Environment and Natural Resources Trust Fund

2026 Request for Proposal

General Information

Proposal ID: 2026-351

Proposal Title: Clean Energy and Water from Iron Range Materials

Project Manager Information

Name: Chris Leighton

Organization: U of MN - College of Science and Engineering

Office Telephone: (612) 625-4018

Email: leighton@umn.edu

Project Basic Information

Project Summary: Minnesota Iron Range resources will be used to establish the synthesis of semiconductor-quality pyrite iron disulfide materials, unlocking multiple new clean energy and water applications for this vital state resource.

ENRTF Funds Requested: $987,000

Proposed Project Completion: June 30, 2029

LCCMR Funding Category: 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.

The Minnesota Iron Range is a vital asset. Through this resource, Minnesota has become the largest iron producer in the country, fueling the US steel industry and significantly boosting the state economy. The Iron Range generates essentially a single revenue stream, however, which is also carbon costly. At the same time, Minnesota, the US, and the world grapple with the enormous problems surrounding clean energy and water production. In essence, this proposal seeks to address these problems together, establishing a new revenue stream for the Iron Range based on a material with extraordinary potential for clean energy and water. That material is pyrite iron disulfide (fool's gold). In a long-standing U of M effort, Prof. Chris Leighton and collaborators have been working to establish FeS2 as a functional semiconductor, to realize its potential as a uniquely low-cost, non-toxic, earth-abundant material for electronic and energy devices. Pyrite is the cheapest known material for solar cells, for example, but has not yet generated competitive power conversion efficiencies. Similarly, pyrite has high potential for catalytic devices that remove nitrogen pollutants from ground water, not only generating drinking water, but also fertilizer for agriculture. These applications remain unrealized, however, due to inadequate investment.

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.

Through a 2022 LCCMR/ENRTF project, Leighton and collaborators at the U made a critical recent advance. Specifically, they demonstrated for the first time that an Iron Range resource (hematite iron oxide generated as a byproduct of titanium production from ilmenite ore) can be used to synthesize semiconductor-quality pyrite iron disulfide via simple processing. The key to this success was the understanding that only certain impurities in the source material impact the semiconducting properties of the produced pyrite. While the iron oxide starting material in this case was relatively high purity, from a pilot-scale process demonstrating titanium production from Iron Range ilmenite, this understanding paves the way to using even certain grades of taconite to generate semiconductor-quality pyrite. This would enable low-cost, non-toxic, earth-abundant semiconductor production from the existing ore output from the Iron Range, unlocking an entirely new revenue stream for a material with abundant potential for clean energy and water production. This project will thus have three aims, focusing on: (1) The mineralogy, metallurgy, and materials science of semiconducting pyrite production from Iron Range ores; (2) The development of semiconducting pyrite for solar applications; and (3) The development of semiconducting pyrite for catalytic devices for clean water applications.

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?

First, this project aims to develop a new revenue stream for a Minnesota resource that is already mined. Second, this new revenue stream will not only be based on an existing resource but will also contribute to efforts toward clean energy and water production, addressing multiple ENRTF Funding Priorities. Specifically, the semiconductor-quality iron disulfide generated from Iron Range resources will be used to develop solar cell and catalytic devices. The former is aimed at renewable energy production by low-cost solar-to-electric power conversion, the latter at low-cost nitrogen removal from ground water, creating drinking water and fertilizer byproducts.

Activities and Milestones

Activity 1: Semiconductor-Quality Pyrite from Minnesota Iron Range Resources

Activity Budget: $340,000

Activity Description:
Activity 1 will build on the recent demonstration of synthesis of semiconductor-quality pyrite from Iron Range ilmenite to expand this capability to taconite. This is more demanding, but also more impactful, as taconite is the existing product from the Iron Range, for which we aim to unlock new revenue streams. Modifying and optimizing procedures developed in Leighton's 2022 LCCMR/ENRTF project, various grades of taconite will be obtained and characterized by Taguta and Mlinar at NRRI. Leighton's group will then thermally reduce these ores to iron powder, then sulfidize to synthetic FeS2. Note that synthetic pyrite is essential, as natural pyrite has uncontrolled impurities and defects that can destroy semiconductivity. Leighton's group will then perform pyrite single crystal growth and thin film deposition, followed by extensive structural, chemical, impurity, and electronic characterization. These measurements will allow us to understand the essential relationships between specific impurities (especially cobalt, which is the only known shallow dopant in FeS2) and charge carrier densities and mobilities. The ultimate goal, via collaborative feedback between Leighton and Taguta/Mlinar, is to understand which grades of taconite can generate pyrite with sufficiently low carrier density / high carrier mobility to attain the electronic quality needed for device development.

