Environment and Natural Resources Trust Fund
2020 Request for Proposals (RFP)

Project Title: **ENRTF ID:** 180-E

Clean Hydrogen Fuel from Sunlight, Wind, and Water

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

Sub-Category:

Total Project Budget: $ 240,000

Proposed Project Time Period for the Funding Requested: June 30, 2023 (3 yrs)

Summary:

Hydrogen is an attractive option for renewable energy storage. This project will develop inexpensive catalysts for hydrogen production via water splitting using electricity from intermittent renewable sources.

Name: Uwe Kortshagen

Sponsoring Organization: U of MN

Job Title: Professor

Department: College of Science and Engineering

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Web Address:

Location:

Region: Statewide

County Name: Statewide

City / Township:

Alternate Text for Visual:

Hydrogen is an attractive option for renewable energy storage. This project will develop inexpensive catalysts for hydrogen production via water splitting using electricity from intermittent renewable sources.

_____ Funding Priorities _____ Multiple Benefits _____ Outcomes _____ Knowledge Base

_____ Extent of Impact _____ Innovation _____ Scientific/Tech Basis _____ Urgency

_____ Capacity Readiness _____ Leverage _______ TOTAL _____%

PROJECT TITLE: Clean Hydrogen Fuel from Sunlight, Wind, and Water

I. PROJECT STATEMENT

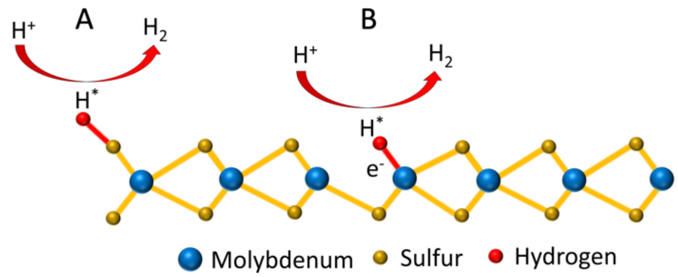


Figure 1: Schematic of hydrogen evolution from atomically thin molybdenum disulfide. (A) edge reaction, (B) reaction at defect.

With renewable energy sources such as wind and solar becoming cheap and abundant, **energy storage is the next frontier in the renewable energy ecosystem**. Wind and solar energy are intermittent and require improved energy storage technologies for increasing adaptation. While battery technology has made great progress, grid-scale energy storage with batteries is still far from the horizon. **Hydrogen** is an attractive alternative for renewable energy storage. It has an energy density 200 times larger than current lithium ion batteries, can be compressed at low cost for storage, can be efficiently converted to electricity with fuel cells, and can be utilized as a clean, carbon-free transportation fuel. Here, we are proposing research to **develop new, efficient and inexpensive catalysts for hydrogen production *via* water splitting using electricity from renewable sources**.

Steam reforming is the predominant way of producing hydrogen, however, it does not lend itself well to integration with renewable energy technologies. Electrical water splitting (electrolysis) can be established at a much smaller scale and is much easier to integrate with wind turbines, wind farms, or solar installations for on-site hydrogen production. However, the cost of this technology is still high, in part, because platinum is the catalyst of choice. Recent research has revealed molybdenum disulfide (MoS_2), which is used in motor oil for its lubricating properties, as a promising low-cost alternative to platinum. The challenge in enhancing the catalytic efficiency of MoS_2 is to make it atomically thin. We will achieve this goal by using a plasma technology developed in Professor Kortshagen's laboratory to deposit atomically thin MoS_2 from an ionized gas.

Water is split only at the edges of an atomic layer flake of MoS_2, Fig. 1(A). Hence, to achieve the maximum amount of edge area (for a given surface area) to enhance the catalytic efficiency of MoS_2, the MoS_2 flakes should only be a few nanometers, meaning a few atoms, in diameter. Professor Kortshagen's plasma technology is naturally capable of this and has been shown to produce MoS_2 flakes measuring just a few nanometers. This is a big advantage compared to the predominant technique of producing atomically thin MoS_2, called exfoliation, which starts from an MoS_2 powder and produces flakes of many 100s of nanometers to some micrometers in diameter.

Another way of enhancing the catalytic efficiency of MoS_2 is to deliberately introduce imperfections. The top and bottom surfaces of perfect MoS_2 (basal planes), such as those produced by exfoliation, are inert and do not participate in water splitting. Professor Kortshagen's plasma technology is believed to be capable of "activating" the MoS_2 surface by deliberately introducing defects to create additional reactive sites, Fig. 1(B). We will study the combination of producing nanometer-scale MoS_2 flakes and introducing imperfections in the MoS_2 basal plane to enhance the efficiency of MoS_2 for hydrogen electrolysis.

