Electromagnetic Energy-Assisted Approaches to Convert Fossil Fuels to Low Cost Hydrogen

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Envergex Sparking Innovations

Program Overview

Opportunity: Produce H_2 from methane rich sources ***without CO_2*** formation

Problem: Carbon deposition and catalyst deactivation

- **$CH_4(g) \xrightarrow{catalyst} C(s) + 2H_2(g)$**
- Catalyst loss – either reactivity or physical loss

Goal: Extend H_2 production through targeted catalyst regeneration

Solution approach: Use an in-situ electromagnetic (EM) energy-assisted mechanism to regenerate catalysts

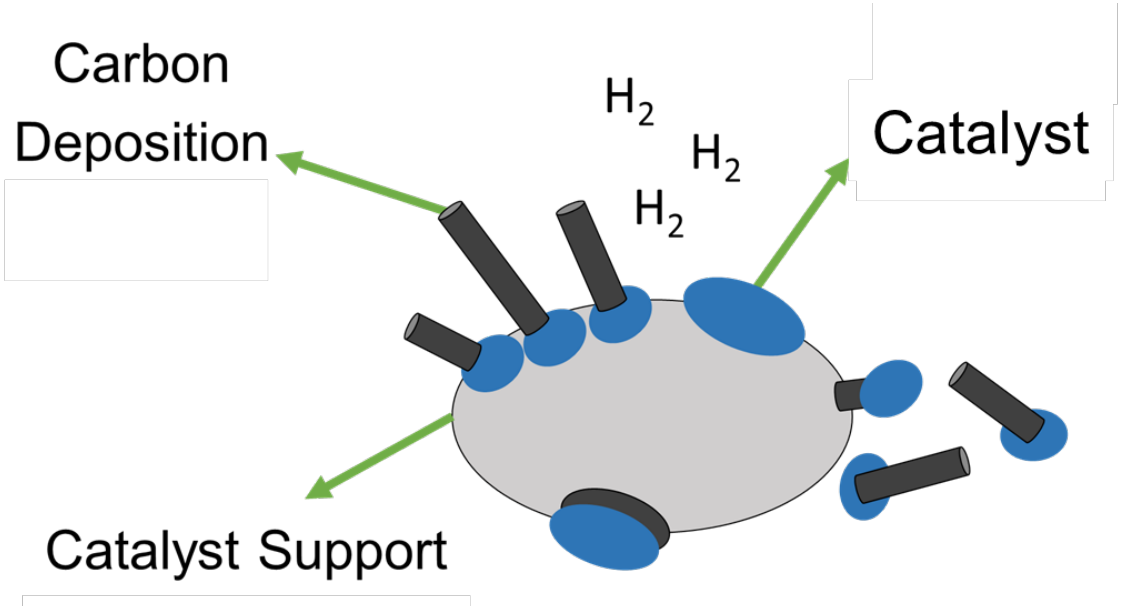
Potential Significance – Catalyst Regeneration

- ***Reduce*** overall catalyst replenishment cost
- ***Purer*** carbon products – less catalyst poisoning
- ***Low-cost & CO_2-free*** process for H_2 production
- Enable ***wider adoption*** of H_2-related technologies from fossil resources
- ***Applicable*** to other catalyst-based processes – coking issues

Background – CH_4 Decomposition

Thermo-catalytic decomposition of CH_4

- $CH_4(g) \rightarrow C(s) + 2H_2\ (g)\ \Delta H_{rxn}$ = ***37 kJ/mol-H_2***
    - Electrolysis ***285 kJ/mol-H_2***
    - Steam methane reforming (SMR) ***41 kJ/mol-H_2***
- Typically conducted at ***500 – 800˚C***
    - Typical catalysts include: Transition metals, even C
    - Without catalyst: 1200˚C requirement



Catalyst deactivation schematic

Background – Catalyst "Cleaning" Approaches

- Physical removal – attrition
  - C remains same
  - Potential catalyst loss & impure catalysts with C
- Chemical removal – Combust/Gasify carbonaceous deposits
  - *Combustion:* $O_2 + C \rightarrow CO_2$
  - *Gasification:* $H_2 + C \rightarrow$ "CH_4" *and* $H_2O + C \rightarrow CO + H_2$
  - *Chemical – Acid leaching to remove and recover metal catalysts*

Approach

Technique:

- In-situ carbon removal using an Electromagnet (EM) Energy-Assisted Thermocatalytic Process
- Mild process applicable to catalyzed reaction temperatures
- Target periodic cleaning
- Mechanism – chemical and physical C removal

How:

- ***Conduct proof-of-concept experiments***
- ***Supplement with computational modeling***
- ***Assess large-scale applicability of approach (integrated setups)***

Technical Summary

Task 1 – PMP and Technology Maturation Plan

Task 2 – Catalyst Preparation and Performance Testing

Task 3 – Computational Fluid Dynamics (CFD) Modeling of Conversion System

Task 4 – Hydrocarbon Conversion Testing using EM Energy-Assisted Thermocatalytic Process

Task 5 – Component Identification for Future Work

Task 6 – PMP (North Dakota Industrial Commission - NDIC)