Activity Milestones:

Description	Approximate Completion Date
Milestone A, initial proof-of-principle conversion of taconite to semiconducting pyrite	June 30, 2027
Milestone B, exploration of various grades of taconite for pyrite synthesis	June 30, 2028
Milestone C, fine-tuning of taconite characteristics for optimization of semiconducting pyrite	June 30, 2029

Activity 2: Renewable Energy Applications of Iron-Range-Derived Semiconducting Pyrite

Activity Budget: $330,000

Activity Description:
Activity 2 will focus on renewable energy applications of Iron-Range-derived semiconducting pyrite. As already noted, pyrite FeS2 has unique potential for low-cost solar cells but currently underperforms. Leighton and collaborators have identified the precise causes of this historical underperformance of pyrite devices and are uniquely positioned to design devices that avoid these problems. Only "p-n" homojunction and "p-i-n" devices will be pursued, circumventing historical problems with surface states and building on Leighton's new capability to n- and p-dope pyrite. Leighton and Frontiera will execute the work, combining the synthesis in Activity 1 with electronic and opto-electronic characterization of single-crystal p-n and p-i-n junctions. Leighton will lead the electronic characterization, while Frontiera will lead the optical characterization, using ultrafast electronic and vibrational spectroscopy. The spectroscopy will identify how to minimize losses after photoexcitation, as well as how to use lattice vibrations to improve photovoltaic performance. Once demonstration solar cells are achieved in single-crystal devicess, the work will shift to thin-film devices, which are required for applications that capitalize on the extreme visible light absorption of pyrite. This work will not only open up solar applications of pyrite but also applications in batteries, where pyrite is attractive for large-scale energy storage.

Activity Milestones:

Description	Approximate Completion Date
Milestone A, completion of research on electronic properties of pyrite	June 30, 2028

Milestone B, completion of research on opto-electronic properties of pyrite	June 30, 2028
Milestone C, demonstration of proof-of-principle pyrite solar cell	June 30, 2029

Activity 3: Clean Water Applications of Iron-Range-Derived Semiconducting Pyrite

Activity Budget: $317,000

Activity Description:

Activity 3 will focus on the use of Iron-Range-derived pyrite in electricity- and sunlight-driven devices for clean water. Nitrogen, in the form of nitrates, is a prevalent contaminant in Minnesota watersheds and groundwater. Treatment approaches exist for this harmful contaminant, but do not scale down eficiently, e.g., to private wells, and result in concentrated waste streams. We will therefore develop alternative processes that use pyrite to mitigate this contaminant without waste, either converting nitrate to benign nitrogen gas, or upgrading it to value-added products for fertilizer production. Stoerzinger's previous research has shown that rationally designed materials (catalysts) can increase the rate of nitrate reduction and favor different end products, with iron-based materials showing particular promise. The sulfur ligands in pyrite provide attractive strategies to improve the overall energy efficiency of such devices for maximum economic impact. We will additionally explore photocatalysis for nitrate reduction, exploiting the extraordinary light absorption of pyrite to transfer optical energy to electronic energy. Frontiera will use spectroelectrochemistry to quantify the photoreduction potential of pyrite, and then use optimized electrocatalytic conditions to drive nitrate reduction, with sunlight as the energy source. Ultimately, this could realize portable, solar-driven devices for conversion of waste nitrate to fertilizer.

