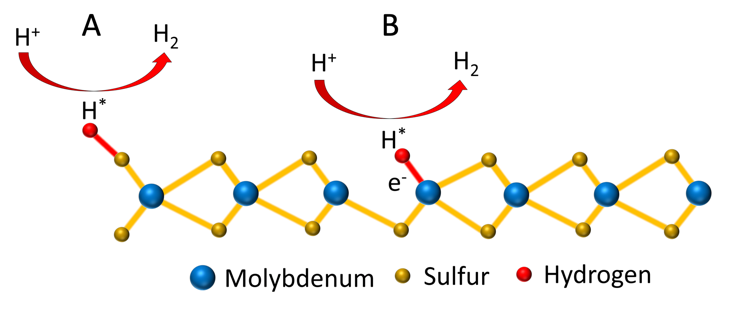
**PROJECT TITLE: Clean Hydrogen Fuel from Sunlight, Wind, and Water**

**I. PROJECT STATEMENT**

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**.

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

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 (MoS2), 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 MoS2 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 MoS2 from an ionized gas.

Water is split only at the edges of an atomic layer flake of MoS2, Fig. 1(A). Hence, to achieve the maximum amount of edge area (for a given surface area) to enhance the catalytic efficiency of MoS2, the MoS2 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 MoS2 flakes measuring just a few nanometers. This is a big advantage compared to the predominant technique of producing atomically thin MoS2, called exfoliation, which starts from an MoS2 powder and produces flakes of many 100s of nanometers to some micrometers in diameter.

Another way of enhancing the catalytic efficiency of MoS2 is to deliberately introduce imperfections. The top and bottom surfaces of perfect MoS2 (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 MoS2 surface by deliberately introducing defects to create additional reactive sites, Fig. 1(B). We will study the combination of producing nanometer-scale MoS2 flakes and introducing imperfections in the MoS2 basal plane to enhance the efficiency of MoS2 for hydrogen electrolysis.

**II. PROJECT ACTIVITIES AND OUTCOMES**

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| **Activity 1 Title: *Evaluate efficiency of nanometer-scale MoS2 for hydrogen production***  **Description:**Nanometer-scale MoS2 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 MoS2 will be evaluated for hydrogen evolution efficiency in a electrochemical cell and its efficiency will be compared to larger-scale MoS2 prepared by exfoliation.  **ENRTF BUDGET: $79,199** |  |

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| **Outcome** | **Completion Date** |
| *1. Prepare nano-scale MoS2, characterize materials properties.* | *Dec. 31, 2020* |
| *2. Compare efficiency for hydrogen production of nano-scale MoS2 compared to larger-scale exfoliated MoS2.* | *June 30, 2021* |

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| **Activity 2 Title: *Study efficiency improvement of nanometer-scale MoS2 through defect production***  **Description:**Nanometer-scale MoS2 will be exposed to plasma conditions that create defects such as missing sulfur atoms (sulfur vacancies) in the basal plane. Defect-treated MoS2 will be evaluated for hydrogen evolution efficiency in a electrochemical cell and its efficiency will be compared to larger-scale MoS2 prepared by exfoliation.  **ENRTF BUDGET: $80,664** |  |

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| **Outcome** | **Completion Date** |
| *1. Plasma-activation of nano-scale MoS2, characterize materials properties.* | *Dec. 31, 2021* |
| *2. Compare efficiency for hydrogen production of defect-enhanced nano-scale MoS2 compared to larger-scale exfoliated MoS2.* | *June 30,2022* |

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| **Activity 3 Title: *Scale-up of MoS2 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** |  |

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| **Outcome** | **Completion Date** |
| *1. Scale-up of MoS2 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.