Task 7 – Evaluation and Characterization of Carbon Products

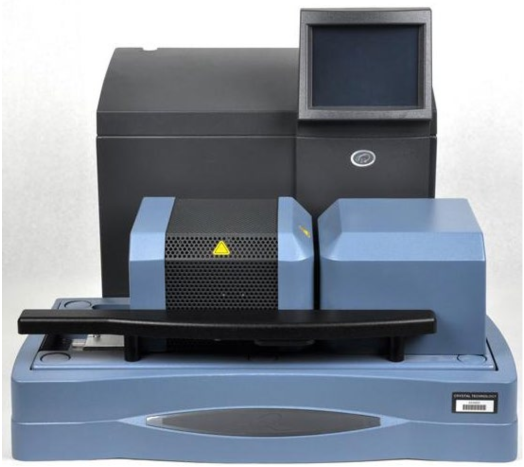
Task 8 – Process Model of Greener H_2 Production System

Extended Scope (Tasks 6–8)

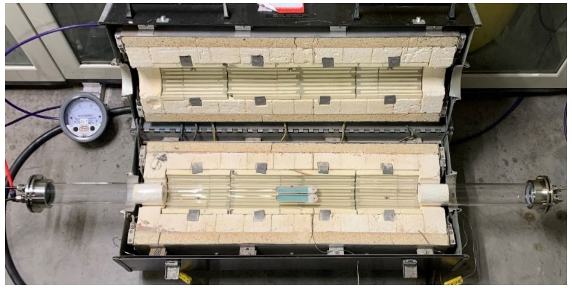
Task 2: Catalyst Preparation and Performance Testing

Subtask 2.1 – Catalyst Preparation

- Catalyst/Support structures identification
- Combinations of different supports tested
  - SiO_2, C, Al_2O_3, and Aerogel Supports
- Catalysts
  - Ni, C and Fe
- Identified promising Ni-SiO_2 catalyst
  - Added Cu-promotor – disperses Ni more evenly



TGA Tests (TA SDT Q600)



2-inch tube furnace

Fluidized/Fixed bed testing in 3/8-inch tube reactor

Task 2: Catalyst Preparation and Performance Testing

Kinetics for CFD

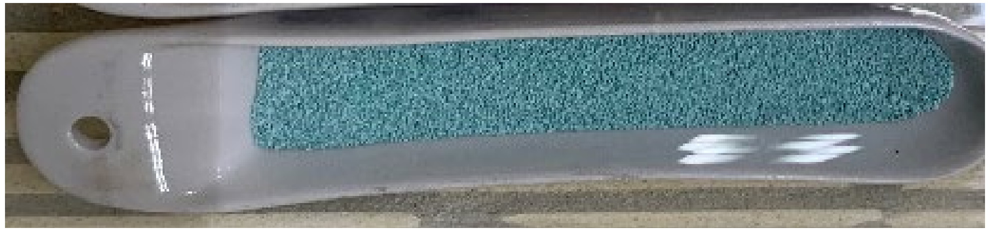
- Conduct kinetic study using TGA
- Ensure sufficient gas flow – mitigate external mass transfer limitations (initially)
- Initial tests – determine optimum flow rate & sample mass
  - 500-650˚C & 30%-50% CH_4 (N_2 balance)
  - Eventually use CFD to develop geometries complementing EM-assisted process

Pre- and post-test with $Ni\text{-}SiO_2$ catalyst

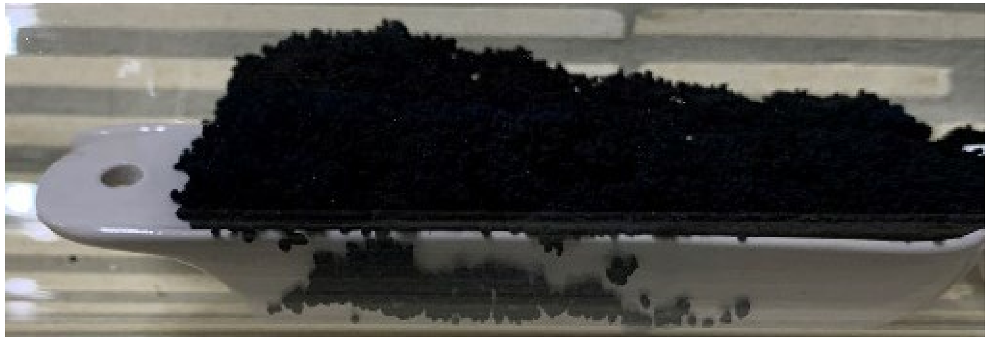
Task 2: Catalyst Preparation and Performance Testing

Subtask 2.2 – Initial High Temperature Catalyst Performance Testing

- TGA testing scaled up to tube furnace
- Tube furnace – easy integration EM Energy-assisted thermocatalytic process
- Just under 70% CH_4 conversion at 650˚C
- Key result - moldable catalyst with suitable performance



Pre-test material



Post-test material with carbon buildup

Task 2: Catalyst Preparation and Performance Testing

- Structured catalyst testing
- Required flat surface for C-deposition and C-removal
- Decided on disk-shape (compatible with tube furnace
- Placed perpendicular to gas flow
- Run short durations for C-growth
- Excessive run time – carbon growth destroys surface

Tube Furnace Testing - Structured

Task 3: Task 3 – Computational Fluid Dynamics (CFD) Modeling of Conversion System

