Environment and Natural Resources Trust Fund

2024 Request for Proposal

General Information

Proposal ID: 2024-259

Proposal Title: Carbon-Free Hydrogen for Sustainable Power and Steel Production

Project Manager Information

Name: Aditya Bhan

Organization: U of MN - College of Science and Engineering

Office Telephone: (612) 626-3981

Email: abhan@umn.edu

Project Basic Information

Project Summary: Methane pyrolysis generates both hydrogen, a carbon-free energy resource, and solid carbon used in steel manufacturing. The proposed plasma-catalytic pyrolysis technology aims to supplant existing carbon-intensive technologies leveraging renewable electricity.

Funds Requested: $490,000

Proposed Project Completion: June 30, 2027

LCCMR Funding Category: Air Quality, Climate Change, and Renewable Energy (E)

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?

During the Project and In the Future

Narrative

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

Natural gas is used to heat 63% of Minnesota homes and it is the primary energy source for heavy industry in Minnesota. While greenhouse gas emissions in Minnesota have decreased 23% since 2005, natural gas emissions from Minnesota's residential and industrial sectors have increased substantially in this period. Power-to-hydrogen, which refers to the use of electricity generated by a carbon-free resource to produce hydrogen, has been identified as a breakthrough technology towards Decarbonizing Minnesota's Natural Gas End Uses in a 2021 report by the Great Plains Institute and the Center for Energy and Environment. Capability to convert natural gas into hydrogen and solid carbon using renewable electricity would enable us to leverage the existing distribution infrastructure of natural gas to produce clean-burning hydrogen on-demand and produce solid carbon for the Minnesota steel industry and reduce considerably CO2 emissions from natural gas use in Minnesota.

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.

Combustion of hydrogen generates only water, this is why it is touted as the "new oil", a basis for energy prosperity in the 21st century that oil has served for the past century. But hydrogen is not readily found in underground resources, it has to be produced from fossil resources. The state-of-the-art catalytic reforming process does so producing 5.5 tons CO2 per ton of hydrogen. Water electrolysis produces hydrogen but costs $5 per kilogram of hydrogen. The US Department of Energy identified $1/kg hydrogen as one of the six Energy Earthshots to address the climate crisis. We propose an electricity-driven plasma-catalytic process with efficiencies exceeding electrolysis, to make carbon-free hydrogen and solid carbon residue. Catalysts that aid in carbon recovery, moving-bed reactors that entrain the solid carbon on the solid catalyst, and renewable electricity-driven plasma-induced low temperature methane pyrolysis are required in tandem to enable carbon-free hydrogen production. The closed loop process operates by recovery of the deposited carbon and regeneration and reuse of the solid catalytic substrate. Converting fossil fuel resources to hydrogen and solid carbon represents a new and versatile strategy to decarbonize Minnesota`s industrial natural gas use and iron and steel industry.

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?

- Our efforts in this project would demonstrate a method to make carbon-free hydrogen and also showcase how the hydrogen and solid carbon product could be used to decarbonize Minnesota`s industrial natural gas use and iron ore processing and steelmaking.
- Development of new catalysts and moving bed reactors in microwave plasmas for recovery of solid carbon in pyrolysis reactions.
- Estimation of CO2 reduction and preliminary techno-economic analysis for scale up.

Activities and Milestones

Activity 1: Development of benchtop size prototype microwave plasma reactor

Activity Budget: $194,287

Activity Description:

Research in activity 1 will be focused on acquiring baseline data for plasma pyrolysis of methane in a microwave (MW) plasma to produce hydrogen and solid carbon. Efficiencies of >300 grams hydrogen per kilowatt-hour (kWh) will be a target for this effort which would make plasma-based technologies more cost effective than state-of-the-art electrolyzers for production of hydrogen. An outstanding challenge in MW plasma pyrolysis of methane is incomplete conversion and the production of gaseous hydrocarbon species and not just solid carbon. This activity will examine the following key questions: (1) What determines flow characteristics in the MW plasma and whether these flow characteristics result in incomplete methane pyrolysis? (2) Can solids (e.g., a catalyst) be readily introduced into the MW plasma? (3) How can energy use in the MW plasma be optimized?