Activity Milestones:

Description	Approximate Completion Date
Milestone A, develop a pyrite-based groundwater nitrate remediation system	June 30, 2027
Milestone B, assess pyrite for waste nitrate conversion to fertilizer feedstocks	June 30, 2028
Milestone C, demonstrate photocatalytic nitrate reduction with pyrite	June 30, 2029

Project Partners and Collaborators

Name	Organization	Role	Receiving Funds
Renee Frontiera	University of Minnesota - Twin Cities	Faculty collaborator. Prof. Frontiera and her group will perform the photophysics and optoelectronic aspects of the characterization of pyrite crystals and films synthesized in this project. Her expertise is in spectroscopic and ultrafast measurements of optical properties of materials.	Yes
Kelsey Stoerzinger	University of Minnesota - Twin Cities	Faculty collaborator. Prof. Stoerzinger and her group will perform the electrocatalysis and electrochemical aspects of the proposed work on pyrite crystals and films synthesized in this project. Her expertise is in electrochemistry, electrochemical devices, batteries, and electrocatalysis.	Yes
Matt Mlinar	Natural Resources Research Institute (NRRI)	Collaborator. Mlinar and his coworkers will perform the work on this project related to procurement, synthesis, and characterization of Iron Range samples including various forms of taconite and processed ilmenite ores. His expertise is in mineral processing and metallurgy.	Yes
Jestos Taguta	Natural Resources Research Institute (NRRI)	Collaborator. Dr. Taguta and his coworkers will perform the work on this project related to procurement, synthesis, and characterization of Iron Range samples including various forms of taconite and processed ilmenite ores. His expertise is in chemical engineering, more specifically mineral processing and metallurgy.	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 first step will be publication and dissemination of the results of the scientific and engineering research underpinning the capability to produce semiconductors from Iron Range resources. Leighton's 2022 LCCMR/ENRTF project has already generated publications and will shortly release the results on synthesis of semiconductor-quality pyrite from Iron Range ilmenite. Extending this in the proposed project to taconite would draw substantial attention, at which point NRRI connections and outreach to groups such as the Iron Mining Association of Minnesota will be leveraged to work towards commercialization. Industrial support for further research and development will then be the highest priority.

Other ENRTF Appropriations Awarded in the Last Six Years

Name	Appropriation	Amount Awarded
Green Solar Cells from a Minnesota Natural Resource	M.L. 2022, , Chp. 94, Art. , Sec. 2, Subd. 07a	$673,000

Project Manager and Organization Qualifications

Project Manager Name: Chris Leighton

Job Title: Distinguished McKnight University Professor

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

Chris Leighton is a Distinguished McKnight University Professor and Distinguished University Teaching Professor of Chemical Engineering and Materials Science at the University of Minnesota (U of M). Following B.Sc. and Ph.D. degrees in Physics at the University of Durham, UK (1994, 1998), and post-doctoral research at the University of California San Diego (1998-2001), he joined the U in 2001. His research focuses on materials for electronic devices, including pyrite iron disulfide. He has authored 260 scientific publications, which have been cited over 17,000 times. He is a Fellow of various scientific societies (e.g., the American Physical Society and Institute of Electrical and Electronics Engineers) and has been

recognized with a Cozzarelli Prize from the National Academy of Sciences, and the U's McKnight Presidential Fellowship, Taylor Distinguished Research Award, and Distinguished McKnight University Professorship. He is Director of the U of M Materials Research Science and Engineering Center.

Most relevant to this proposal, Leighton has led a multi-year effort at the U of M aimed at developing iron disulfide for energy and other applications. This material, otherwise known as pyrite or fool's gold, is a uniquely low-cost, earth-abundant, non-toxic semiconductor, with tremendous untapped application potential. This proposed project will build on success in a 2022 LCCMR/ENRTF project to establish new applications in clean energy and water based on pyrite materials synthesized directly from Minnesota Iron Range resources, unlocking a new and environmentally friendly resource stream from this productive natural resource. In terms of project management, Leighton has 24 years of experience directing complex, collaborative research and development projects. These have been funded by a wide range of government and industrial sources and have generated numerous publications and patent applications. As noted above, Leighton managed a 2022 LCCMR/ENRTF project that recently resulted in particularly noteworthy success.

