is to advance the rural processing technology to make H₂ for ammonia and diesel such that it can be developed commercially via a startup company independent of the university. The PI has already communicated with a venture capital firm, and formation of a future startup company will use private equity combined with a license to the technology developed in this project to form a company in Minnesota to manufacture these devices. The results and findings developed during this project will serve to generate patents and to identify the required manufacturing stages required for device commercialization.

Budget Summary

Category / Name	Subcategory or Type	Description	Purpose	Gen. Ineligible	% Benefits	# FTE	Classified Staff?	\$ Amount
Personnel								
Graduate Student 1		Evaluates charge-swing condenser electronic characteristics			25%	3		\$149,667
Graduate Student 2		Operates the charge-swing reactor to evaluate the rate of water splitting			25%	3		\$149,667
Graduate Student 3		Optimizes the sputtering of condenser oxide films			25%	3		\$149,667
Principal Investigator		Paul Dauenhauer, Principal Investigator			27%	0.06		\$12,574
Co-Investigator 1		Chris Bartel, Co-Investigator			27%	0.03		\$6,448
Co-Investigator 2		Chris Leighton, Co-Investigator 2			27%	0.03		\$11,052
Co-Investigator 3		C. Daniel Frisbie, Co-Investigator 3			27%	0.03		\$12,834
							Sub Total	\$491,909
Contracts and Services								
University of Minnesota Characterization Facility	Internal services or fees (uncommon)	Characterization techniques include X-ray diffraction to analyze the crystallinity of surface metals and interior stack oxides, electron microscopy to evaluate the distribution of metal and metal oxide clusters, atomic force microscopy to measure the distribution of surface roughness, X-ray photoelectron spectroscopy and ion beam analysis to measure the chemical composition				0.36		\$40,000
University of Minnesota Nanofabrication Center	Internal services or fees (uncommon)	Nanomaterials fabrication equipment with support of research staff. Services in the Minnesota Nanofabrication facility include sputtering and atomic layer deposition (ALD) to deposit oxide, carbon, and film layers along with thin film patterning tools to fabricate controllable surface architectures.				0.6		\$60,000
							Sub Total	\$100,000

Equipment, Tools, and Supplies								
	Tools and Supplies	<p>The cost of consumables is estimated at \$45,000 in year 1, \$45,000 in year 2, and \$44,091 in year 3. The category of “consumables” includes the purchase of chemicals, materials, and spare parts that all cost less than \$5,000 per item which enable the synthesis and fabrication of thin-film devices and the operation of analysis equipment including materials characterization and chemical analysis. This category enables the experiments and synthesis steps that allow for the experimental tasks related to evaluating thin film catalyst devices. For substrate film growth, this includes ultrahigh purity O2 both normal and isotopically labeled O2, sputtering reagent targets, ALD precursors, contact deposition metals, cryogenics. Consumables for materials processing include glassware, crucibles, etch masks, and related hardware, while consumables for characterization include atomic force microscopy probes. Consumables for chemical reaction include gas cylinders including oxygen, nitrogen, helium, and argon, along with mixtures of gases, mass flow controllers, piping and valving connections, thermocouples. In addition, consumables includes analysis equipment supplies including gas chromatography parts including seals, columns, and valves as well as infrared spectroscopy and mass spectrometry parts. Reactor supplies include CF crosses and flanges, a temperature controller, a miniature feedthrough, gaskets, leak valves, linear actuators, pressure gauges, and electronic controllers. Supplies also include safety equipment including gloves, laboratory coats, safety glasses, and related safety equipment. The precise number of each category of consumable is determined based on the number of each type of experiment and the rate of equipment spart parts, which is determined as the selection of specific experiments</p>	<p>The category of “consumables” includes the purchase of chemicals, materials, and spare parts that all cost less than five thousand dollars per item which enable the synthesis and fabrication of thin-film devices and the operation of analysis equipment including materials characterization and chemical analysis. This category enables the experiments and synthesis steps that allow for the experimental tasks related to the research tasks of evaluating thin film catalyst devices.</p>					\$134,091

		are identified or equipment parts need replacement.						
							Sub Total	\$134,091
Capital Expenditures								
							Sub Total	-
Acquisitions and Stewardship								
							Sub Total	-
Travel In Minnesota								
							Sub Total	-
Travel Outside Minnesota								
							Sub Total	-
Printing and Publication								
							Sub Total	-
Other Expenses								
							Sub Total	-
							Grand Total	\$726,000

Classified Staff or Generally Ineligible Expenses

Category/Name	Subcategory or Type	Description	Justification Ineligible Expense or Classified Staff Request
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Non ENRTF Funds

Category	Specific Source	Use	Status	\$ Amount
State				
			State Sub Total	-
Non-State				
			Non State Sub Total	-
			Funds Total	-

Total Project Cost: \$726,000

This amount accurately reflects total project cost?

Yes

Attachments

Required Attachments

Visual Component

File: [8a83c303-e96.pdf](#)

Alternate Text for Visual Component

Figure 1. Charge-swing condenser for H₂O splitting to H₂ and O₂ gases. A charge-swing reactor converts water, carbon dioxide and air to H₂, ammonia, and chemicals such as methanol. The price of H₂ can be manufactured below \$1/kg-H₂ for low electrical prices below \$0.03/kWhr....

Supplemental Attachments

Capital Project Questionnaire, Budget Supplements, Support Letter, Photos, Media, Other

Title	File
Letter of Approval, U of Minnesota Sponsored Projects Administration	5346a3db-e5a.pdf

Difference between Proposal and Work Plan

Describe changes from Proposal to Work Plan Stage

The work plan contains all of the original tasks and goals but will reduce the number of catalytic devices synthesized, characterized, and analyzed. This will maintain all of the original objectives of the proposed work but will reduce the total number of data points collected for each variation of the engineered catalytic devices.

Additional Acknowledgements and Conditions:

The following are acknowledgements and conditions beyond those already included in the above workplan:

Do you understand and acknowledge the ENRTF repayment requirements if the use of capital equipment changes?

N/A

Do you understand that travel expenses are only approved if they follow the "Commissioner's Plan" promulgated by the Commissioner of Management of Budget or, for University of Minnesota projects, the University of Minnesota plan?

N/A

Does your project have potential for royalties, copyrights, patents, sale of products and assets, or revenue generation?

Yes

Do you understand and acknowledge IP and revenue-return and sharing requirements in 116P.10?

Yes

Do you wish to request reinvestment of any revenues into your project instead of returning revenue to the ENRTF?

No

Does your project include original, hypothesis-driven research?

No

Does the organization have a fiscal agent for this project?

Yes, Sponsored Projects Administration

Does your project include the pre-design, design, construction, or renovation of a building, trail, campground, or other fixed capital asset costing \$10,000 or more or large-scale stream or wetland restoration?

No

Do you propose using an appropriation from the Environment and Natural Resources Trust Fund to conduct a project that provides children's services (as defined in Minnesota Statutes section 299C.61 Subd.7 as "the provision of care, treatment, education, training, instruction, or recreation to children")?

No

Provide the name(s) and organization(s) of additional individuals assisting in the completion of this project:

None

Do you understand that a named service contract does not constitute a funder-designated subrecipient or approval of a sole-source contract? In other words, a service contract entity is only approved if it has been selected according to the contracting rules identified in state law and policy for organizations that receive ENRTF funds through direct appropriations, or in the DNR's reimbursement manual for non-state organizations. These rules may include competitive bidding and prevailing wage requirements

N/A