



Environment and Natural Resources Trust Fund

2023 Request for Proposal

General Information

Proposal ID: 2023-171

Proposal Title: Environment-Friendly Decarbonizing of Steel Production with Hydrogen Plasma

Project Manager Information

Name: Uwe Kortshagen

Organization: U of MN - College of Science and Engineering

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Project Basic Information

Project Summary: Conventional ironmaking requires massive amounts of fossil fuels and generates significant waste and CO2 emissions. Our microwave hydrogen plasma ironmaking eliminates fossil fuel use and CO2 emissions while reducing waste.

Funds Requested: \$769,000

Proposed Project Completion: June 30, 2026

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?

Statewide

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.

Producing iron and steel - our most important industrial metals - carries an enormous environmental footprint. Globally, iron and steel making accounts for 8-10% of total carbon dioxide emissions. Each year, Minnesota produces 30-40 million metric tons of heat-consolidated blast furnace pellets for the iron and steel industry, which contributes roughly three million metric tons of CO₂ emissions to the atmosphere. In addition, significant amounts of poor quality ore and tailings containing unused minerals are discharged into the landscape as waste products. The global steel industry aims to reduce CO₂ emissions by 50% by 2050, creating an urgent need for disruptive technologies that will decarbonize the iron and steel production process. It is also critical that new decarbonization technologies can efficiently process alternative iron resources like the low-quality ores and tailings that are currently regarded as waste. The proposed project aims to create a disruptive technology that can efficiently use a broad spectrum of iron ores and eliminates the energy-intensive pelletization process and its associated emissions. This technology will dramatically reduce CO₂ emissions and allow for the efficient use of alternative iron resources that are currently being discarded as waste and tailings.

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.

Conventional iron ore processing is energy- and carbon-intensive, using fossil fuel for both heat and chemical reduction. We propose a fossil fuel-free iron ore reduction process using microwave hydrogen plasma (an ionized gas), which is a technology recently developed in the High Temperature and Plasma Laboratory at the University of Minnesota (provisional patent filed 5/9/2022). The proposed process eliminates both carbon-intensive reduction and energy-intensive pelletization steps in conventional iron ore processing. Hydrogen plasma reduction is a fully electric technology and, when operated with renewable electricity and “green” hydrogen produced by electrolysis, completely obviates the need for fossil fuels and thus has the potential to decarbonize the ironmaking process. Our plasma technology has already demonstrated over 90% reduction of magnetite and other iron ores (hematite) and may enable the utilization of lower quality ores, as well as existing tailings and waste piles. In addition, as a virtually instant on-off technology without significant thermal inertia, hydrogen plasma is exceptionally compatible with intermittent renewable electricity supplied by renewable sources. Finally, hydrogen plasma reduction occurs up to one hundred times faster than reduction using other carbon-free hydrogen approaches, which will ultimately lead to significant advantages in efficiency and economics.

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?

- Development of a fossil fuel free ironmaking technology based on hydrogen plasma that can utilize lower quality alternative iron resources and iron ore waste piles
- Demonstration of potential for scale up by continuous operation for more than 10 hours with less than 5% variation of process conditions and product quality
- Estimation of CO₂ emission reductions by replacing iron ore pelletization with hydrogen plasma reduction
- Preliminary techno-economic analysis of the proposed process with scale up assessment
- Early-stage anticipatory life cycle study focused on scale-up potential for the plasma technology

Activities and Milestones

Activity 1: Fundamental Evaluation of the Hydrogen Plasma Reduction System

Activity Budget: \$283,166

Activity Description:

Research in Activity 1 will be focused on generating baseline data for the hydrogen plasma reduction system using reagent grade iron minerals – magnetite, hematite, and goethite. Hydrogen plasma reduction of iron minerals has been demonstrated by the High Temperature and Plasma Laboratory on a benchtop size reactor, demonstrating more than 90% reduction of reagent grade magnetite and hematite with ore particles passing through the hydrogen plasma in less than one tenth of a second. This activity will investigate the following important questions: 1) What is the impact of iron mineralogy on hydrogen plasma reduction? 2) What are the characteristics of the input and exhaust streams of the reactor? 3) What is the energy budget of the hydrogen plasma process? 4) How do these metrics scale with larger reactor size?

