HyMARC: Hydrogen Carriers R&D Activities for Bulk Hydrogen Storage & Transport

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***Project ID*: ST204**

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Pacific Northwest NATIONAL LABORATORY

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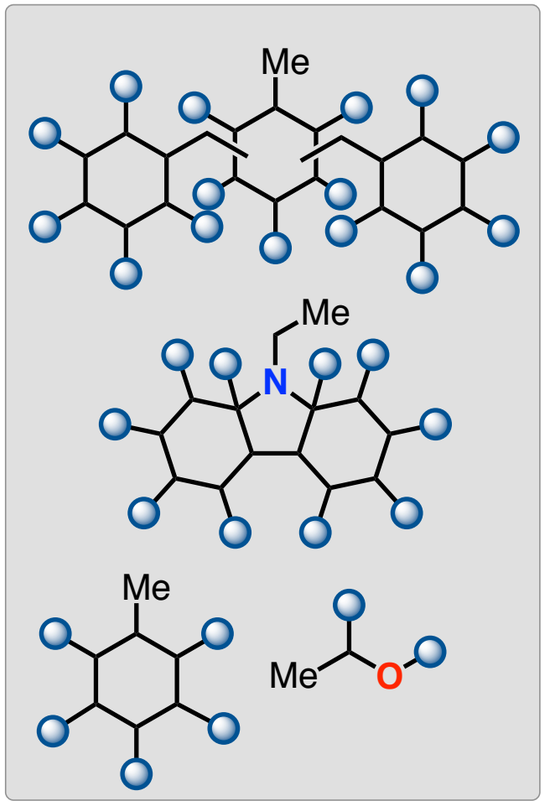
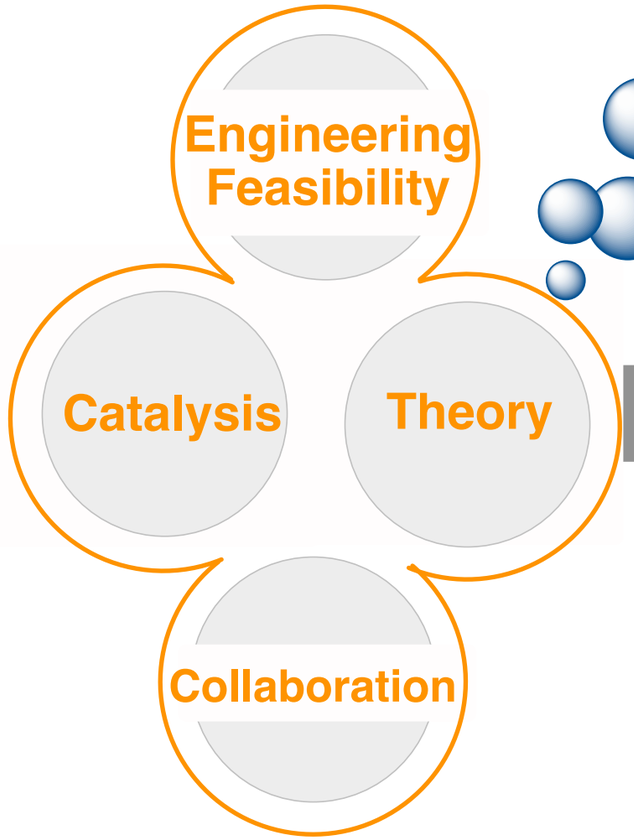
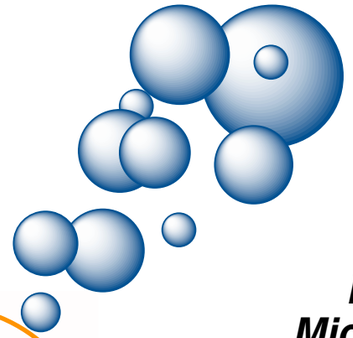
What we do at PNNL

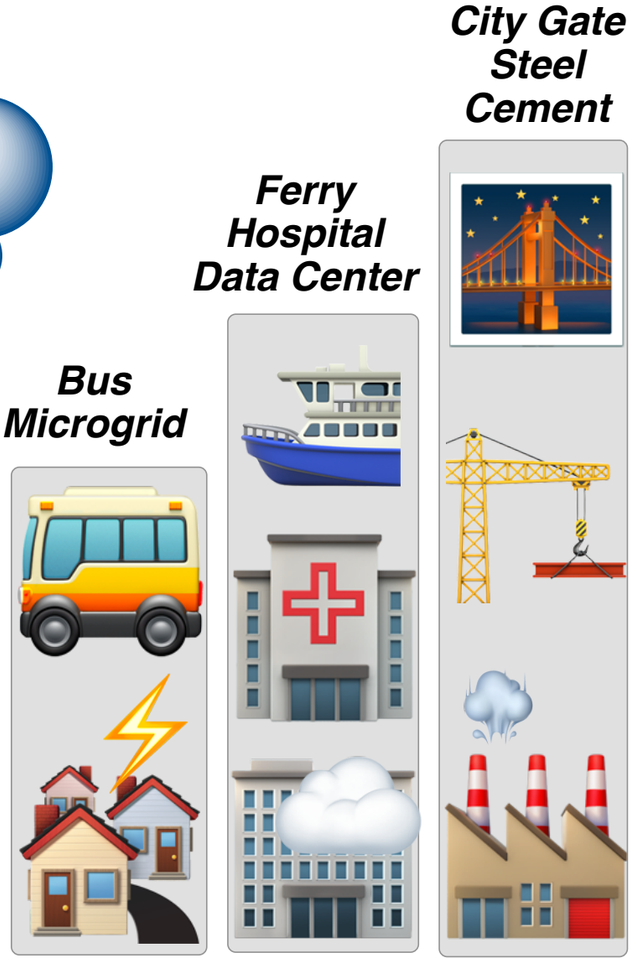
At PNNL, we use a top-down integrated approach driven by engineering feasibility and collaboration with HyMARC partners to explore the applications of LOHCs for end uses of varying scales



Liquid Organic H_2 Carriers



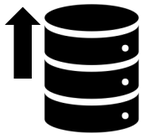




Scaling End Uses

Far from perfect: Defining an ideal LOHC

Low MP (<–30 °C). High BP (>300 °C): H_2 purification by simple condensation



High hydrogen storage capacity (>56 kg/m^3 or >6 wt%)

Low heat of desorption (42–54 kJ/mol-H_2): low dehydrogenation temperature 1 bar P_{H2} (e.g., <200 °C)

Long cycles of selective hydrogenation-dehydrogenation
(***This area needs a lot more development***)

Compatible with existing infrastructure for fuels

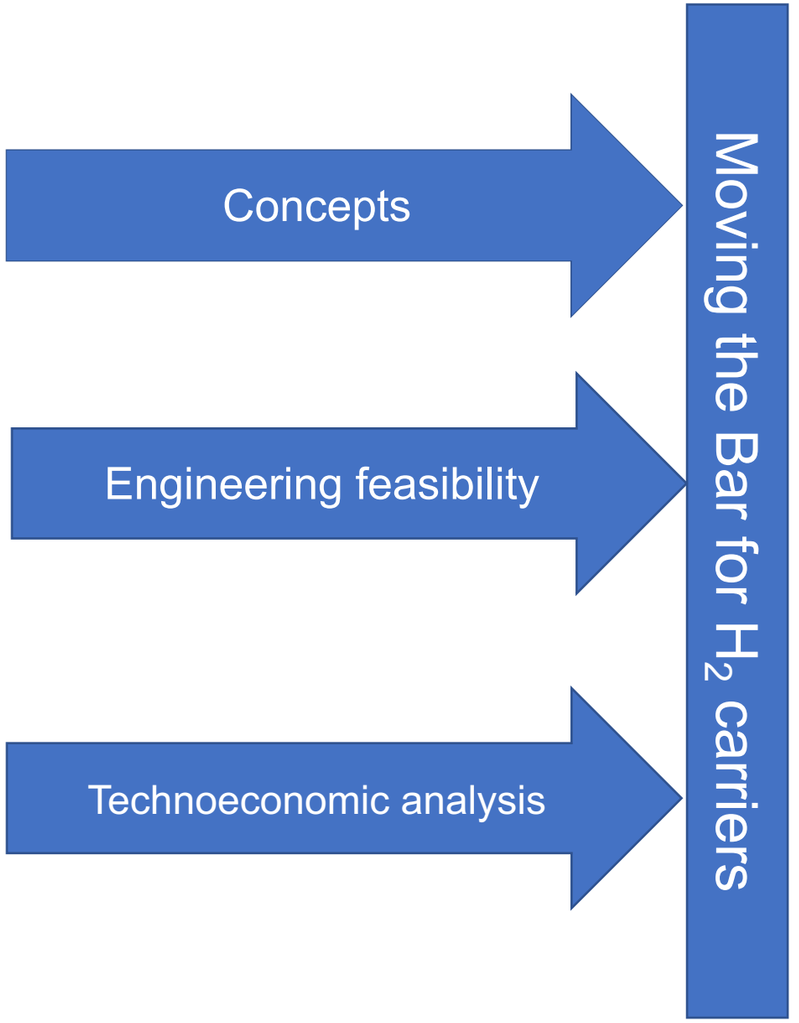
Low production costs and good technical availability

Toxicological and eco-toxicological safety during transportation and use

Relevance

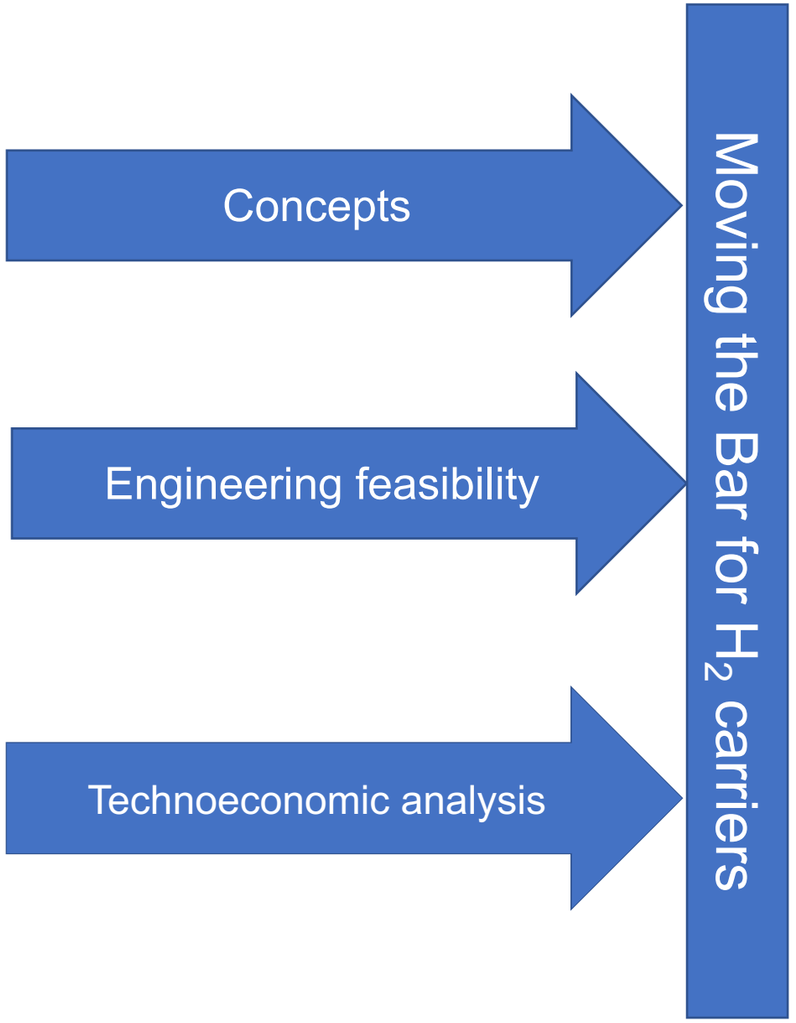
Moving the bar forward for H_2 carriers

- HyMARC is working to identify off-board scenarios that will benefit from solid and liquid phase carriers of hydrogen.
- Our approach to move the bar forward is to address a defined set of questions for a series of applications
- (i) what is a minimum footprint for each H_2 carrier
- (ii) Are known catalysts capable of providing a sufficient rate of H_2 release;
- (iii) is the power (W/l) and energy (Wh/l) for a given H_2 carrier sufficient to meet the demand.