II. PROJECT ACTIVITIES AND OUTCOMES

Activity 1 Title: *Evaluate efficiency of nanometer-scale MoS_2 for hydrogen production*
Description: Nanometer-scale MoS_2 will be produced via plasma deposition. Initial work will focus on small scale samples in an experimental reactor currently available in Kortshagen's laboratory. Nanometer scale MoS_2 will be evaluated for hydrogen evolution efficiency in a electrochemical cell and its efficiency will be compared to larger-scale MoS_2 prepared by exfoliation.
ENRTF BUDGET: $79,199

Outcome	Completion Date
1. Prepare nano-scale MoS_2, characterize materials properties.	*Dec. 31, 2020*
2. Compare efficiency for hydrogen production of nano-scale MoS_2 compared to larger-scale exfoliated MoS_2.	*June 30, 2021*

Activity 2 Title: ***Study efficiency improvement of nanometer-scale MoS_2 through defect production***
Description: Nanometer-scale MoS_2 will be exposed to plasma conditions that create defects such as missing sulfur atoms (sulfur vacancies) in the basal plane. Defect-treated MoS_2 will be evaluated for hydrogen evolution efficiency in a electrochemical cell and its efficiency will be compared to larger-scale MoS_2 prepared by exfoliation.

ENRTF BUDGET: $80,664

Outcome	Completion Date
1. Plasma-activation of nano-scale MoS_2, characterize materials properties.	*Dec. 31, 2021*
2. Compare efficiency for hydrogen production of defect-enhanced nano-scale MoS_2 compared to larger-scale exfoliated MoS_2.	*June 30,2022*

Activity 3 Title: ***Scale-up of MoS_2 deposition process***
Description: The experimental reactor currently available in Kortshagen's laboratory allows for deposition of 1 cm x 1 cm samples. This is sufficient for initial materials evaluations. Based on results of the first two activities, we will scale up the plasma process by modifying another reactor to attempt larger scale (15 cm x 15 cm) deposition.

ENRTF BUDGET: $80,137

Outcome	Completion Date
1. Scale-up of MoS_2 deposition process. Explore plasma conditions suitable for scale-up.	*Dec. 31, 2022*
2. Compare materials properties with those obtained in small scale deposition, determine important parameters for further scale-up of technology.	*June 30,2023*

III. PROJECT PARTNERS AND COLLABORATORS:

The project director, Professor Kortshagen, brings unique expertise in plasma materials synthesis. He is an inventor of a plasma technology that has been patented by the University of Minnesota and licensed to three companies. The project can leverage the research which is performed by the "Sustainable Nanocrystal Materials" group of the National Science Foundation-funded Materials Research Science and Engineering Center, a $17.8M federal grant from the National Science Foundation.

IV. LONG-TERM IMPLEMENTATION AND FUNDING:

This project will contribute to the improvement of a renewable energy storage technology, and subsequently will ameliorate the intermittency of renewable energy sources such as wind and solar. If successful, the outcomes of this work will contribute to the scientific knowledge base, but also hold prospect for commercialization. Based on the team's unique expertise and prior success with technology commercialization, we hope to advance this technology into an asset for the State of Minnesota.

Attachment A: Project Budget Spreadsheet
Environment and Natural Resources Trust Fund
M.L. 2020 Budget Spreadsheet
Legal Citation:
Project Manager: Uwe Kortshagen
Project Title: Clean Hydrogen Fuel from Sunlight, Wind, and Water
Organization: University of Minnesota
Project Budget: 240,000
Project Length and Completion Date: 3 years, July 1, 2020, through June 30, 2023
Today's Date: April 15, 2019

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET		Budget	Amount Spent	Balance
BUDGET ITEM				
Personnel (Wages and Benefits)		$ 198,000	$ -	$ 198,000
Uwe Kortshagen (2 week (.06FTE) + fringe 36.0% fringe) for 3 years	$ 45,000	$ -		
One-Graduate Research Assistant in ME (advised by Kortshagen), 50% FTE (fall & spring include 16.1% fringe plus $20.50/hour tuition, summer 16.1% fringe only) for 3 years	$ 153,000	$ -		
Professional/Technical/Service Contracts		$ -	$ -	$ -
Equipment/Tools/Supplies		$ 42,000	$ -	$ 42,000
Cost for purchasing precursor gases ($4,500), sample substrates ($3,000), and chemicals ($3,000) for nanoparticle synthesis. Purchasing of characterization accessories, including AFM tips, TEM grids, electrical current sources, probes, among others ($12,500). All cost are given for three years and based on historical data for expenditures in Professor Kortshagen's group.	$ 23,000	$ -		
User fees for rental and usage of facilities at the campus CharFac center for materials structural/property characterization (X-ray diffraction, secondary electron microscopy, Raman spectroscopy, tunneling electron microscopy, $19000). All cost are given for three years and based on historical data for expenditures in Professor Kortshagen's group.	$ 19,000	$ -		
Capital Expenditures Over $5,000				
		$ -	$ -	$ -
Fee Title Acquisition				
		$ -	$ -	$ -
Easement Acquisition				
		$ -	$ -	$ -
Professional Services for Acquisition				
		$ -	$ -	$ -
Printing				
		$ -	$ -	$ -
Travel expenses in Minnesota				
		$ -	$ -	$ -
Other				
		$ -	$ -	$ -
COLUMN TOTAL		$ 240,000	$ -	$ 240,000