The ultimate goal of Activity 1 is to better understand how changing the iron mineralogy will impact the performance of the hydrogen plasma system – from the mass and energy balance, through product quality. This baseline data will be compared to work using lower quality alternative iron ore resources and iron ore waste materials. A thorough characterization of the feed and product materials will be undertaken.

Activity Milestones:

Description	Completion Date
Exploration of optimal conditions for the reduction of different iron mineral types	June 30, 2024
Analysis of input and exhaust streams and energy efficiency of hydrogen plasma	June 30, 2025
Determination of scaling laws with larger scale reactor	June 30, 2026

Activity 2: Evaluation of the Hydrogen Plasma Reduction System using Iron Ore Concentrates

Activity Budget: \$243,916

Activity Description:

Research in Activity 2 will be focused on assessing the response of the H₂ plasma reduction process relative to baseline operating conditions determined in Activity 1. The activity will use existing iron ore concentrates and potential iron ore concentrates produced from Minnesota iron ore waste.

Iron ore concentrates for Activity 2 will be acquired from industry partners and beneficiated from lower quality alternative iron ore resources and iron ore waste materials. A series of experiments will be conducted under baseline conditions, established in Activity 1, using magnetite, hematite, mixed magnetite-hematite, and hematite-goethite-magnetite concentrates. This will inform on the H₂ Plasma reduction systems response to gangue materials present with the iron minerals. A series of follow-up experiments will be conducted to improve the efficiency of H₂ plasma reduction of the various ore types. A thorough characterization of the feed and product materials will be undertaken.

Activity Milestones:

Description	Completion Date
Acquire iron ore concentrates that are representative of current industry standards	June 30, 2024
Beneficiate lower quality Minnesota iron ores and iron ore waste materials to produce a concentrate	June 30, 2024
Compare performance of the reagent grade material to iron ore concentrates	June 30, 2025
Determination of optimal operating conditions for iron ore concentrate reduction	June 30, 2025
Explore reduction conditions, input & exhaust streams, energy efficiency for scaling up	June 30, 2026

Activity 3: Techno-Economic-Environmental Analysis of Hydrogen Plasma Reduction System

Activity Budget: \$241,918

Activity Description:

To assess the viability of the proposed technology, we will perform a comprehensive techno-economic-environmental analysis (TEEA) of the whole system. To this end, we will first combine first-principles knowledge and the experimental data obtained in Activity 1 to build a hybrid model of the plasma-based iron ore reduction process, which will then be integrated with models for the upstream green hydrogen production and the downstream metal processing processes to form the full manufacturing system. The design of the system will be optimized with respect to its economic and environmental performance metrics, where the latter will focus on CO₂ emissions evaluated via life cycle assessment. The TEEA will be performed for plants of different scales. Importantly, our model will incorporate intermittent renewable energy input and the corresponding operational constraints, which will enable adequate sizing of the process units and additional energy and product storage capacities. Moreover, we will analyze a potential deployment of the proposed technology in Minnesota at the supply chain level. Our geographically explicit supply chain model will allow us to determine the most suitable locations for such plants and the best logistics strategy for distributing the products to customers in and out of the state.