HyMARC is working to identify off-board scenarios that will benefit from solid and liquid phase carriers of hydrogen

- Concepts
  - Identifying use case scenarios
    - ✓ Transport of H_2 from production facility to city gate
    - ✓ Transport of H_2 from city gate to refueling station
    - ✓ Backup power for data centers
    - ✓ Microgrid energy storage
    - ✓ Passenger ferry, train, bus
  - Identifying materials
  - Identifying approaches
    - ✓ One way carriers
    - ✓ Round trip carriers
    - ✓ H_2 carriers without generating hydrogen
- Engineering feasibility
  - minimum footprint for each H_2 carrier
- Technoeconomic analysis
  - Collaboration with LBL
  - Adapting, evolving



Evolution of HyMARC from CoE to H_2 carriers

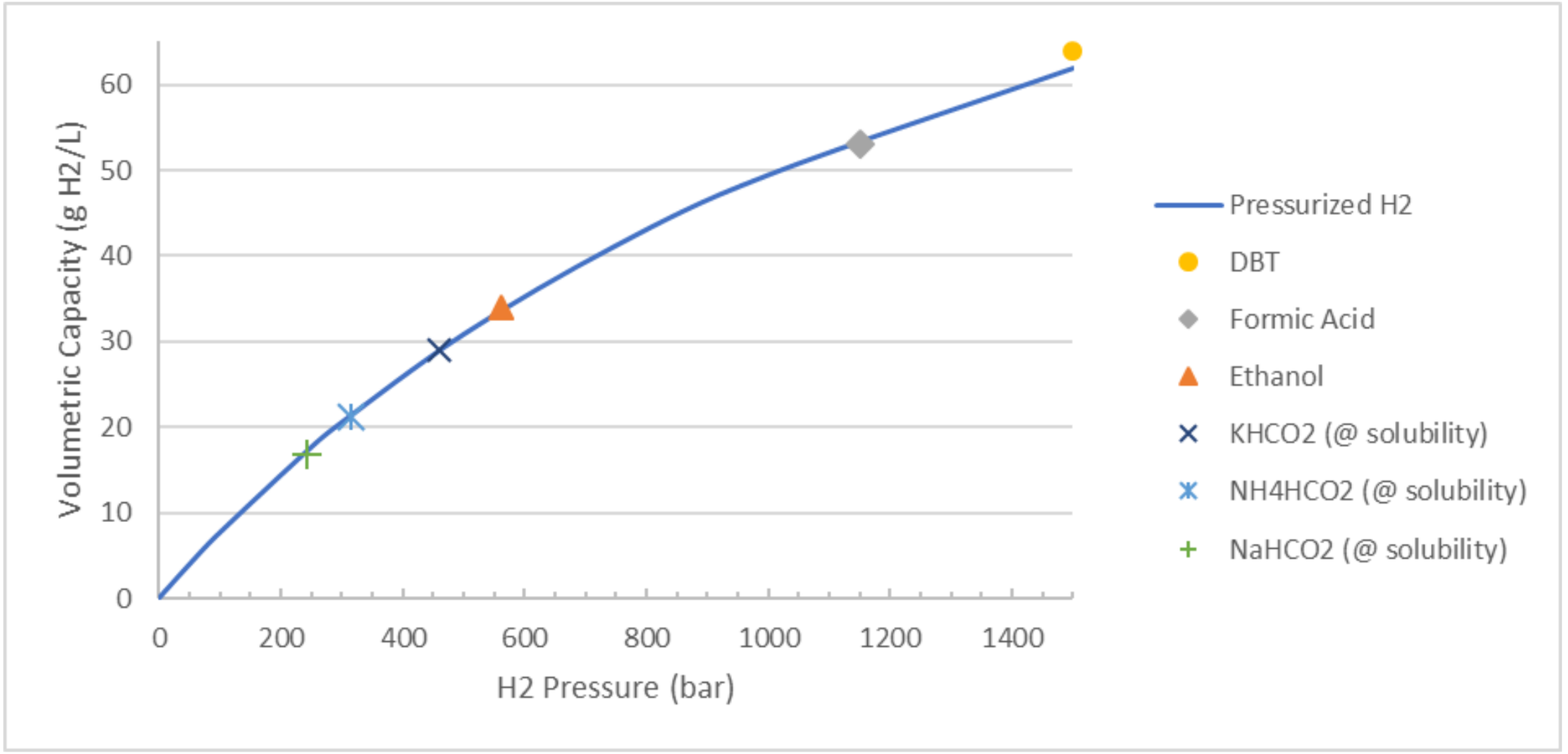
- **Identify promising *use cases*** (refueling station, city gate, emergency backup, …)
  - Define power and duration requirements
  - Identify benefits and challenges to put *use case* into practice
- **Identify promising *carriers*** (formates, formic acid, ethanol)
  - Compare promising carriers to compressed hydrogen
  - Identify benefits and challenges to put *material* into practice
  - Use information from the literature when available, when not available
    - Use theory, experiment, modeling
- **Utilize Engineering analysis to provides methods of *comparison***
  - Energy: Compare round trip efficiency
  - Cost: Estimate operating costs
  - Size: “Kristone” Plots
  - Benefits: Chemical Compression
- **Utilize Technoeconomic Analysis**
  - Operating and capital costs
  - Insight into ancillary benefits
  - Insight into research areas to reduce cost

Bottom line – develop metrics for a set of achievable use cases

Relevance

H_2 carriers are scalable and have the potential to *store*, *transport* and produce *usable* hydrogen

equivalent volumetric density of H2 carriers relative to comp H_2 gas



Bottom line – ethanol provides a storable H_2 density equivalent > 500 bar compressed H_2 gas

Approach

Identifying promising H_2 carriers (liquid phase)

	Example: EtOH to EtOAc
• Is the gravimetric/volumetric density greater than 250 bar H_2?	35 g H_2/liter
▪ what is the volumetric footprint of the system	
• What 'use case' are you targeting?	Microgrid (5 MT H_2)
▪ How much hydrogen carrier is needed?	
• What is the enthalpy release on regen?	37 kJ/mol H_2
▪ extra needs for heat management?	
• What temperature is required to reach 1 bar H_2 ($T = \Delta H/\Delta S$)?	100 ºC
▪ Minimum required energy input for release of H_2	
• What is $\Delta G_{(350\ C,\ 5\ bar)}$ H_2 release?	7 kJ/mol H_2
▪ are extra compressors needed?	
• What is $\Delta G_{(400\ C,\ 200\ bar)}$ H_2 uptake?	-15 kJ/mol H_2
▪ Regeneration possible under moderate conditions?	
• Are catalysts currently available to yield 1 kg H_2/minute?	TBD
▪ How much catalyst is needed? What flow rate of carrier is needed?	
• What is the selectivity for H_2 release?	> 99%
▪ How pure is the H_2? What separation processes are required?	
• What is the viscosity, melting point, vapor pressure at the release temperature?	0.98 cP, -114 C, 53 kPa
▪ Are there special needs for pumping or separations?	

Approach

Focus on high impact use cases

- Mobile Distributed (Refueling at City Gate, Transportation)
  - Benefits vs. Current Technology: Store stranded power, Environmental Concerns
  - Benefits vs. Gaseous H_2: Reduced volume and tankage cost
- Stationary Back-Up (Power Outage, Seasonal Storage)
  - Benefits vs. Current Technology: Store low cost electricity, Reliability vs. diesel, Size vs. batteries
  - Benefits vs. Gaseous H_2 : Less hazardous and reduced volume

Categorize Applications to Reduce to Reasonable Number

Mobile Distributed Power

use case	footprint	Duration hrs	Power MW	Energy MWh	MT [H2] /day	days	rate Kg H2/min	transport	ancillary considerations
city gate	large	25	4	100	50	365	35	miles to last mile	
ferry	medium	4.2	1.6	6.72	4.2	365	1.92		
long haul	small	20	0.24	0.84	0.06	365	0.73		

Stationary Back-Up

use case	footprint	Duration hrs	Power MW	Energy MWh	MT [H2] /day	days	rate Kg H2/min	transport	ancillary considerations
steel mill	extreme	TBD	146		205	365	143	transport or on site	
data center	large	72	20	1440	28	3	19.6	on site generation	fraction of base line power
hospital	medium	168	0.586	99	0.83	7	0.57	on site generation	
microgrid	small	1000	0.065	65	0.112	180	0.078	transport or on site	sell product
Relion backup	smaller	TBD	0.0029	0.49	0.004	7	0.0028	on site generation	

