# The Energy Venture Investment Summit

# **COLORADO SCHOOL** OF MINES



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# **THURSDAY, FEBRUARY 17** 2:30 PM (MT)

# HAYNES BOONE

# **Clean Combustion via Ammonia**

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*The* Energy Venture Investment *Summit* 



## H2@Scale Vision

Renewable Electricity Growing Fast

- Wind/solar now competitive with conventional sources
- Challenge: Transportation & Industrial sectors

Hydrogen as the Energy Hub

- Renewable electricity to H<sub>2</sub>
- Fuel cell electric vehicles (FCEVs)
- Industrial chemical, fuels, combustion

Challenges

- Distributed vs. centralized production
- Cost of H<sub>2</sub> storage and transportation

## Idea: Use Ammonia as a H<sub>2</sub> Carrier





# Why Ammonia?

## Attributes as a H<sub>2</sub> Carrier

- Ammonia: 17.7 wt. %
- Liquid at ambient temp, 10 bar
- Clean H<sub>2</sub>, carbon-free combustion:  $2NH_3 \rightarrow 3H_2 + N_2$  $2NH_3 + 1.5O_2 \rightarrow 3H_2O + N_2$
- Distribution infrastructure in place





A. Valera-Medina et al., "Ammonia for power," Progress in Energy and Combustion Science 69, 63-102 (2018)

## Ammonia: Fuel Flexible



Combustion

#### % Dissociation



90%: AFC



10%



50%

#### Target Market Hydrocarbons

- Natural gas
- Gasoline
- Fuel oil
- Jet Fuel





## Technology: Ammonia Decomposition

Conventional: PBR: P = 1 atm, T>600°C







R. Sitar, J. Shah, Z. Zhang, H. Wikoff, J. D. Way and C. A. Wolden, "Compact ammonia reforming at low 5 temperature using catalytic membrane reactors," *Journal of Membrane Science* **644**, 120147 (2022).







## Advantages

- More Power
- Less NO<sub>x</sub>

50%

40%

40% 30% 20% 10%

0%

0%

10%

20%

- Tunable H<sub>2</sub>/NH<sub>3</sub> ratio
- Pressure for free



RPM

S. Frigo and R. Gentili, "Analysis of the behaviour of a 4-stroke Si engine fuelled with ammonia and hydrogen," International Journal of Hydrogen Energy 38, 1607-1615 (2013).

M. Comotti and S. Frigo, "Hydrogen generation system for ammonia-hydrogen fuelled internal 6 combustion engines," International Journal of Hydrogen Energy 40, 10673-10686 (2015).

## CMR: Pressure for free

- Pump cold liquid vs. compress hot gasses
- ~1000X less energy required



Nose et al., "Gas turbine plant having thermal decomposition of ammonia and pressurization of the decomposed gas and method thereof," US Patent 11,156,168 (2021)

# Team & Capabilities

Validation & Modeling

- CMR Fabrication
- CMR Performance
- Prototype Module (>kg H<sub>2</sub>/day)



Techno-economic Analysis

- Systems level modeling (ASPEN)
- Quantify energy/economic advantages











## Market and Business Plan

### **Market Analysis**

- Competitive advantages
- Identify most promising applications

## Identify Partners

- Combustion applications
- Confirm performance, emissions, etc.

## **Commercialization Strategy**

- IP protection in place
- Advisors & investors
- License/startup/partners/etc.

### **Technology**





A. Yapicioglu and I. Dincer, "A review on clean ammonia as a potential fuel for power generators," *Renewable and Sustainable Energy Reviews* **103**, 96-108 (2019).