Activity Milestones:

Description	Completion Date
Build preliminary hybrid model of the plasma-based iron ore reduction process	June 30, 2024
Build preliminary model for the whole system and perform design optimization	December 31, 2024
Update model with new experimental data and perform update design optimization	June 30, 2025
Perform life cycle assessment for the whole system	December 31, 2025
Perform supply chain optimization and life cycle assessment considering the State of Minnesota	June 30, 2026

Project Partners and Collaborators

Name	Organization	Role	Receiving Funds
Peter J. Bruggeman	University of Minnesota - College of Science and Engineering	Professor Bruggeman is an expert in plasma technology and co-inventor of the hydrogen plasma reduction. He will work on further developing the process.	Yes
Qi Zhang	University of Minnesota - College of Science and Engineering	Prof. Zhang's research in the area of process systems engineering lies at the intersection of chemical engineering and operations research, focusing on computational discovery and decision making in complex process systems. He will lead the techno-economic analysis of the process.	Yes
Rodney Johnson	University of Minnesota - Duluth - Natural Resources Research Institute	Dr. Johnson holds the Endowed Taconite Chair. He is respected geologist, mineralogist, and geometallurgist with over thirty years of experience in exploration, mining, research, and mineral processing and will lead efforts in production of iron ore concentrates and product characterization.	Yes
Brett Spigarelli	University of Minnesota - Duluth - Natural Resources Research Institute	Dr. Spigarelli, Metallurgical Engineer at the NRRI Coleraine labs, received his Ph.D. in Chemical Engineering from Michigan Technological University. He will work on iron ore concentrates and product characterization.	Yes
Pat Schoff	University of Minnesota - Duluth - Natural Resources Research Institute	Dr. Schoff teaches in the Biology Department and Integrated Biosciences graduate program at UMD. Current research includes studies on the effects of chemicals and other stressors on the early developmental stages of fish and amphibians, endocrine disruption, and recently, sustainable development. He will lead the environmental life cycle 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 proposed research will help establish the full potential of the hydrogen plasma iron ore reduction technology. Once this is achieved, we expect that there will be significant interest both by federal funding agencies and by industry. The team will pursue research funding from the Advanced Research Projects Agency-Energy (ARPA-E), the Department of Energy, and the National Science Foundation. The University is already seeking patent protection for the technology and the team will pursue collaborations with NRRI's industrial partners in the iron and steel processing field.

Other ENRTF Appropriations Awarded in the Last Six Years

Name	Appropriation	Amount Awarded
Develop Solar Window Concentrators for Electricity	M.L. 2018, Chp. 214, Art. 4, Sec. 2, Subd. 07a	\$350,000

Project Manager and Organization Qualifications

Project Manager Name: Uwe Kortshagen

Job Title: Professor

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

Uwe Kortshagen is Professor of Mechanical Engineering at the University of Minnesota. Professor Kortshagen is an expert in materials processing with plasmas and co-inventor of the plasma hydrogen reduction technology. He holds the Ronald L. and Janet A. Christenson Chair in Renewable Energy. His work has been published in more than 220 scientific articles in peer-reviewed journals. His invention of silicon nanoparticle inks produced by plasmas has been patented by the University of Minnesota and licensed to a total of four industrial partners. He was issued 4 patents that generated royalty income exceeding \$1M and led to 2 start-up companies.

Professor Kortshagen has considerable leadership experience of multi-investigator teams, having led three interdisciplinary research groups of the National Science Foundation-funded UMN Materials Research Science and Engineering Center from 2007-2021. He also directs an Army Research Office funded Multidisciplinary University Research Initiative project, involving partners at Caltech, the University of Michigan, University of Iowa, and Washington University at St. Louis. He also gained significant management experience by serving for 10 years as Head of the Department of Mechanical Engineering at the University of Minnesota, which comprises more than 40 faculty, 40 staff members, and ~280 graduate students with an annual combined operations, maintenance, and research budget of ~\$26M, while still managing his research group of about 15 graduate students.

He will oversee the project and be responsible for the day-to-day operations.

Organization: U of MN - College of Science and Engineering

Organization Description:

The University of Minnesota offers world-class infrastructure for this project. The High Temperature and Plasma Technology lab (Professors Kortshagen and Bruggeman) is one of the best equipped plasma technology laboratories in the world. The team has access to a large number of shared materials characterization instruments at the University of Minnesota Materials Characterization Facility ("CharFac," <http://www.charfac.umn.edu/>), including a small angle X-ray scattering facility, and an electron microscopy center. Several machine shops are also available at the University of Minnesota.