Subtask 3.1 – Establish Baseline CFD and Kinetic Model

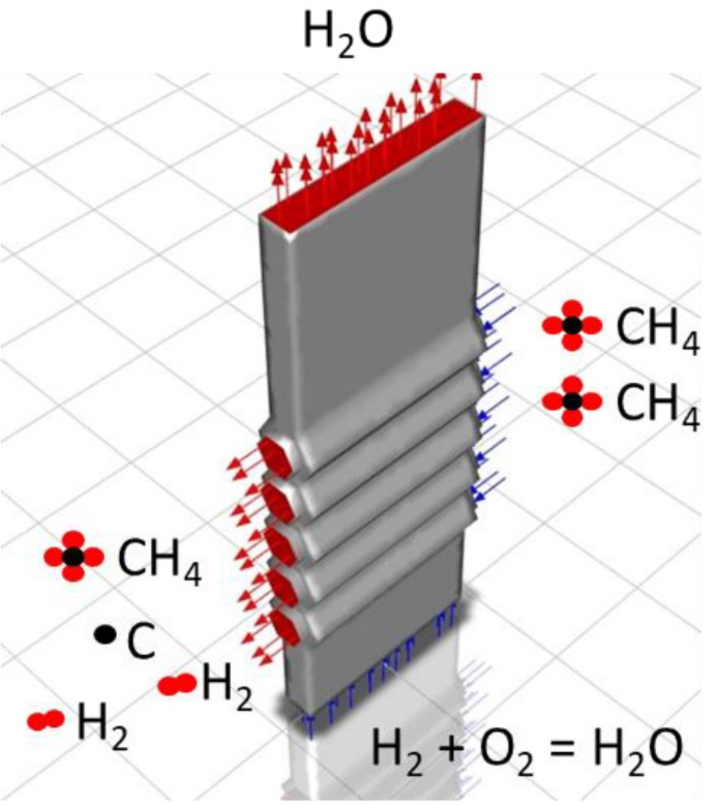
- Capture decomposition reaction behavior

Subtask 3.2 – Update CFD and Kinetic Model to Include Effects of the Electromagnetic Energy-Assisted Mechanism

- Assess geometries/setups enhancing removal technique

Results: 2D & 3D models

- Depicting zones of high C-deposition
- Temperature profiles (heat addition points)
- Locational aspects of EM Energy-Assisted Mechanism



Reaction Modeling

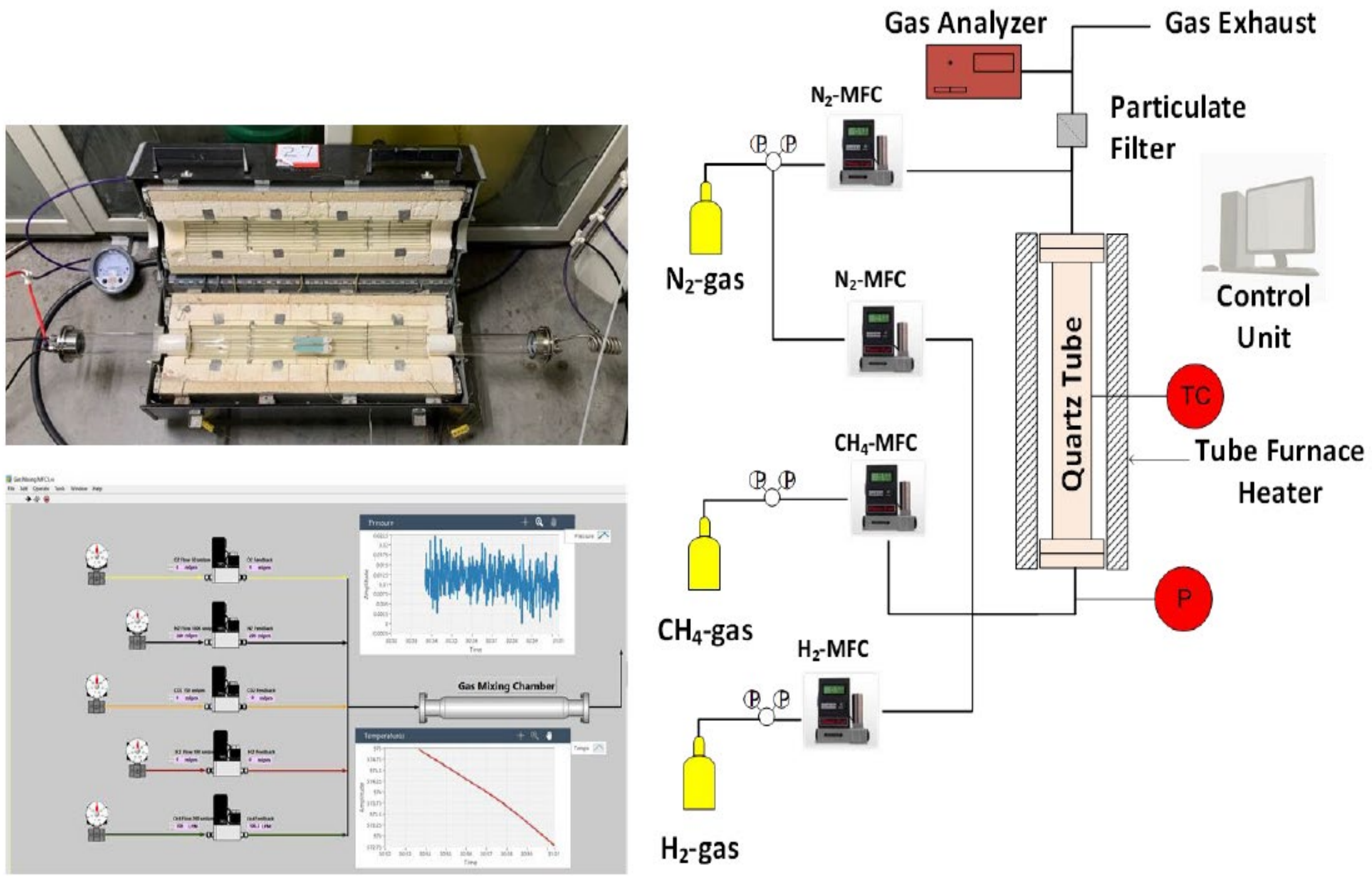
Task 4: Hydrocarbon Conversion Testing using EM Energy-Assisted Thermocatalytic Process