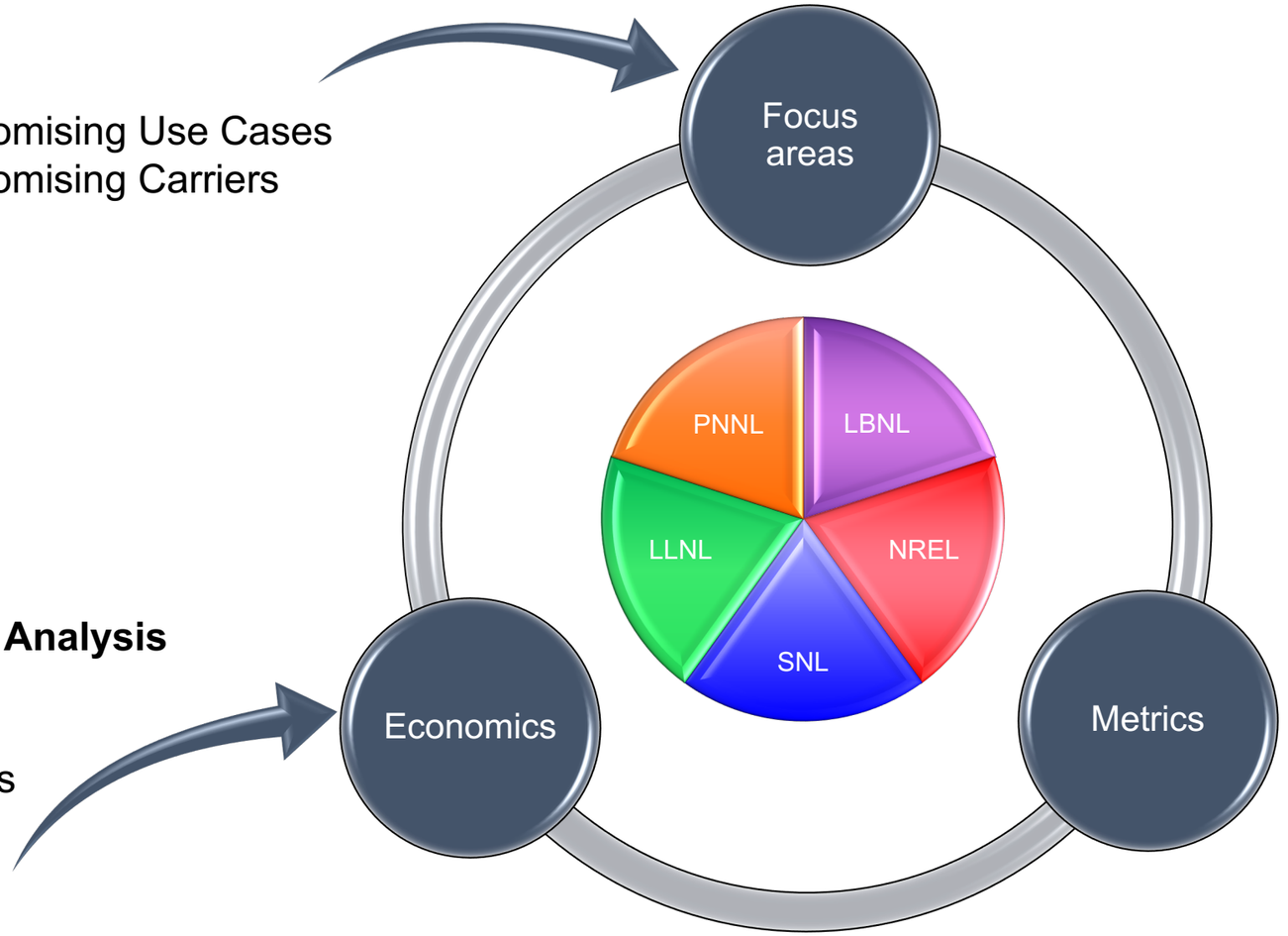
Approach

Accelerating progress through collaboration

Concepts
- Identify Promising Use Cases
- Identify Promising Carriers

Engineering Feasibility
- System Design
- Round Trip Efficiency
- *Kristone* plots
- Chemical compression

Techno economic Analysis
- Capital costs
- Operating costs
- Ancillary benefits



Collaboration

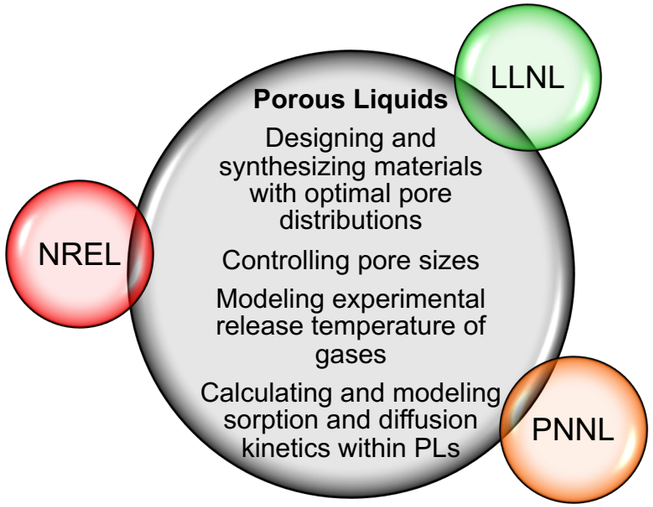
Leverage and share broad experience through monthly conference calls with Hymarc partners and seedling projects

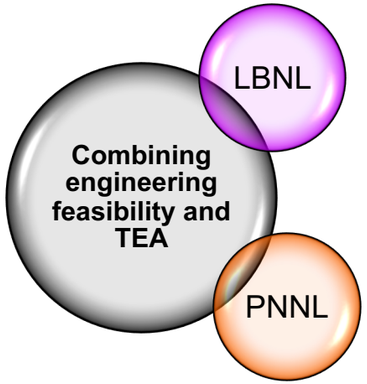
- DOE HyMARC
- WSU Hongfei, Tom, Kat
- USC Travis, Sam, Tom
- SNL Vitalie, Mark, John, Tom
- NREL Wade, Gennett, Tom, Abhi
- NREL Hawaii Gennett, Steve, Noemi, Jensen, Tom, Ba, Mark
- LBNL Hanna, Katarina, Kriston, Mark, Abhi, Ba
- LBNL Ji, Jinghua, Tom
- LLNL Brandon, Tom, Sam, Kat
- MSU, Nick, Abhi, Mark

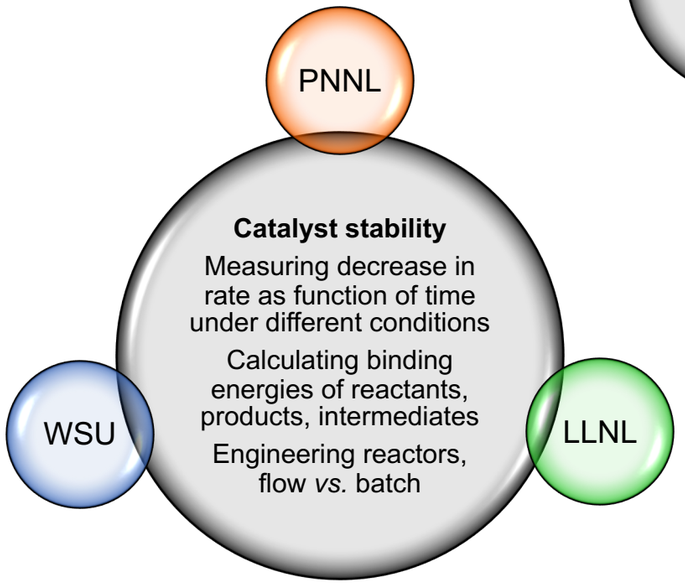
Sunday	Monday	Tuesday	Wednesday	Thursday	Friday
1 Week 1	2	3 WSU H2 carriers 1-2 PM	4	5	6
8 Week 2	9 USC H2 carriers 1-2 PM	10 SNL H2 carriers 11-12 PM	11 NREL H2 cariers 11-12 PM	12 NREL/Hawaii 3-4 PM	13 LBNL TEA 11-12 PM
15 Week 3	16	17 LBNL 3-4 PM	18 LLNL Catalysis 11-12 PM	19	20
22 Week 4	23 MSU 1-2 PM	24	25	26 Hawaii H2 carriers 3-4 PM	27

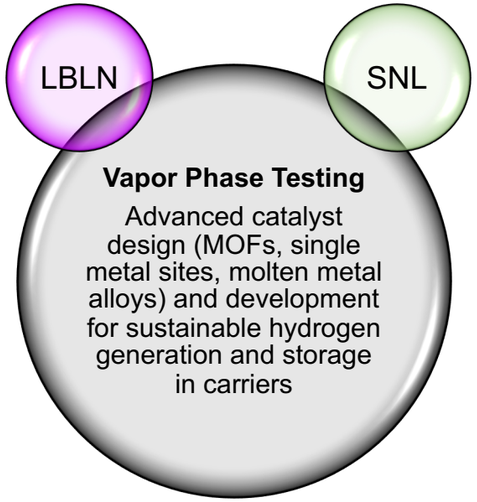
Collaborations

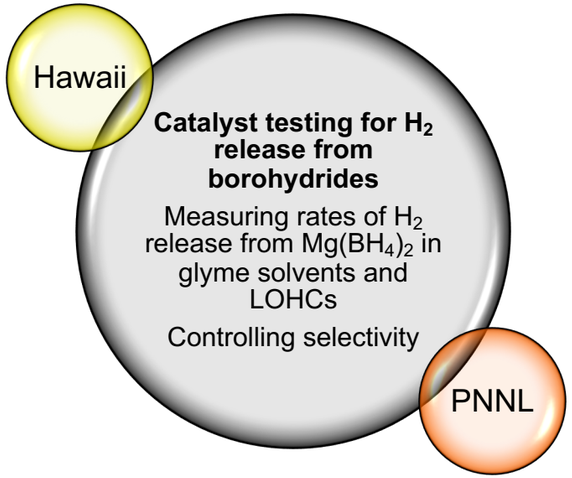
multiply projects involving experts on focused concepts

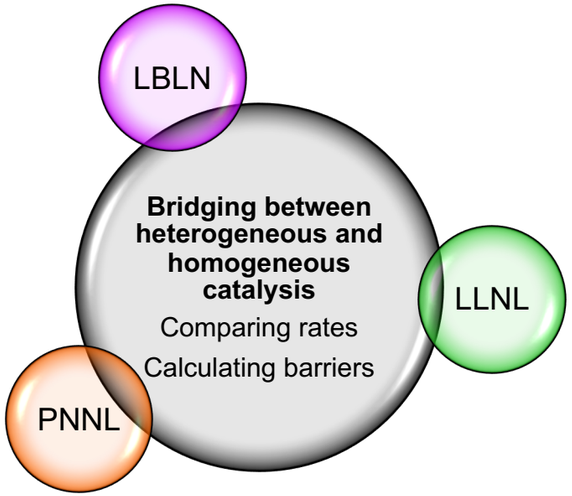












Accomplishments

determining volumetric foot print and minimum rate required for H_2 release for targeted use cases

- A city gate will need to store 50,000 kg/H_2/day (equivalent to 800 MWh) requiring 1,000,000 liters (LOHC) ca. 1000 m^3
  - To generate 50,000 kg H_2/day at a city gate requires a H_2 release rate of 35 kg H_2/minute (i.e., 1440 minutes/day) from a H_2 carrier

- A refueling station that requires 1,500 kg H_2/day needs to store 30,000 liters LOHC/day and release H_2 at an average rate of 1 kg H_2/min (i.e., 1440 minutes/day)
  - To generate 1,500 kg H_2/day a day from a H_2 carrier at a refueling station requires a H_2 release rate at an average rate of 1 kg H_2/min.