The Natural Resources Research Institute (NRRI) was established by the Minnesota legislature in 1983 as an applied science and engineering research organization to inform state citizens and decision-makers while leveraging the power of the University of Minnesota. NRRI employs over 140 scientists, engineers, technicians, staff and students in two industrial research facilities. Through collaborative partnerships, NRRI delivers the innovative tools and solutions needed to utilize and sustain Minnesota's precious natural resources. The project team based at the NRRI with locations in Duluth and Coleraine, MN, has extensive experience with iron ore processing, pellet induration, iron ore reduction, and carbo-thermic reduction.

Budget Summary

Category / Name	Subcategory or Type	Description	Purpose	Gen. Ineligible	% Benefits	# FTE	Classified Staff?	\$ Amount
Personnel								
Uwe Kortshagen		Principal Investigator / Project Manager (UMN-TC)			25%	0.15		\$50,882
Peter Bruggeman		co-Principal Investigator: plasma technology, UMN-TC			25%	0.15		\$29,568
Qi Zhang		co-Principal Investigator, economic analysis, UMN-TC			25%	0.15		\$22,168
Rodney Johnson		co-Principal Investigator, Endowed Taconite Chair, UMD NRRI			25%	0.27		\$42,387
Brett Spigarelli		Metallurgical Engineer, iron ore processing, UMD NRRI			25%	0.24		\$30,566
Pat Schoff		Research Associate, Environmental life cycle analysis, UMD-NRRI			25%	0.18		\$20,149
Stephen Monson Geerts		Geologist, iron ore processing, UMD NRRI			25%	0.09		\$9,519
Julie Mutchler		Chemical Lab Supervisor, UMD NRRI			22%	0.06		\$3,798
Laboratory technicians		3 lab technicians, UMD NRRI			22%	0.45		\$36,975
Graduate Student Researchers		3 graduate student researchers, 2 in Mechanical Eng., 1 in Chem. Eng. Mat. Sci, UMN-TC			43%	3.75		\$428,675
Research Project Manager		Research Project Manager UMD NRRI			25%	0.15		\$15,832
							Sub Total	\$690,519
Contracts and Services								
							Sub Total	-
Equipment, Tools, and Supplies								
	Equipment	Scaled up plasma reactor	A larger version of the current plasma reactor will be built to explore scaling laws					\$20,000

							Sub Total	\$20,000
Capital Expenditures								
							Sub Total	-
Acquisitions and Stewardship								
							Sub Total	-
Travel In Minnesota								
	Miles/ Meals/ Lodging	Travel of project participants between UMN-Twin Cities and UMD NRRI	Travel to discuss project progress, visit partner sites, participate in off-campus research					\$12,000
							Sub Total	\$12,000
Travel Outside Minnesota								
							Sub Total	-
Printing and Publication								
	Publication	Cost of publication charges	Cost of article preparation fees in open access scientific journals					\$15,000
							Sub Total	\$15,000
Other Expenses								
		Materials and Supplies	Process gases, glass ware, filters, general laboratory supplies					\$16,481
		Laboratory Services	Use of Materials Characterization Center					\$15,000
							Sub Total	\$31,481
							Grand Total	\$769,000

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	-

Attachments

Required Attachments

Visual Component

File: [5f5de6f8-6b7.pdf](#)

Alternate Text for Visual Component

The image demonstrates carbon-free iron ore reduction, using renewable energy to produce hydrogen from electrolysis and power the hydrogen plasma. Ground iron ore and existing mining waste of lower quality ores are fed into the plasma, which converts them to pure iron and water....

Optional Attachments

Support Letter or Other

Title	File
Letter of Endorsement	31e62286-a5d.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