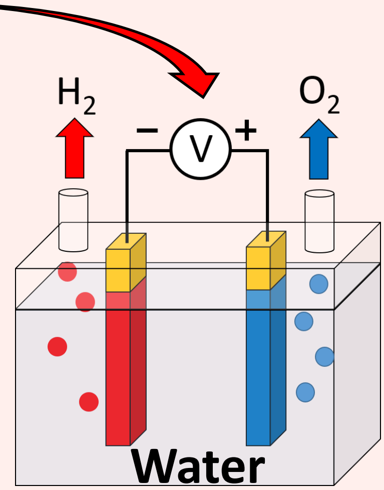
SOURCE AND USE OF OTHER FUNDS CONTRIBUTED TO THE PROJECT	Status (secured or pending)	Budget	Spent	Balance
Non-State:		$ -	$ -	$ -
State:		$ -	$ -	$ -
In kind:		$ -	$ -	$ -

Other ENRTF APPROPRIATIONS AWARDED IN THE LAST SIX YEARS	Amount legally obligated but not yet spent	Budget	Spent	Balance
		$ -	$ -	$ -

Clean Hydrogen Fuel from Sunlight, Wind and Water

WHAT it is:

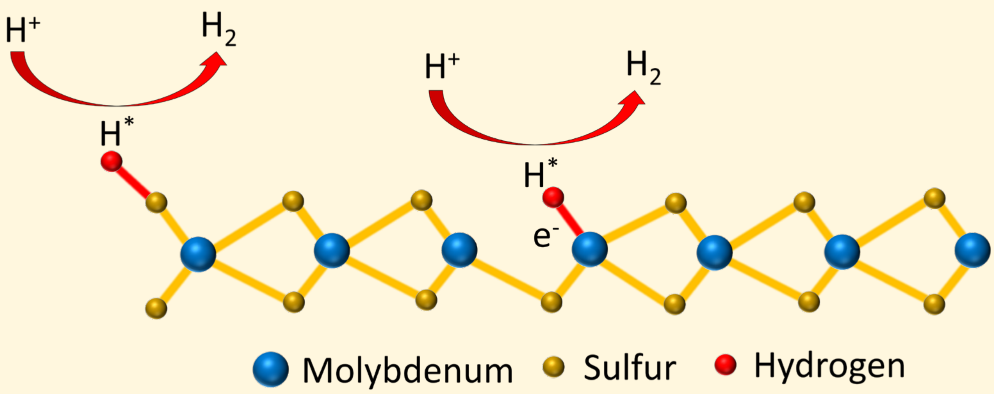
(Image Credit: smithsonianmag.com)



Hydrogen fuel production from water using electricity generated by the sun or wind

HOW does it work?:

Hydrogen radicals combine with ionized hydrogen from water to produce hydrogen gas



What is the impact?

A Rich Renewable Energy Source Formed Without Emissions

- ✓ No Emission Vehicles
- ✓ Carbon-free Alternative to Fossil Fuels
- ✓ Renewable Energy Source from Water

Hydrogen Fuel Powered Vehicles

(Image Credit: Rene Frampe)

(Image Credit: wikipedia.org)

Project Manager Qualifications & Organization Description

Uwe Kortshagen is a Distinguished McKnight University Professor in the Department of Mechanical Engineering at the University of Minnesota, with graduate faculty appointments in Physics, Chemical Engineering, and Materials Science. His research is in the area of low temperature plasmas processing science and in the plasma synthesis of nanomaterials and their applications. He earned his Diploma degree in Physics in 1988, his Ph.D. in Physics in 1991, and his Habilitation in Experimental Physics in 1995 from the Ruhr University Bochum, Germany. In 1996, he joined the Department of Mechanical Engineering at the University of Minnesota as Assistant Professor, where he was promoted to Associate Professor in 1999, and to Professor in 2003. He served the Department as Director of Graduate Studies from 2006-2008 and as Department Head from 2008-2018. He is Fellow of the American Physical Society, the American Society of Mechanical Engineers, the Institute of Physics (UK), and the International Plasma Chemistry Society, and recipient of the 2015 Plasma Prize of the American Vacuum Society.

His cumulative research funding is about $34M. He has directed several multi-investigator research teams, including a recent Army Research Office MURI project on "New Materials from Dusty Plasmas." His work has been published in about 200 journal articles, including papers in several *Nature* family journals, *Nano Letters*, *Advanced Materials*, and *Physical Review Letters* and received more than 12,000 citations. He holds 4 US patents. His plasma synthesis technique has been licensed to 3 different companies.

The **University of Minnesota** offers world-class infrastructure for this project. The MoS_2 synthesis will be performed in Kortshagen's laboratory, which is part of the **High Temperature and Plasma Laboratory** in the Department of Mechanical Engineering. This lab is one of the best equipped plasma technology laboratories in the world. His laboratory includes ten custom-built plasma reactors and facilities for nanocrystal processing that will be available to this project. In addition, 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 and glass shops are also available at the University of Minnesota.