Activity Milestones:

Description	Approximate Completion Date
Operational reactor with ability to capture solid carbon and quantification of products	March 31, 2025
Model describing gas flow in MW plasma reactor	September 30, 2025
Prototype reactor with solid catalysts in MW plasma reactors	June 30, 2026
Integration of plasma and catalytic processes in moving bed reactors	December 31, 2026
Case studies of plasma-catalytic process with carbon recovery	June 30, 2027

Activity 2: Evaluation of methane pyrolysis catalysts and moving bed reactors

Activity Budget: $189,330

Activity Description:

Research in Activity 2 will be focused on determining the use of iron and carbon-based catalysts for the pyrolysis of methane to form solid carbon and hydrogen. The research will build upon a precedent literature showing that iron-based catalysts can lead to high value carbon fibers and carbon nanotubes from methane pyrolysis. Our efforts however, will be focused on probing material and process parameters that allow iron-based catalysts to form solid carbon deposits that allow ready recovery of the iron catalyst i.e., the solid carbon products can be separated from the catalyst by mechanical separation. A chemical engineering approach to achieve this is to have moving bed reactors in which solid catalysts are entrained in the gas flow and only deposit small amounts of carbon per pass; this carbon can then be recovered by using a cyclone separator and a filter. As an alternative, we will evaluate the use of carbon-based catalysts that incorporate trace amounts of iron so that the carbon deposits themselves become a part of the solid catalyst. Compositional and structural characteristics of the carbon deposits will be examined using X-ray diffraction, Raman Spectroscopy, and X-ray photoelectron spectroscopy, readily available at UMN Characterization Facility.

Activity Milestones:

Description	Approximate Completion Date
Evaluation of iron-based catalysts for methane pyrolysis	December 31, 2024
Moving bed reactor set up for methane pyrolysis	September 30, 2025
Characterization of carbon deposits formed in fixed bed and moving bed reactors	December 31, 2025
Integration of plasma and catalytic processes in moving bed reactors	December 31, 2026

Activity 3: Scale-up and process design for plasma catalytic reactor and estimation of CO_2 emission reduction in iron and steel manufacturing

Activity Budget: $106,383

Activity Description:
To assess viability of the proposed technology, we will perform process scale-up and process design calculations. Baseline knowledge of catalytic and plasma processes will be combined with data acquired in activities 1 and 2 to developed an integrated model for the process. This model will be used to optimize the reactor design and separation train to achieve optimal hydrogen and solid carbon flux and optimal catalyst lifetime per kWh of power input into the plasma reactor. Output from this model will then be used to determine CO_2 reduction in iron and steel processing based on life cycle assessment. This model will incorporate operational constraints for mineral processing and supply chain logistics for availability of both natural gas and mineral resources.

Activity Milestones:

Description	Approximate Completion Date
Preliminary model for plasma catalytic reactor system	December 31, 2025
Optimization and scale up scenarios for plasma catalytic reactor system	June 30, 2026
Techno-economic and environmental analysis for iron ore processing	March 31, 2027

Project Partners and Collaborators

Name	Organization	Role	Receiving Funds
Peter Bruggeman	University of Minnesota - College of Science and Engineering	Professor Bruggeman is Professor and Associate Head of Mechanical Engineering at the University of Minnesota. He is an expert in plasma technology and will lead the development of the microwave (MW) plasma reactor.	Yes
Prodromos Daoutidis	University of Minnesota College of Science and Engineering	Professor Daoutidis is an expert in process design and systems engineering. His research lies at the crossroads of chemical engineering and operations research. He will lead the effort on techno-economic and environmental analysis.	Yes

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 US Department of Energy announced $7 billion to create regional clean energy hydrogen hubs in 2022. In 2023, another $200 million was allocated for Energy Earthshot Research Centers. These initiatives particularly target “hard to decarbonize sectors” including petroleum refining and steelmaking. A tremendous amount of future government funding is expected in this area from the Department of Defense, Department of Energy, National Science Foundation, and the Advanced Research Projects Agency-Energy. Initial support through LCCMR will position us to attract future funding while developing an out-of-the-box technology with extraordinary potential for decarbonizing industrial natural gas use, iron-ore mining, and steelmaking

Project Manager and Organization Qualifications

Project Manager Name: Aditya Bhan

Job Title: Distinguished McKnight University Professor

Provide description of the project manager’s qualifications to manage the proposed project.

Aditya Bhan is a Distinguished McKnight University Professor in the Chemical Engineering and Materials Science Department at the University of Minnesota Twin Cities (UMN). Following B.Tech. and Ph.D. degrees in chemical engineering from IIT Kanpur (2000) and Purdue University (2005), and post-doctoral research at the University of California Berkeley, he joined UMN in 2007. He leads a research group that focuses on developing innovative catalytic processes for energy conversion and petrochemical synthesis. His group at the University of Minnesota has been recognized with the Paul H. Emmett Award in Fundamental Catalysis from the North American Catalysis Society (2023), the Young Researcher Award from the Acid-Base Catalysis Society (2017), the Ipatieff Prize from the American Chemical Society (2016), and the Richard A. Glenn Award from the Energy & Fuels Division of the American Chemical Society (2016). He was awarded both the Department of Energy Early Career Award (2012) and the National Science Foundation Career Award (2011). He serves as Editor for Journal of Catalysis, is Past-Chair of the American Chemical Society Catalysis Science & Technology Division, and has served on the Board of Directors of the International Symposium of Chemical Reaction Engineering and for the Chemical Reaction Engineering Division of the American Institute of Chemical Engineers.