Series of experiments devoted to

- Decomposition testing
- Surface regeneration

Assembled integrated test unit

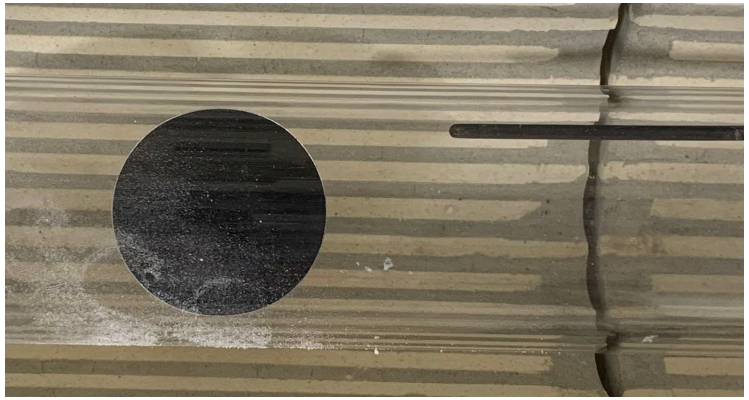
- 2”-ID glass reactor
- Mass flow controllers
- Gas analyzer
- EM Energy-Assisted Module (not shown)



Experimental Unit Setup

Task 4: Hydrocarbon Conversion Testing using EM Energy-Assisted Thermocatalytic Process

- Structured catalyst/support testing
- Initial tests failed (inset images)
  - Aggressive CH_4 decomposition (too long)
  - Refined binding technique
- Process refined: samples subjected to ~10 minutes of CH_4 decomposition
- Thin layer approach – lines up with CFD and viable C-removal technique