Bottom line – H_2 carriers are scalable – to accommodate a wide range of use cases

Accomplishments

Concept (defining storable, transportable, usable capacity):

Hydrogen Carrier Based on Formate/Bicarbonate Cycle

$$NaHCO_2 + H_2O \rightleftharpoons H_2 + NaHCO_3$$

Δ_rH^0=20.4 kJ/mol, Δ_rG^0 = 1.4 kJ/mol, Δ_rS^0=59.9 J/mol K

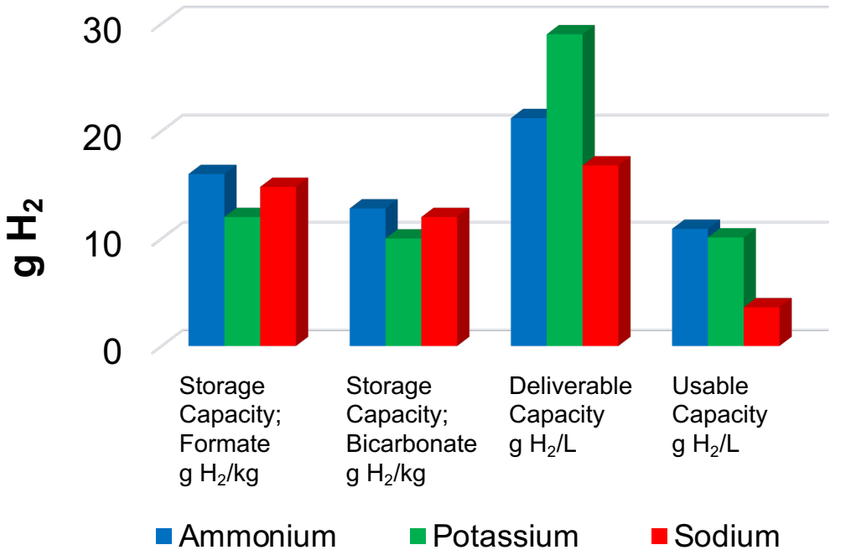
Advantages:

- High volumetric H_2 density
- Water provides ½ the H_2
- ΔG ~ 1 for H_2 release and uptake
- Reversible at room temperature
- Low toxicity
- Provides >10 bar H_2 pressure

Limitations:

- Catalyst decomposition
- Slower reaction kinetics
- Dilution *(due to low solubility of $HCOO^-/HCO_3^-$ in solvents)*

H_2 carrier	Volumetric density, g H_2/L in solution at max. solubility at 30 °C	Pure
H2CO2	-	**53.4**
$LiHCO2.H_2O$	31.4	**41.7**
NaHCO2	19.6	**56.5**
KHCO2	29.7	**45.4**
NH_4HCO2	21.4[a]	**40.3**
CsHCO2	9.6	**11.5**



Bottom line – the formate / bicarbonate cycle operates at moderate temperature and pressure

Accomplishments

Concept (un-catalyzed release of H_2): Hydrogen Carrier Based on Formate Hydrothermal Decomposition

$$2HCOONa + H_2O \rightarrow 2H_2 + Na_2CO_3 + CO_2$$

$\Delta_r H^0$=68.3 kJ/mol, $\Delta_r G^0$ =17.15 kJ/mol,
$\Delta_r S^0$=164.8 J/mol K T1bar = 412 K (140 C)

Advantages:

- High volumetric H_2 density
- Water provides ½ the H_2
- Overcome challenges associated with limited solubility of formate/ bicarbonate
- Provides >10 bar H_2 pressure

Limitations:

- CO_2 byproduct
- Higher temperature reaction

- Pressure sensitivity: Proposed system can deliver high P hydrogen (>50 bar at 350 °C (<30 min) compared to the conventional LOHC (eg. In PDBT systems, to shift eq. from 90% dehydrogenation to 90% hydrogenation, H_2 pressure has to be increased only by a factor of 2 or 3)
- Rehydrogenation: (a) Proposed system: 30-100 °C in the presence of a catalyst. (b) Conventional LOHCs: 100-300 °C in the presence of a catalyst.

Table 2 – Enthalpies of dehydrogenation and, where relevant, evaporation for the chemical hydrides.

Storage medium	Enthalpy of dehydrogenation [kWh/kg H_2]	Typical temperatures for hydrogen release [C]	Boiling point of hydrogenated form [C]	Enthalpy of evaporation (if gas phase during dehydrogenation) [kWh/kg H_2]	Total heat which must be provided [kWh/kg H_2]
Methanol	2.3	250	64.7 (100 for water)	4.4[a] (1.8 for water)	6.7
Ammonia	4.2	>425	33.3	2.1	6.3
Formic acid	4.3	<100	100.8	-	4.3
MCH	9.7	350	101	1.5	11.2
DNEC	7.6	220	>220	-	7.6
PDBT	9.0	300	390	-	9.0

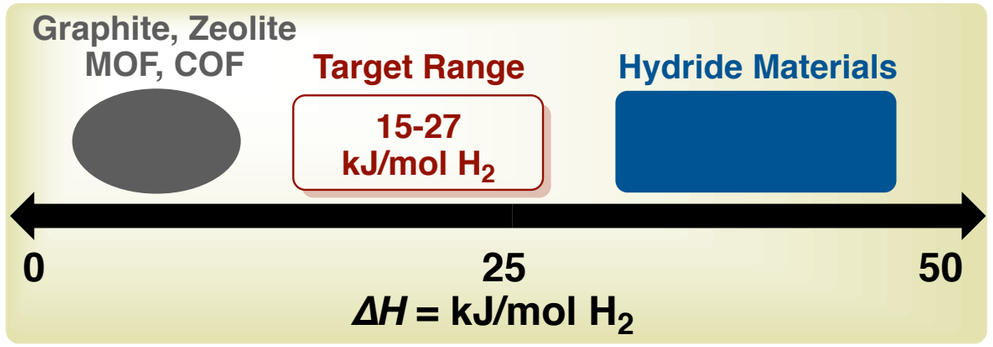
[a] For steam reforming of methanol, one must evaporate both methanol and water. In a real case, a stoichiometric excess of water of approximately 50% is typically used; this excess ratio is used to generate the value above [163].

Int. J. Hydrog. Energy, 2019, 44, 11901-11919
Energy Environ. Sci., 2017, 10, 1652—1659
Green Chem., 2010, **12**, 2214–2224

Bottom line – non-catalytic hydrothermal formate decomposition temperature is comparable to the conventional LOHCs that use noble metal catalysts (Ru, Pt etc) to release H_2.

Accomplishments

Concept: Dehydrogenative coupling provides a means to modify thermodynamics. Molecular catalyst that enables both H_2 release and uptake can provide an approach for microgrid technology

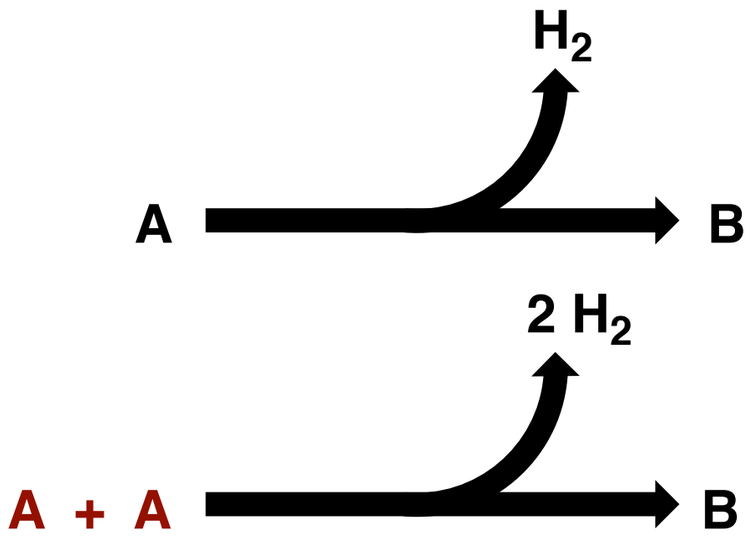


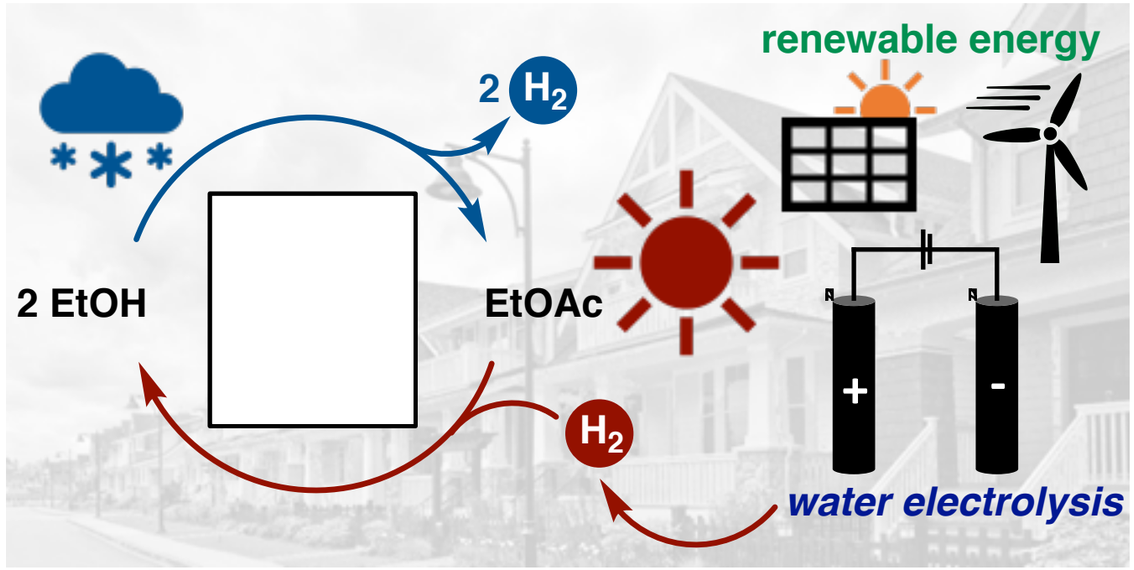
Gas-phase calculation
***ΔH* = 12 kJ/mol H_2**
ΔS = 30 J/K/mol H_2
(*ΔG*^{0} ca. 4 kJ/mol)

2 EtOH → 2 H_2 + EtOAc

Liquid phase calculation
Δ*H* = 37 kJ/mol H_2
Δ*S* = 100 J/K/mol H_2
(Δ*G*^{o} = 8 kJ/mol H_2)

Modifying thermodynamics

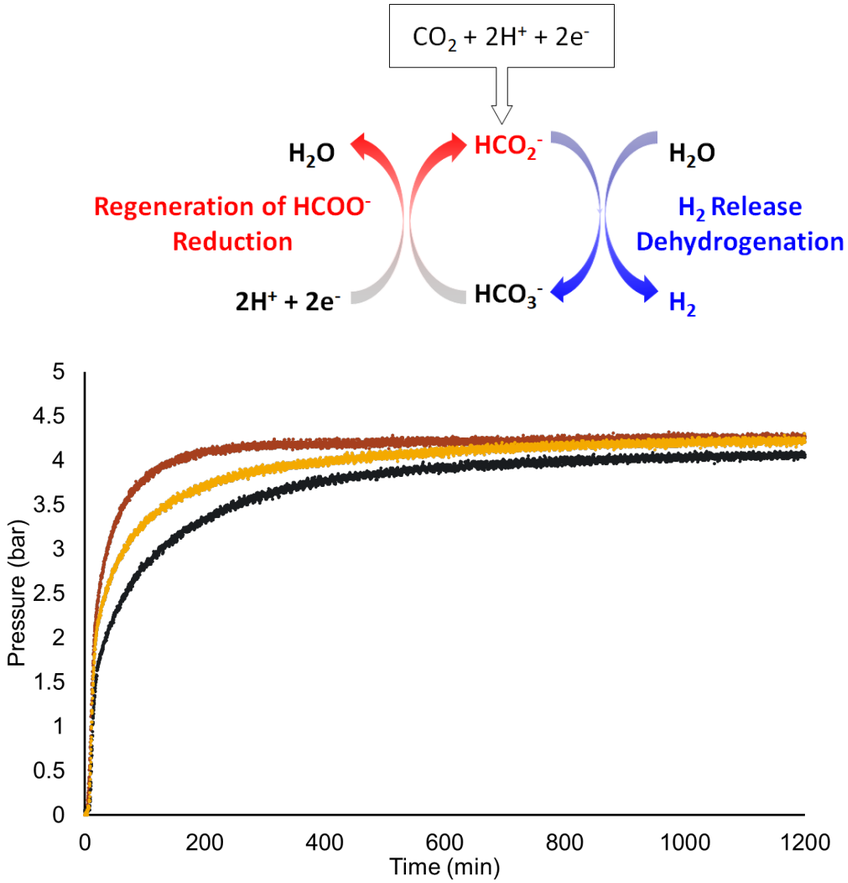




Bottom line – the EtOH/ EtOAc cycle operates at moderate temperature and pressure