Organization: U of MN - College of Science and Engineering

Organization Description:
The proposed work will be performed in the College of Science and Engineering, U of M – Twin Cities, and the Natural Resources Research Institute (NRRI), U of M – Duluth. Project manager Prof. Chris Leighton and faculty collaborator Prof. Kelsey Stoerzinger are in the Department of Chemical Engineering and Materials Science at the U, while faculty collaborator Prof. Renee Frontiera is in the Department of Chemistry. At the NRRI, Matt Mlinar and Dr. Jestos Taguta form the remainder of the collaborative team. In combination, this team has each and every aspect of the expertise needed to successfully execute the proposed work, from mineralogy and metallurgy, through the core materials science, physics, and chemistry, to the chemical and electrical engineering required for device development. The laboratories of these faculty and technical staff members, complemented with shared facilities at the U, also provide all technical capabilities required for the work. Most importantly, as emphasized throughout this proposal, this project is based on a multi-year effort specific to the U of M, including a critical advance made through a 2022 LCCMR/ENRTF award. This confluence of research capabilities, in the country's largest iron-producing state, leaves this team uniquely qualified to pursue this opportunity.

Budget Summary

Category / Name	Subcategory or Type	Description	Purpose	Gen. Ineligible	% Benefits	# FTE	Classified Staff?	$ Amount
Personnel								
Chris Leighton, U of M - Twin Cities Faculty		Project Manager			36.6%	0.06		$23,256
Kelsey Stoerzinger, U of M - Twin Cities Faculty		Faculty collaborator			36.6%	0.06		$14,352
Renee Frontiera, U of M - Twin Cities Faculty		Faculty collaborator			36.6%	0.06		$19,530
Graduate Student (Leighton Group), U of M - Twin Cities		Graduate Research Assistant			23.2%	3		$192,466
Graduate Student (Leighton Group), U of M - Twin Cities		Graduate Research Assistant			23.2%	1		$72,700
Graduate Student (Stoerzinger Group), U of M - Twin Cities		Graduate Research Assistant			23.2%	3		$192,466
Graduate Student (Frontiera Group), U of		Graduate Research Assistant			23.2%	3		$186,083

M - Twin Cities								
Matt Mlinar, NRRI - Duluth		NRRI Staff Collaborator			36.6%	0.09		$15,666
Jestos Taguta, NRRI - Duluth		NRRI Staff Collaborator			36.6%	0.36		$66,727
NRRI Technical Support Staff		NRRI Technical Support. This is an aggregate of partial support for 6 technicians at NRRI.			32.3%	0.75		$77,244
							Sub Total	**$860,490**
Contracts and Services								
							Sub Total	**-**
Equipment, Tools, and Supplies								
	Tools and Supplies	Lab materials and supplies	Materials and supplies required for scientific and engineering research, such as raw materials, gases, substrates, glassware, cryogens, etc.					$57,000
							Sub Total	**$57,000**
Capital Expenditures								
							Sub Total	**-**
Acquisitions and Stewardship								
							Sub Total	**-**
Travel In Minnesota								
	Miles/ Meals/ Lodging	Travel between NRRI and Twin Cities for project meetings. 9 person-meetings per year.	Necessary regular contact to maintain active collaboration for Activity 1					$12,510
							Sub Total	**$12,510**

Travel Outside Minnesota								
							Sub Total	**-**
Printing and Publication								
							Sub Total	**-**
Other Expenses								
		Lab services	Payment for shared facility access at the U of M, in the CSE Characterization Facility, Minnesota Nano Center, NRRI, etc.					$54,000
		Sample shipping (FedEx) from NRRI to U of M - Twin Cities and vice versa.	Required for provision of samples for Activity 1					$3,000
							Sub Total	**$57,000**
							Grand Total	**$987,000**

Classified Staff or Generally Ineligible Expenses

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

Non ENRTF Funds

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

Total Project Cost: $987,000

This amount accurately reflects total project cost?

Yes

Attachments

Required Attachments

Visual Component

File: 7f9e5b62-6b7.pdf

Alternate Text for Visual Component

Schematic of overall process flow, from MN Iron Range taconite/ilmenite to pyrite iron disulfide single crystals, thin films, and devices. Synthetic pyrite is essential for this project as naturally occurring pyrite has uncontrolled impurities that can destroy semiconducting properties....

Supplemental Attachments

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

Title	File
Required letter from U of M Sponsored Projects Agency	ad9a2b6e-10b.pdf

Administrative Use

Does your project include restoration or acquisition of land rights?

No

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?

Yes, I understand the UMN Policy on travel applies.

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?

Yes

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 proposal:

Project team: C. Leighton, R. Frontiera, K. Stoerzinger, M. Mlinar, J. Taguta. Administrative support: A. Tran, M. Gorder, V. Troxler

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