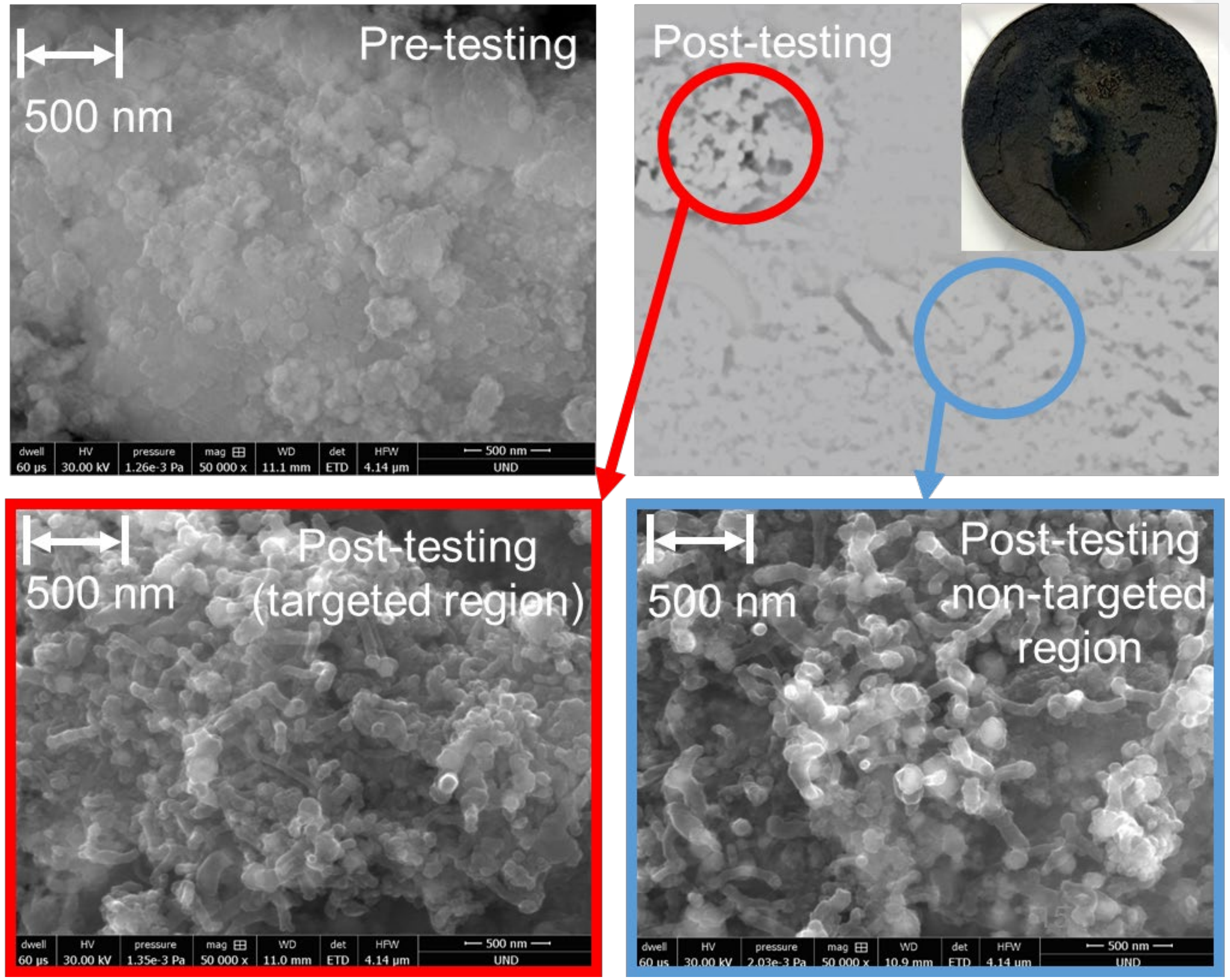


Pre-decomposition structured catalyst/support disk

Post-decomposition structured catalyst/support disk

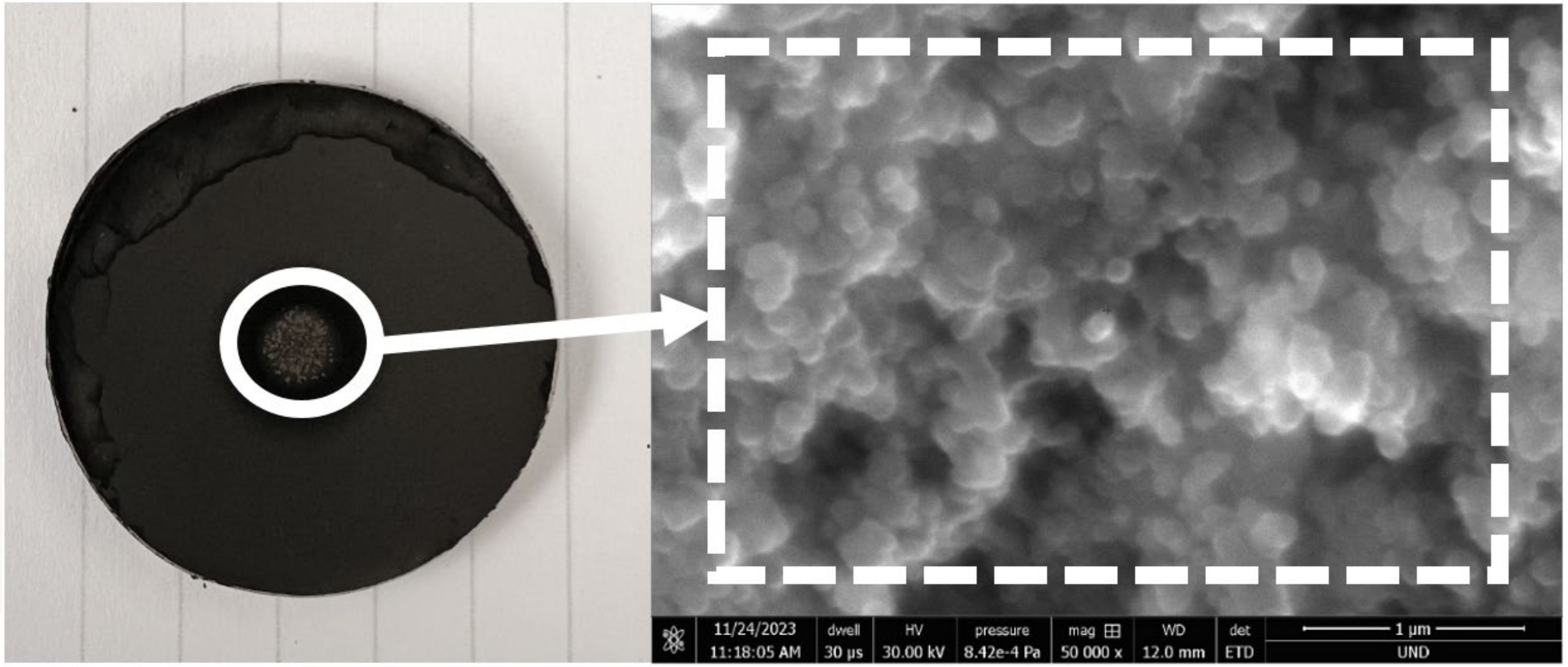
Task 4: Hydrocarbon Conversion Testing using EM Energy-Assisted Thermocatalytic Process

- EM-assisted mechanism on structured catalyst
- Ambient testing – no effect
- At 650˚C visible surface changes
- SEM-EDX on removal/non-removal area
- Tubular-shaped C visually detected both cases
- EDX inconclusive (rough surface)



Task 4: Hydrocarbon Conversion Testing using EM Energy-Assisted Thermocatalytic Process

- Increased regeneration intensity following CH_4 decomposition
- Post cleaning surface indicating lack of carbonaceous material
- Excessive cleaning → catalyst inactivity



Catalyst surface after decomposition, regeneration and additional decomposition cycle

Task 4: Hydrocarbon Conversion Testing using EM Energy-Assisted Thermocatalytic Process

Change operating regime

- Alter regeneration intensity (<5 min.)