Accomplishments

Concepts: (i) Formation of H_2 carriers without H_2 (ii) Engineering approach to catalyst reactivation)



- Investigated potential for regeneration of H_2 carrier, formate, by electrochemical process
- Screened multiply Pd-supported catalysts (commercially available and from collaborators)
- Confirmed catalyst reactivation by washing with water
- Demonstrated ability to generate 3-4 bar H_2 backpressure (at the formate/bicarbonate equilibrium)

Bottom line – (i) The formate / bicarbonate cycle provides an opportunity to regenerate H_2 carriers without needing a discrete step to make H_2. (ii) Use double reactor to regenerate catalyst

Approach

Engineering feasibility: Developing Ragone plots of Energy vs Power for multiply H_2 carriers

A data center may need 10 MW Power for 100 hours (1GWh)

★ Interpolation from Ragone plot for liq. NH_3 PEM FC provides an estimate of the system 'foot print'

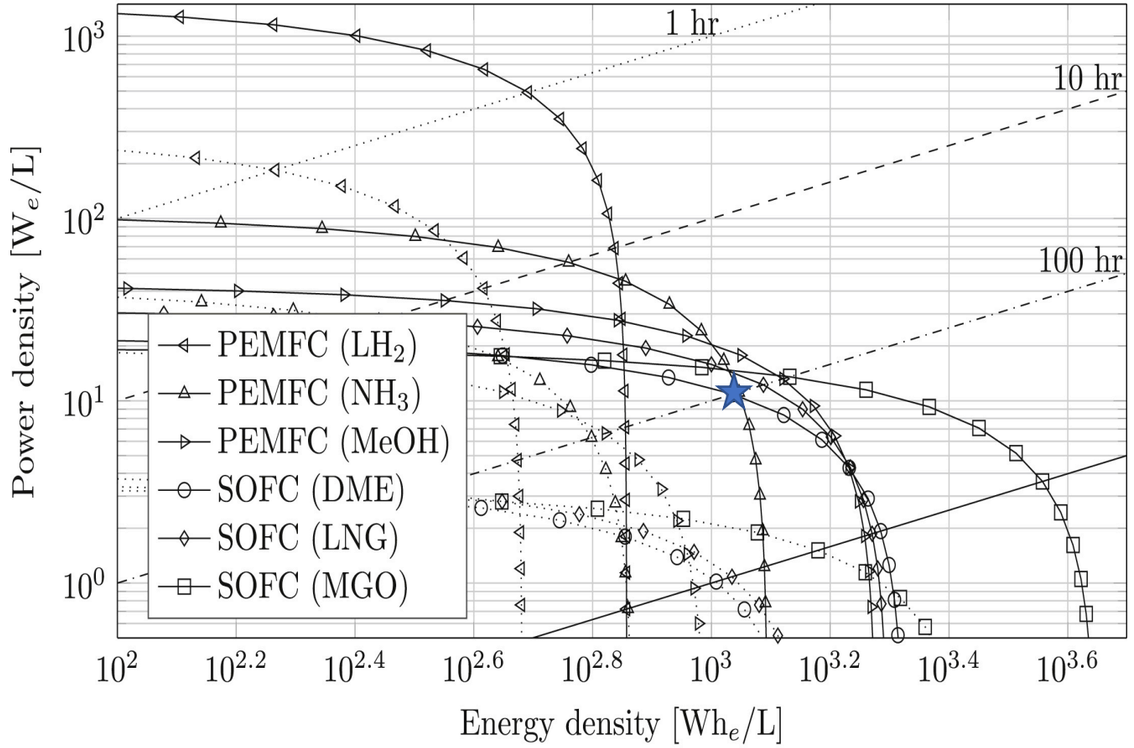
Power 10 W/liter (10 MW/10 W/liter = 1,000,000 liters)
Energy 1000 Wh/liter (1 GWh/1000 Wh/liter = 1,000,000 liters)

Liq NH_3 = 0.17 kg H_2/liter * 20 kWh/kg H_2 = 3.4 kWh/liter
(1 GWh/3400 Wh/liter NH_3 = 300,000 liters of liq NH_3)

Power ~ combination of volume of FC and BOP
Energy ~ volume of 'fuel' and tank

What does the footprint look like for a: passenger ferry, bus, train, city gate, refueling station, microgrid, … using formic acid, formate salt, EtOH, methylcyclohexane, …

Also need to consider a material and system capable of delivering 10 kg H_2/minute for the data center backup



(b) Volumetric density of fuel cell systems with various logistic fuels.

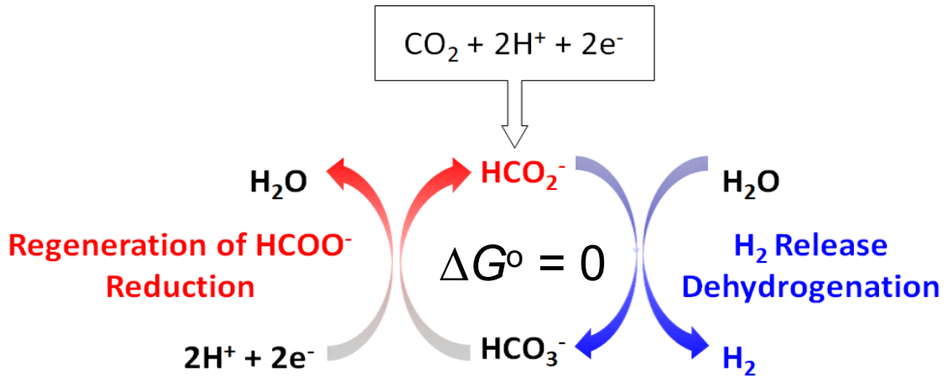
Figure 3 from A review of fuel cell systems for maritime applications. L. van Biert, M. Godjevac, K. Visser, P.V. Aravind. *Journal of Power Sources 327 (2016) 345-364*

Bottom line – Ragone/Kristone plots provide a means to compare physical footprints for different H_2 carriers for different sets of use cases

Accomplishments

TEA of Formate regeneration from Bicarbonate suggests water removal most costly step

Electrochemistry enables regeneration of H_2 carrier '*without hydrogen*'



Bottom line – initial EF and TEA suggests water removal is the expensive step. Need to think about special use case where heat is cheap (nuclear) or develop catalysts that work under more concentrated conditions

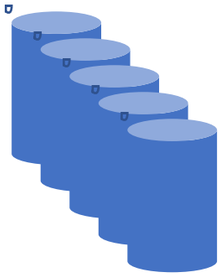
Microgrid

5 MT H_2 Annual Storage

5 tanks **8 M $NaHCO_2$**

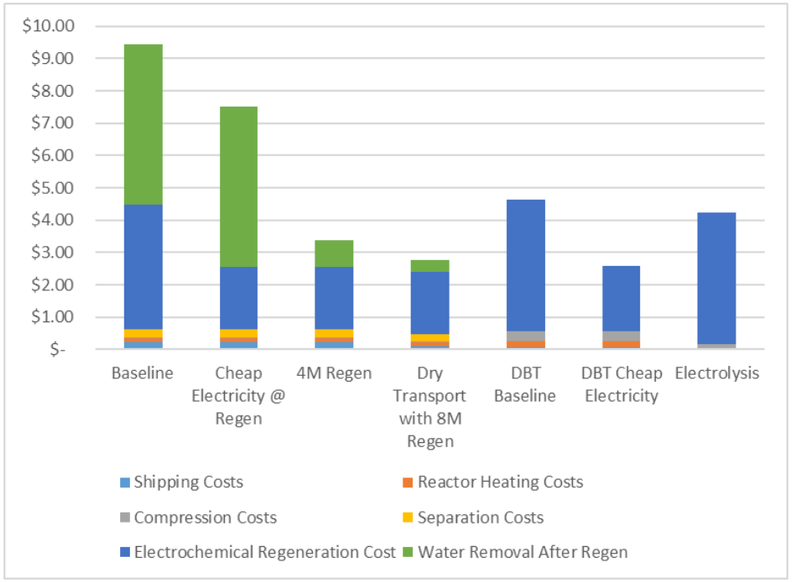
300,000 L

11' ID x 22' tall



Materials are inexpensive, non-flammable and non toxic ($KHCO_3$ is used as a de-icer)

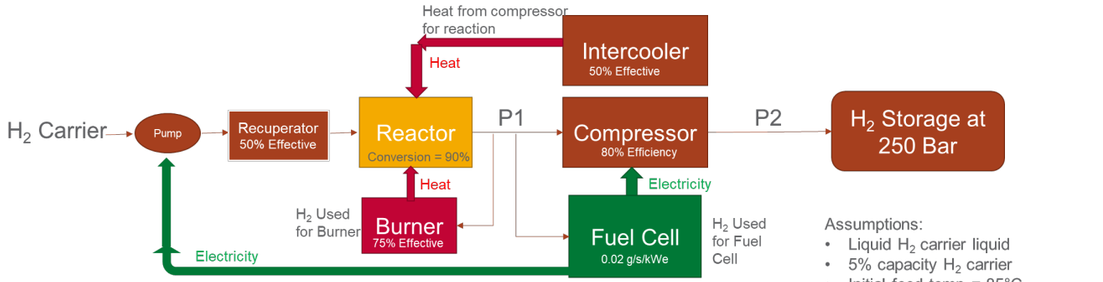
Preliminary TEA suggest water removal is great expense



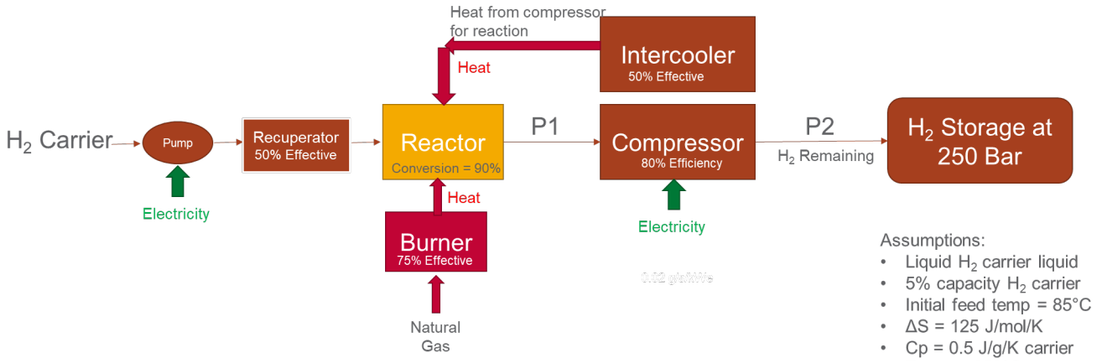
TEA analysis suggests efforts are needed to perform regeneration at higher concentrations or a use case with cheap source of heat, e.g., nuclear reactor

Accomplishments:

Engineering feasibility optimizing the temperature for H_2 release can provide initial stage of chemical compression