Organization: U of MN - College of Science and Engineering

Organization Description:

The College of Science and Engineering at UMN houses 12 departments and a multitude of research centers and posted

$141 million in research expenditure in FY2021. Over the past five years, CSE research has generated more than 779 invention disclosures, 479 patents, and 51 startup companies. The Characterization Facility (UMN Charfac) housed in the College of Science and Engineering provides state-of-the-art materials characterization facilities for UMN researchers that is maintained and upgraded by experts.

Budget Summary

Category / Name	Subcategory or Type	Description	Purpose	Gen. Ineligible	% Benefits	# FTE	Classified Staff?	$ Amount
Personnel								
Principal Investigator		Prof. Bhan will lead the research effort			26.9%	0.12		$19,210
Co-Investigator		Prof. Bruggeman will lead the plasma technology effort			26.9%	0.12		$17,631
Co-Investigator		Prof. Daoutidis will lead the process design and technoeconomic analysis			26.9%	0.12		$28,951
Graduate Research Assistant		One student in Chemical Engineering and Materials Science working on pyrolysis catalysts			41%	1.35		$170,226
Graduate Research Assistant		Senior graduate student (low tuition) working on scale up and technoeconomic analysis in Chemical Engineering			23.8%	0.36		$36,604
Graduate Research Assitant		Graduate student researcher in Mechanical Engineering working on prototype microwave plasma reactor			43.2%	1.11		$128,935
							Sub Total	**$401,557**
Contracts and Services								
							Sub Total	-
Equipment, Tools, and Supplies								
	Tools and Supplies	Laboratory supplies (e.g., glassware) and chemical reagents	The laboratory supplies and chemical reagents are essential to evaluate the plasma-catalytic methane pyrolysis technology for carbon-free hydrogen production.					$30,000
							Sub Total	**$30,000**
Capital Expenditures								
		Plasma-catalytic moving bed reactor system	Technology to be developed and demonstrated in this research effort	X				$40,000

							Sub Total	**$40,000**
Acquisitions and Stewardship								
							Sub Total	**-**
Travel In Minnesota								
							Sub Total	**-**
Travel Outside Minnesota								
	Conference Registration Miles/ Meals/ Lodging	Approximately 1 trip per year for each of the three research groups involved.	To present results from the ensuing research at conferences pertaining to hydrogen production and natural gas use.	X				$9,000
							Sub Total	**$9,000**
Printing and Publication								
							Sub Total	**-**
Other Expenses								
		University of Minnesota Characterization Facility Use	The University of Minnesota Characterization Facility houses many of the advanced laboratory instruments essential for this research. These instruments are accessed on an hourly-charge basis by researchers					$9,443
							Sub Total	**$9,443**
							Grand Total	**$490,000**

Classified Staff or Generally Ineligible Expenses

Category/Name	Subcategory or Type	Description	Justification Ineligible Expense or Classified Staff Request
Capital Expenditures		Plasma-catalytic moving bed reactor system	No such reactors exist or are available. The key technology that we propose to develop relies on a moving-bed plasma catalytic reactor, while both plasma reactors and moving-bed catalytic reactors exist, no reactors combine these attributes. We propose to develop the first prototype of this reactor which we believe is critically enabling for carbon-free hydrogen production. **Additional Explanation :** With follow up funding from either federal support grants or industry this equipment will be leveraged to acquire data for catalytic pyrolysis technologies through its useful life.
Travel Outside Minnesota	Conference Registration Miles/Meals/Lodging	Approximately 1 trip per year for each of the three research groups involved.	The prototype technology we propose to develop is of broad interest to the scientific community as well as to the industry. Results will be presented at meetings like the Natural Gas Conversion Symposium Meeting (NGCS) to engage the broader science and technology community in furthering the use of this technology.

Non ENRTF Funds

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

Attachments

Required Attachments

Visual Component

File: abd7a23c-251.pdf

Alternate Text for Visual Component

Overview of proposed technology to harness renewable electricity and distributed methane supply to produce hydrogen and solid carbon by plasma-assisted catalytic pyrolysis. Hydrogen finds use as an energy carrier for transportation and heating. Iron ore can be reduced with hydrogen to make iron which is mixed with carbon for steelmaking....

Optional Attachments

Support Letter, Photos, Media, Other

Title	File
UMN SPA letter	df9f9ca3-082.pdf

Administrative Use

Does your project include restoration or acquisition of land rights?

No

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

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?

Yes

Does the organization have a fiscal agent for this project?

No

Does your project include the design, construction, or renovation of a building, trail, campground, or other capital asset costing $10,000 or more?

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?

No