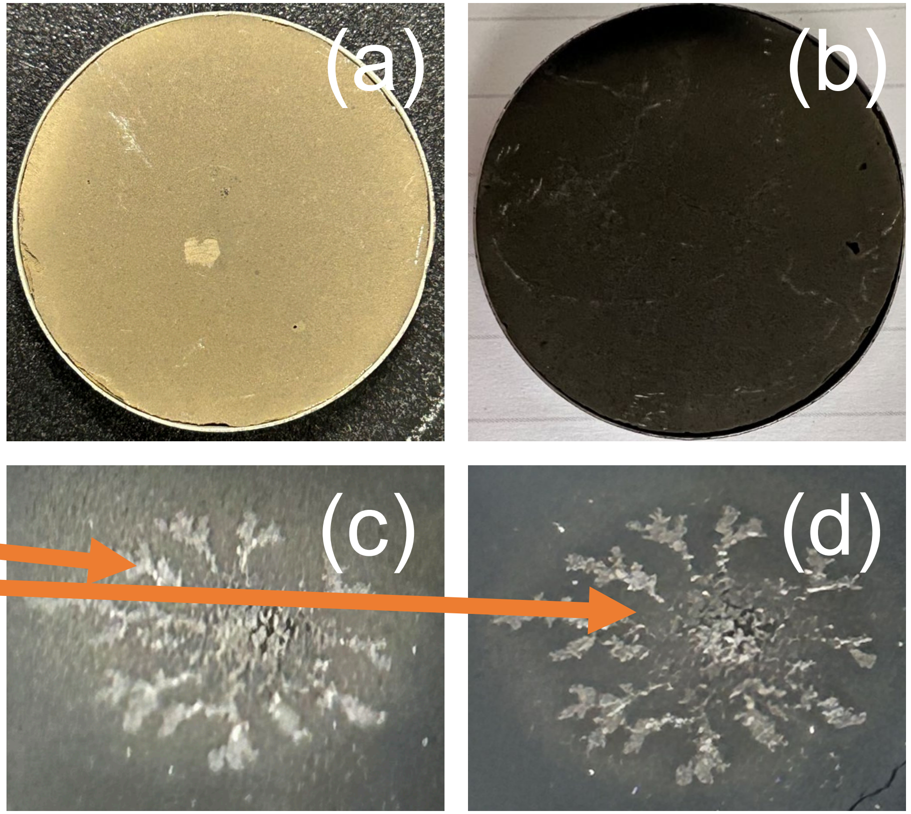
Start with:

- Structured catalyst (a)
- Decompose methane (b)
- Surface after catalyst regeneration (c)
- Surface after additional decomposition stage (d)

High intensity regions no activity

- Surrounding areas darkened (carbon deposition)

Ongoing: Assess surfaces for carbon deposition post-regeneration (TGA, SEM, TC/TIC)

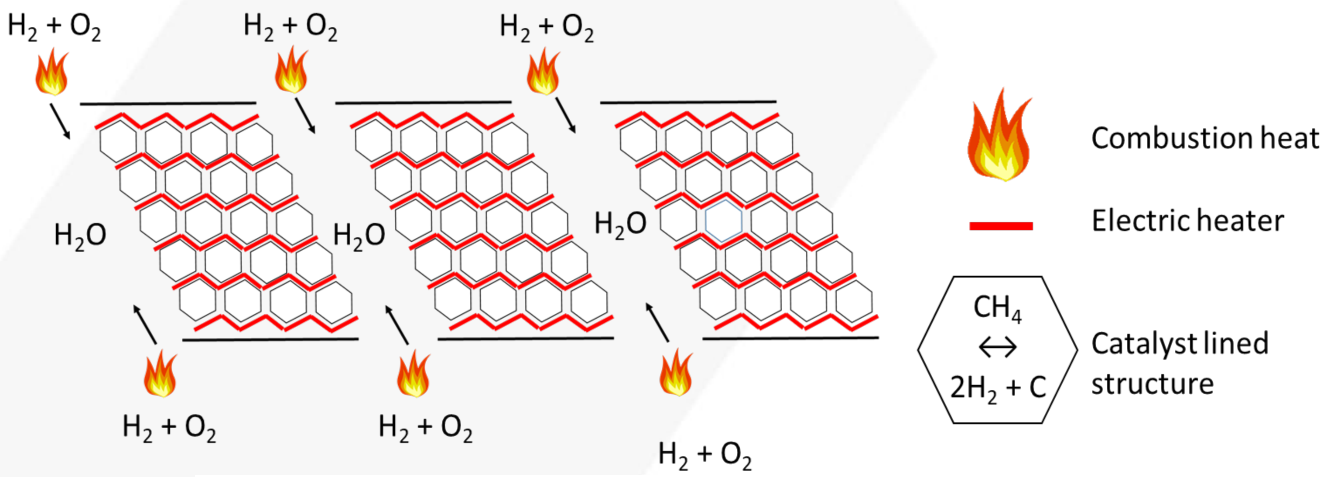


Carbon buildup and removal sequences

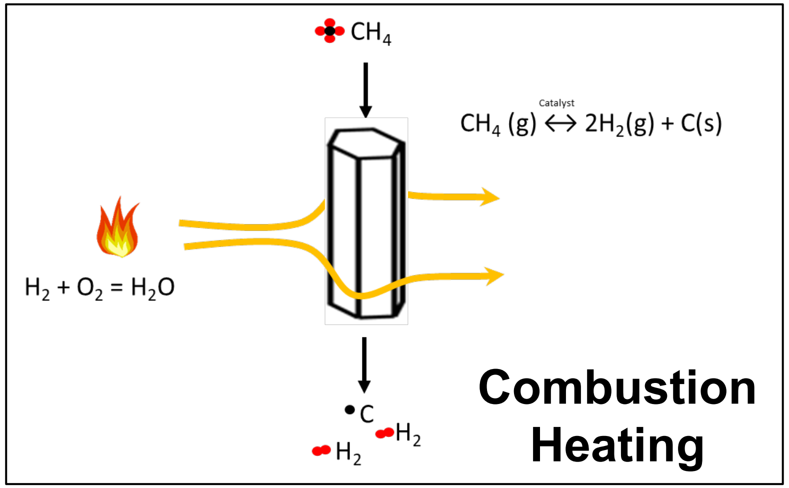
Task 5: Component Identification for Future Work