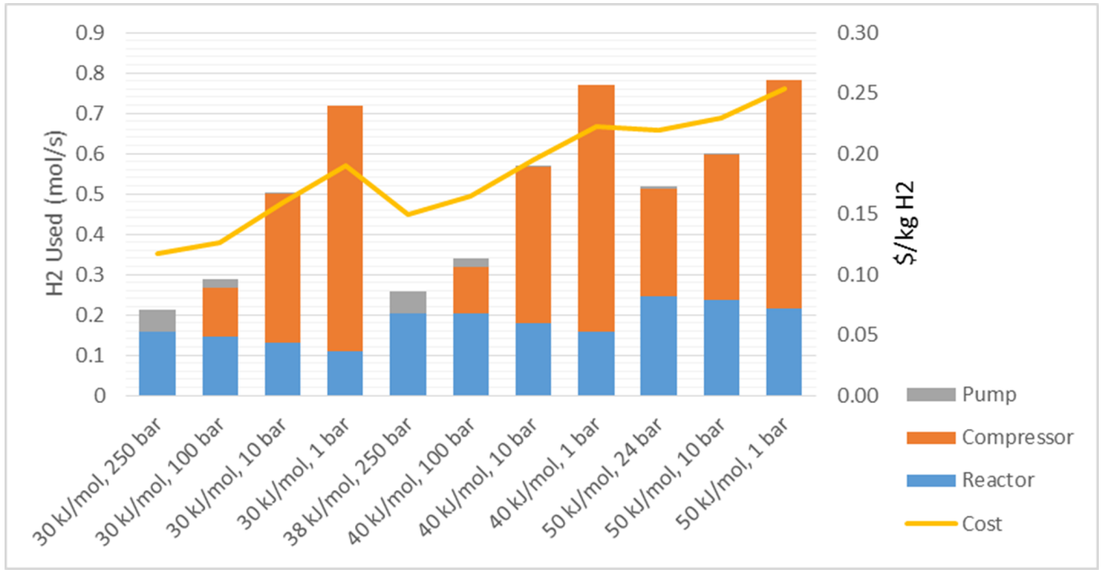


Assumptions:
- Liquid H_2 carrier liquid
- 5% capacity H_2 carrier
- Initial feed temp = 85°C
- ΔS = 125 J/mol/K
- Cp = 0.5 J/g/K carrier
- $T_{reactor} \leq 350°C$
- No H_2 loss due to purification step



$/kg H_2 compressed

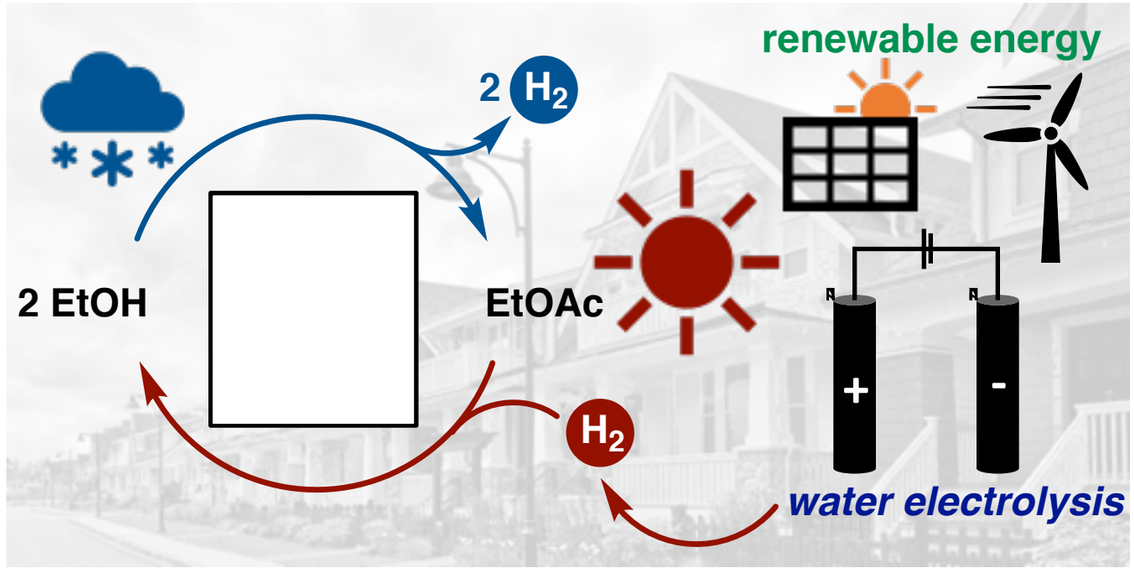
Assumptions:
- Liquid H_2 carrier liquid
- 5% capacity H_2 carrier
- Initial feed temp = 85°C
- ΔS = 125 J/mol/K
- Cp = 0.5 J/g/K carrier
- $T_{reactor} \leq 350°C$
- No H_2 loss due to purification step
- $0.054/kWh electricity
- $0.02/kWh natural gas

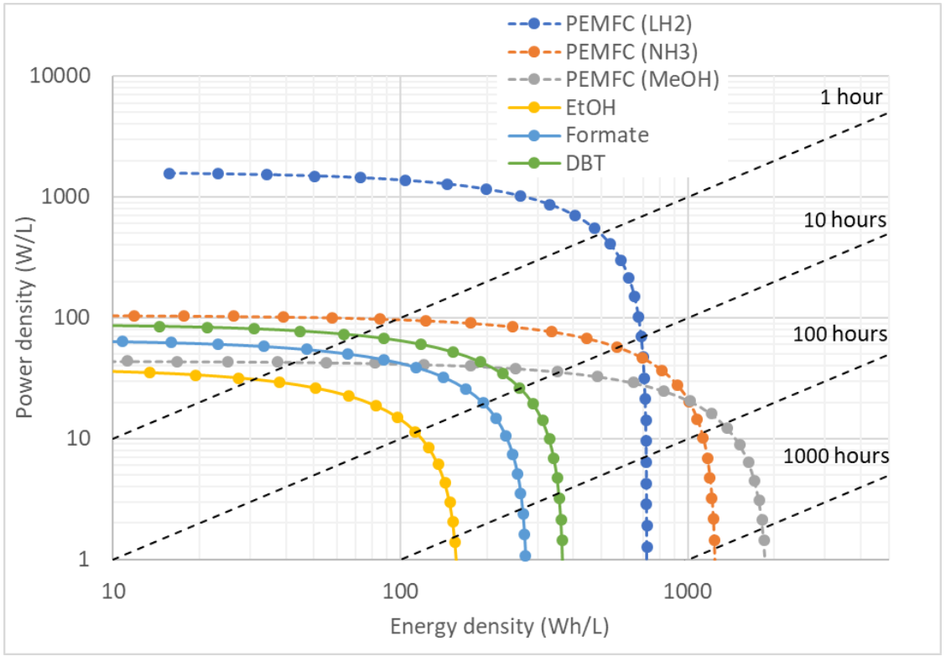


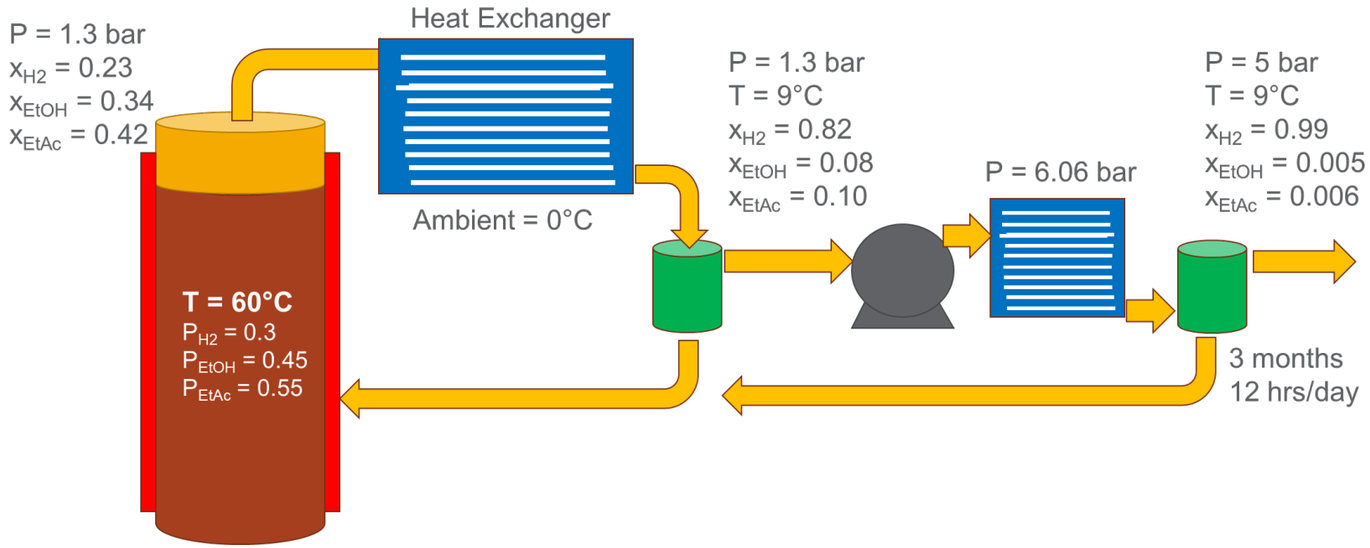
Bottom line – chemical compression can reduce the needs of physical compression.

Accomplishment

Engineering Analysis using Kristone plot shows footprint of Ethanol/Ethyl Acetate Cycle







Bottom line – Ragone plots provide insight into the physical footprint for EtOH for multiply use cases ranging from seasonal storage, to data centers to a passenger ferry.

Summary of HyMARC accomplishments for H_2 carriers

- **Concepts**
  - Dehydrogenative coupling to alcohols (35 g H_2/liter)
    - ✓ modify ΔH and ΔS to obtain ΔG in range of 4-8 kJ/mol H_2.
    - ✓ One pot reversible release and uptake of H_2 with a molecular catalyst
    - ✓ condensed phase thermodynamics of alcohols are substantially different then gas phase thermodynamics
  - Formate / bicarbonate cycle (30-50 g H_2/liter)
    - ✓ Synthesis of H_2 carriers without making H_2 in a discrete step – electrochemical regeneration
    - ✓ Regeneration of formate from bicarbonate under moderate conditions (5 bar H_2, 40 C)
- **Engineering feasibility**
  - Ragone plots to determine the volumetric footprint
    - ✓ EtOH for a microgrid (5 Mt H_2)
    - ✓ NH_3 and liq H_2 for a Data Center (1 GWh)
  - Analysis of chemical compression to enable initial compression step
    - ✓ Formic acid (xxx bar H_2)
  - Compiled list of existing catalysts that can provide >1 kg H_2/min
    - ✓ from formate xx kg Pd
    - ✓ formic acid xx kg Pd
- **Technoeconomic analysis**
  - electrochemical regeneration of formate from bicarbonate
    - ✓ removal of water most costly step

Back up slides

Task 3.D.2. Porous liquids as hydrogen carriers

Relevant technical targets

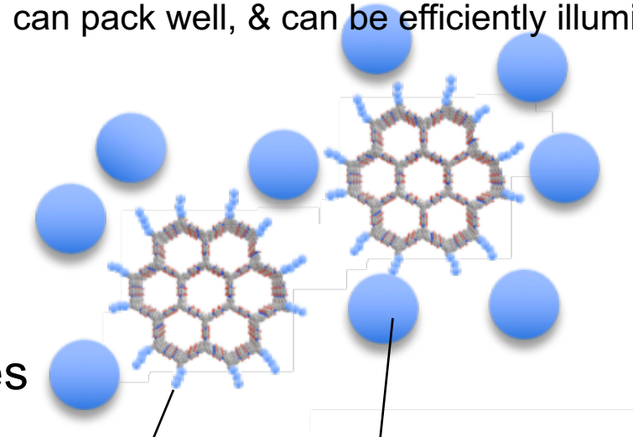
- Volumetric - better sorbent packing
- Desorption Time – alleviate mass transport issues in monoliths
- Heats of Adsorption
  - ***Decreasing*** high Q_{ST} when coupled with illumination strategy
  - 'Trapping' gas from low Q_{ST} sites and ***increasing*** desorption temps.