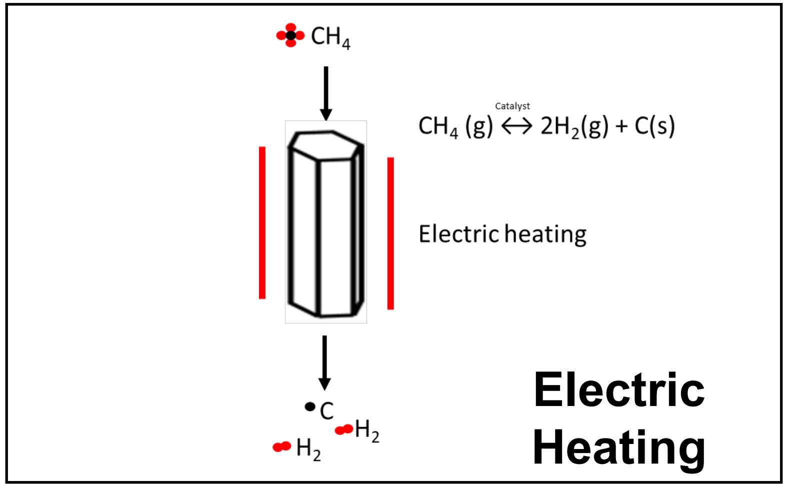
System Design:

- Design large-scale system for CDM process
- CO_2-free process (with renewable electricity)
- 1 tonne H_2 per hour



CO_2-free Production route for H_2





Extended Scope

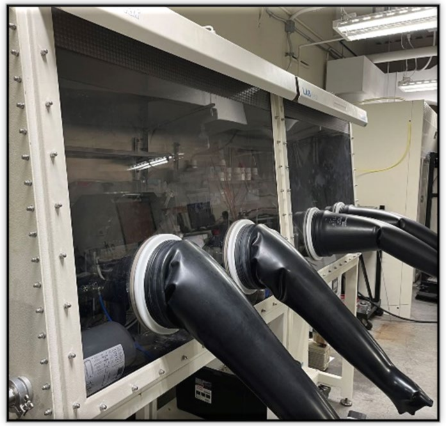
- Cost-share provided by North Dakota Industrial Commission (NDIC)
- Scope extended to:
  - Examining uses for carbonaceous products
  - Implementing strategy for producing H_2 using process at large scale
  - Focus on H_2 production without CO_2 formation
  - Project end date: 07/31/24 (DOE and NDIC)
- Added Tasks 6, 7 and 8 to project
- Task 6 – PMP for NDIC

Task 7: Evaluation and Characterization of Carbon Products

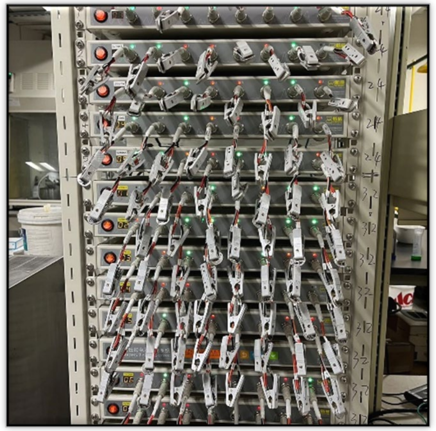
Task 7: Evaluation and Characterization of Carbon Products

- Produced bulk carbon sample
- Tested carbon purity
- Acid leached carbon
- Prepared coin cells and testing
- Compare to commercially procured carbon

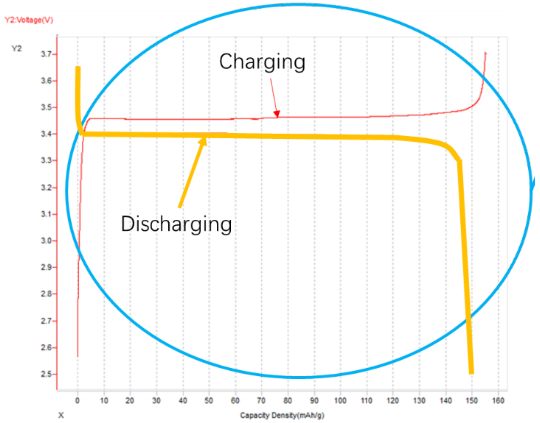
Bulk carbon production



Coin cell production



Coin cell testing



Results

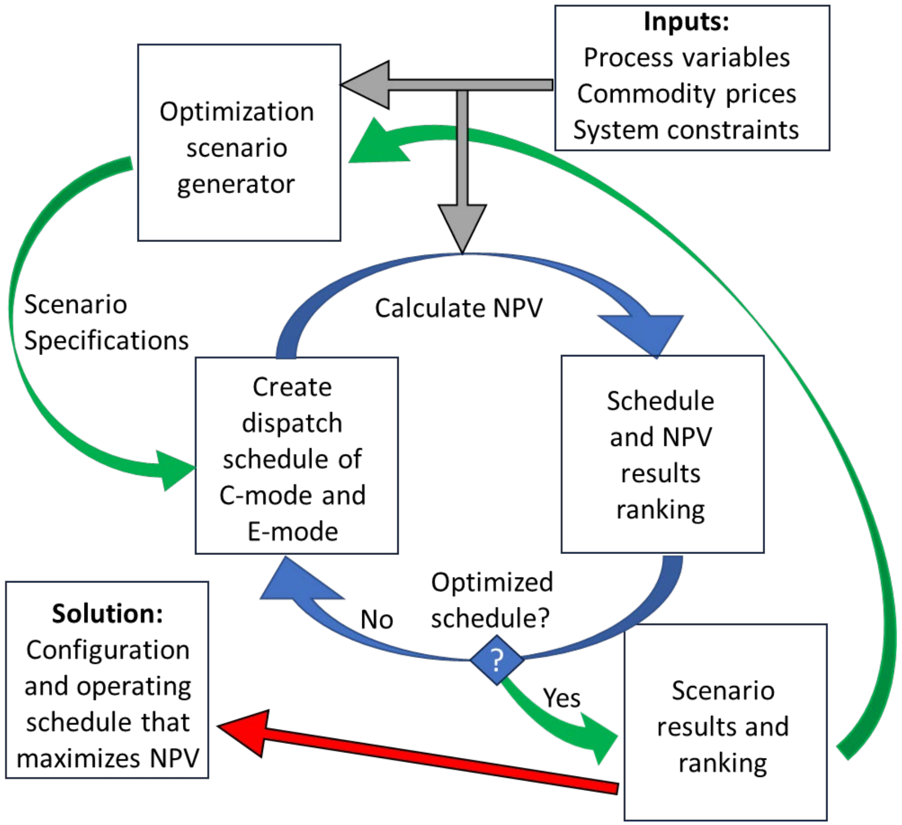
Task 8: Process Model of Greener H_2 Production System