Project success

- 'Fluid' monolith with improved volumetric capacity and fast desorption times
- 'On demand' H_2 delivery when coupled with illumination strategies

Approach:

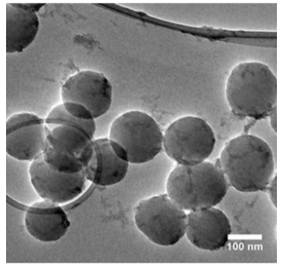
Synthesize COF colloids so they stay suspended,
can pack well, & can be efficiently illuminated



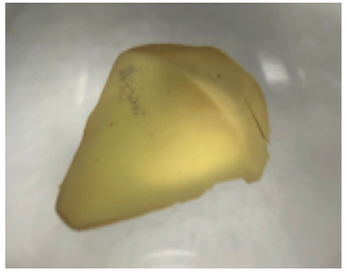
Use Size-excluded solvent w/ no vapor pressure for lubrication/fluidity

Tethered groups stabilize colloids against irreversible aggregation, enhance solubility

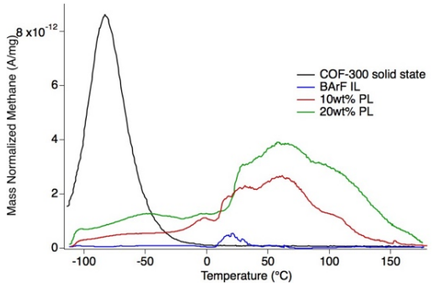
Well-defined
100 nm COF Colloids



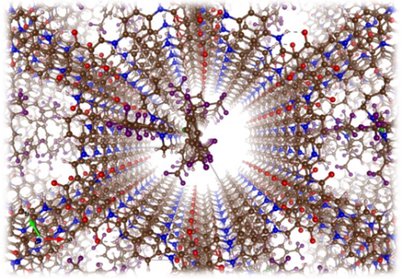
COF Monolith



Enhanced Gas Uptake &
Influence on Desorption Temp.



Modeling Porous
Liquid Dynamics



Lawrence Livermore National Laboratory

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

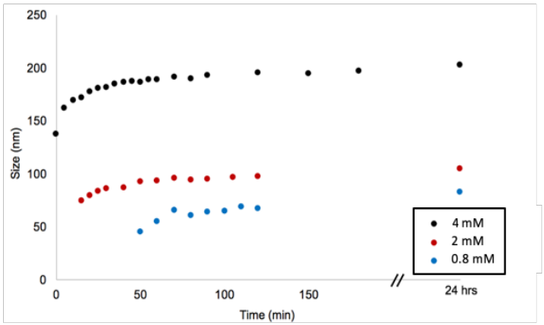
Pacific Northwest
NATIONAL LABORATORY

COLORADO SCHOOL OF MINES

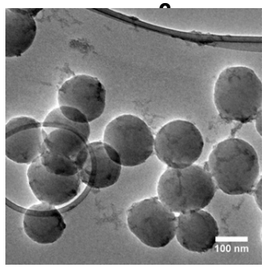
Task 3.D.2. Porous liquid Accomplishments

1. Control over COF Colloid Size & Surface Area

Dynamic Light Scattering

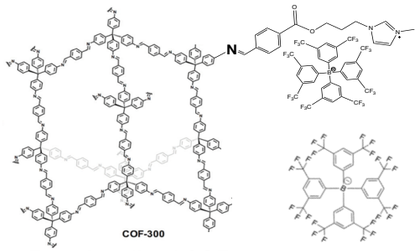


~100 nm particles



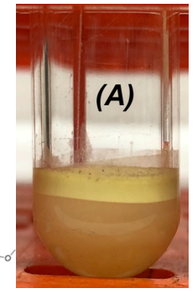
[M] < 6 mM in CH_3CN, r.t, 0.16 eq. $Sc(Otf)_3$ Catalyst

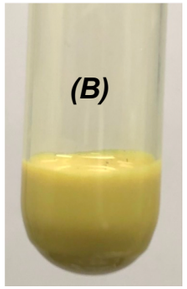
2. COF Functionalization for Indefinite Colloid Stability



Functionalized COF

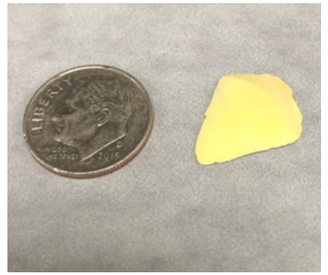
Ionic Liquid





(A) No functionalization = separation with time
(B) Functionalization = Stable suspension > 6 months

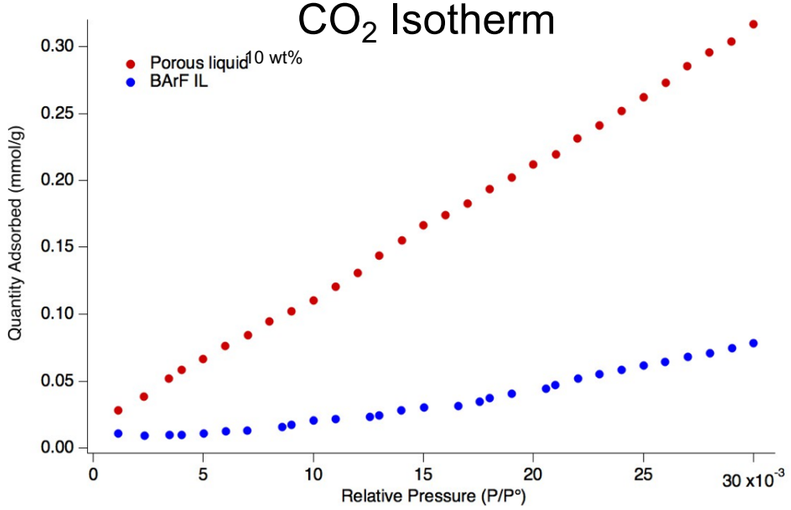
3. Colloids Used to Synthesize Monolith



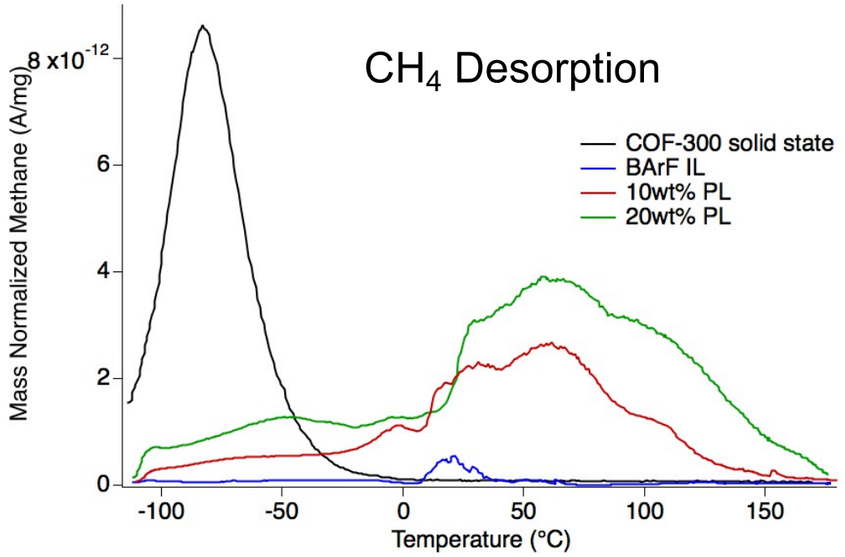
400 m^2/g, ~0.5 g/cm^3

4. Enhanced Gas Uptake Demonstrated for Porous Liquid

CO_2 Isotherm



CH_4 Desorption



CO_2 data indicates near 100% of theoretical pores remain open for gas binding

CH_4 data indicates dramatic uptake in gas relative to solvent (>20 fold increase), also dramatic effect on desorption temperature

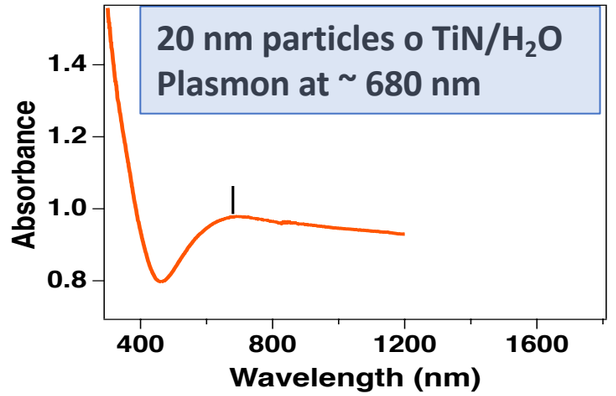
3f:9 Plasmon interactions for on-demand hydrogen release in hydrogen carriers

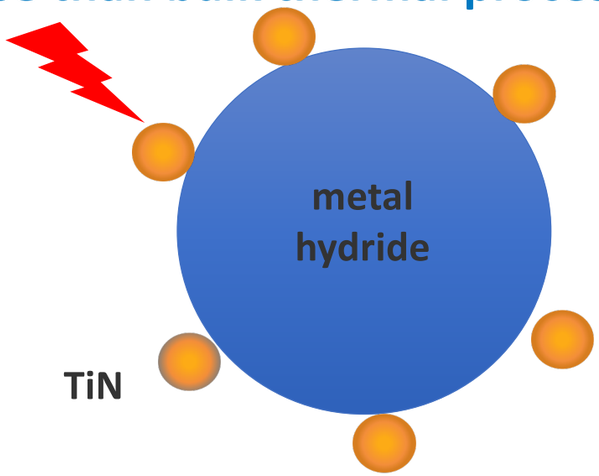
Approach:

Reversibly release and store hydrogen at near-ambient conditions via an optically driven process.

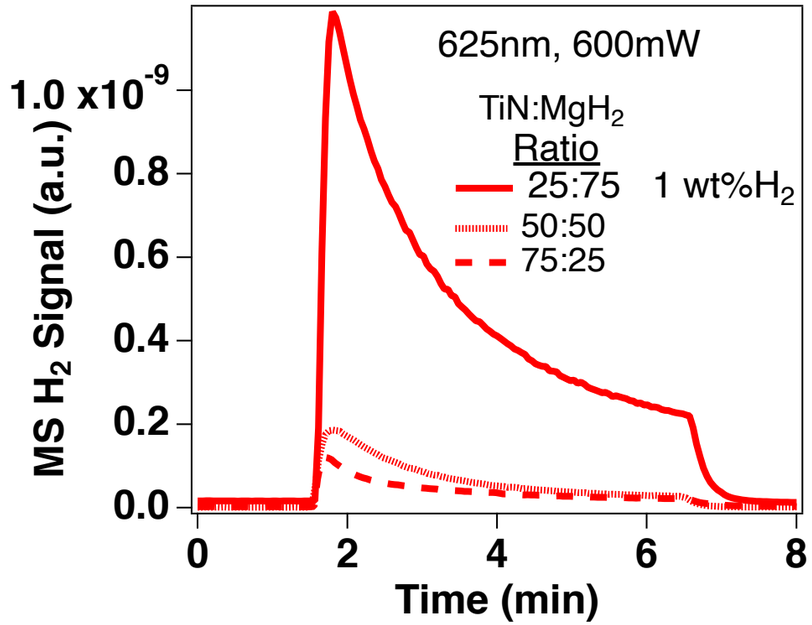
Impact:

Deliver hydrogen using less energy and with a faster response than bulk thermal processes.