Approach

- CH_4 decomposition for H_2
- C-mode and E-mode for production flexibility
- CO_2-free process (with renewable electricity)

Key Questions

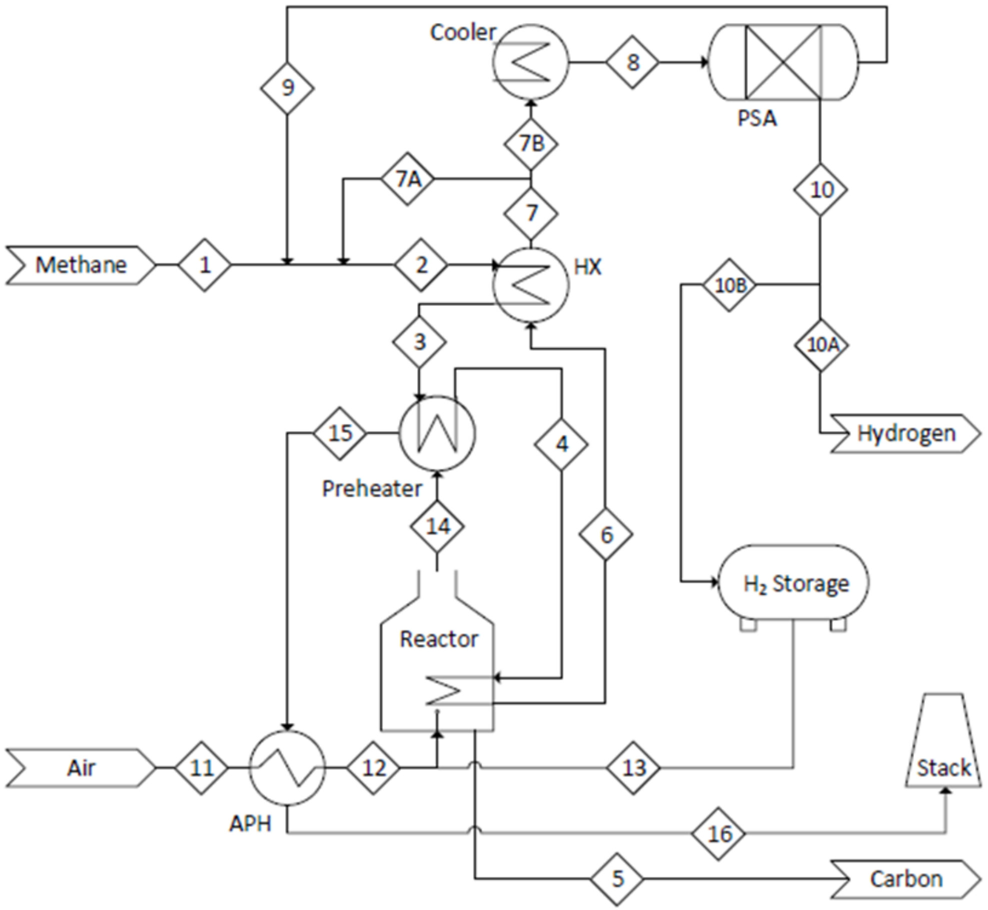
- Time ratio in each mode
- Impact of electricity and hydrogen prices
- Optimal hydrogen storage



Electric and Combustion Heating Loop Optimization Routine Depiction

Task 8: Process Model of Greener H_2 Production System

- H_2 Production Scenarios:
  - ND-MISO
  - NREL future system scenario analysis
  - H_2 supply by pipeline or liquid tankers
- Next steps:
  - Getting Plant CAPEX
  - Process optimization (sizing variations)
- Inset figure – general process layout
  - 1 tonne H_2 per hour



CO_2-free H_2 Production Pathway

Future Work

Task 1 – PMP and Technology Maturation Plan

Task 2 – Catalyst Preparation and Performance Testing

Task 3 – Computational Fluid Dynamics (CFD) Modeling of Conversion System

Task 4 – Hydrocarbon Conversion Testing using EM Energy-Assisted Thermocatalytic Process

- ***Catalyst regeneration verification – SEM, TGA and TC/TIC***

Task 5 – Component Identification for Future Work

Task 6 – PMP (NDIC)

Task 7 – Evaluation and Characterization of Carbon Products

- ***Compare lab-grown C in batteries to commercially procured C***

Task 8 – Process Model of Greener H_2 Production System

- ***Update equipment costing from simulation results and input information for inner-outer loop approach for process optimization***

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Thank you
Questions?

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