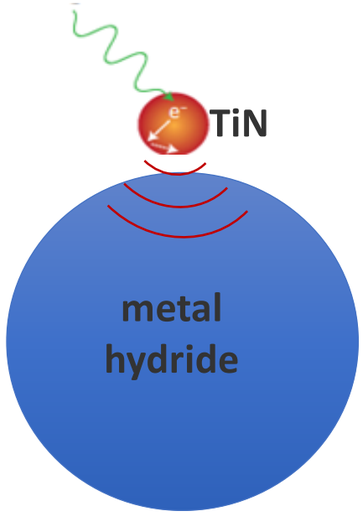
Photoexcite the TiN plasmon to drive rapid H_2 release

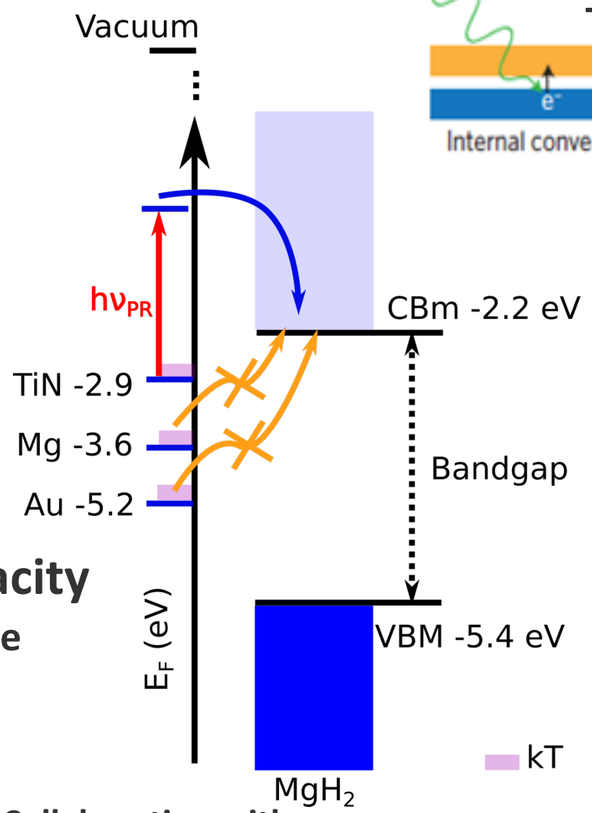


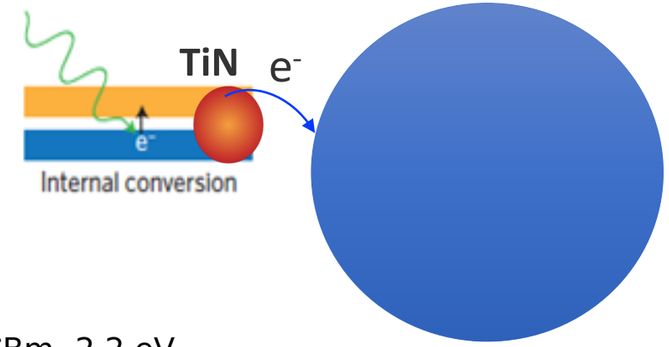
Result: 1 wt% H_2 in 5 min TiN/MgH_2

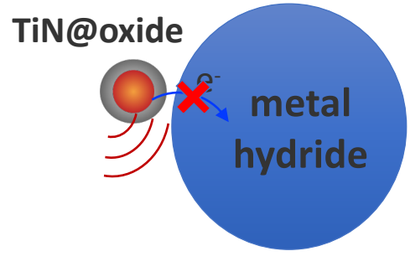
Developing a mechanistic understanding

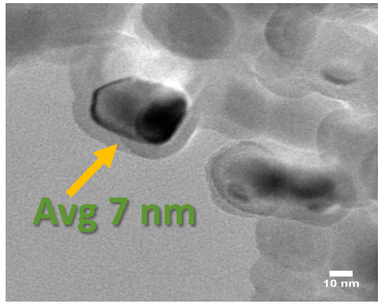
Plasmonic heating vs. Photo-excited electron transfer











Path forward to increase capacity

- **better interface TiN/metal hydride**
- **Confirm H_2 quantitative dehydrogenation by Sieverts measurements**
- **Resolve mechanism**

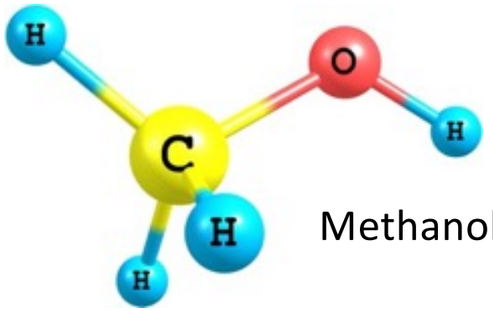
Collaboration with:

Prendergast, Sanz-Matias, Verma (LBNL)

- Charge transfer of photoexcited TiN electrons to the conduction band of MgH_2 is favorable
- charge transfer from Au, Mg or nonexcited TiN surfaces is thermodynamically disfavored.

for Methanol dehydrogenation

Background



Methanol

1. High gravimetric H_2 density. (~12%)
2. Low cost
3. Easy handleability and transportation
4. Being manufactured from a variety of renewable sources

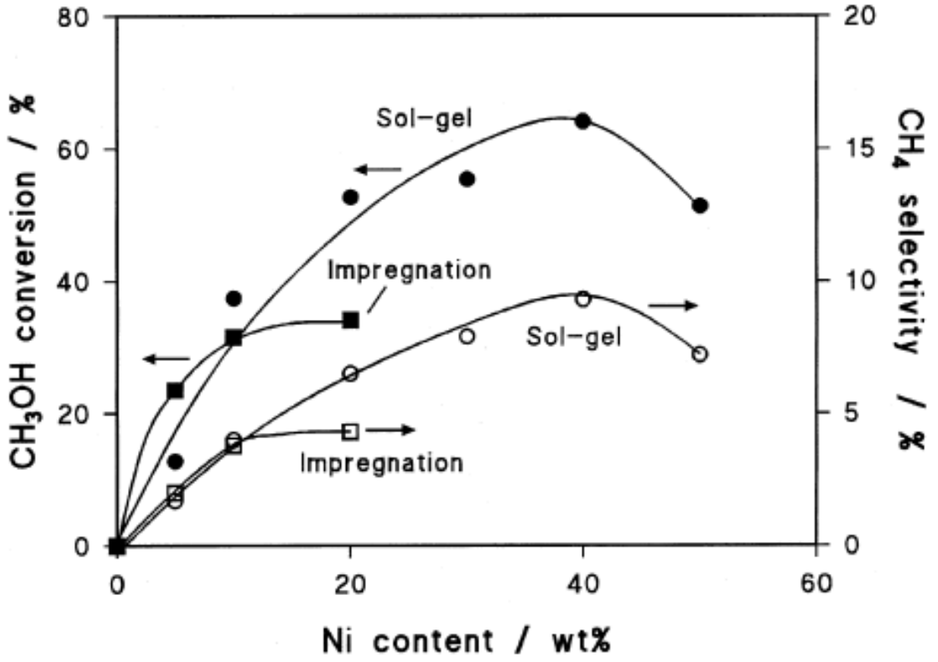


Figure. Methanol decomposition over nickel supported on silica at 250 °C. [1]

Note:

1. Noble-metal-based catalysts: high activity, exorbitant price, low abundance.
2. Transition-metal-based catalysts: Lower price, low selectivity and low reactivity.

[1] Journal of Molecular Catalysis A: Chemical 152 2000. 157–165.

Zhuolei Zhang, Jeff Urban

Modulation of Electronic Metal-Support Interaction for Catalysis

Ultrasmall Nickel Nanoclusters deposited on defective BN nanosheets as the Catalyst

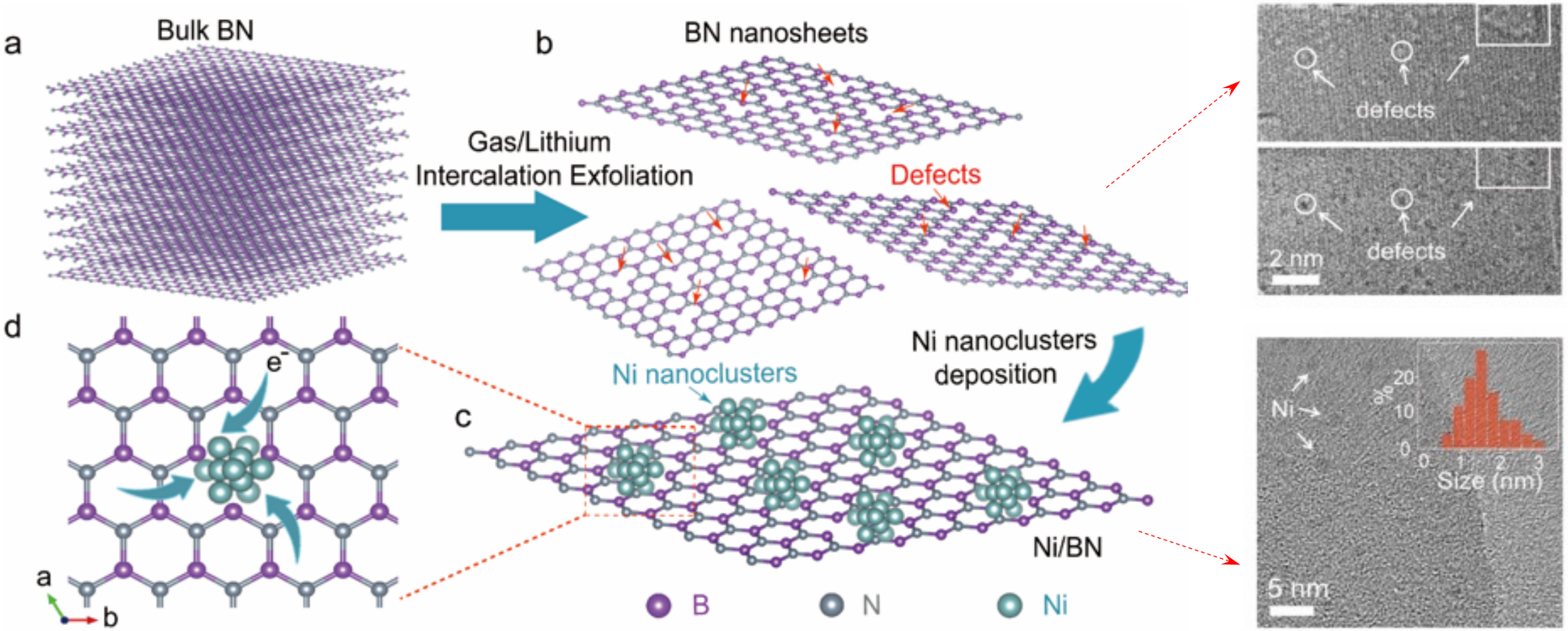
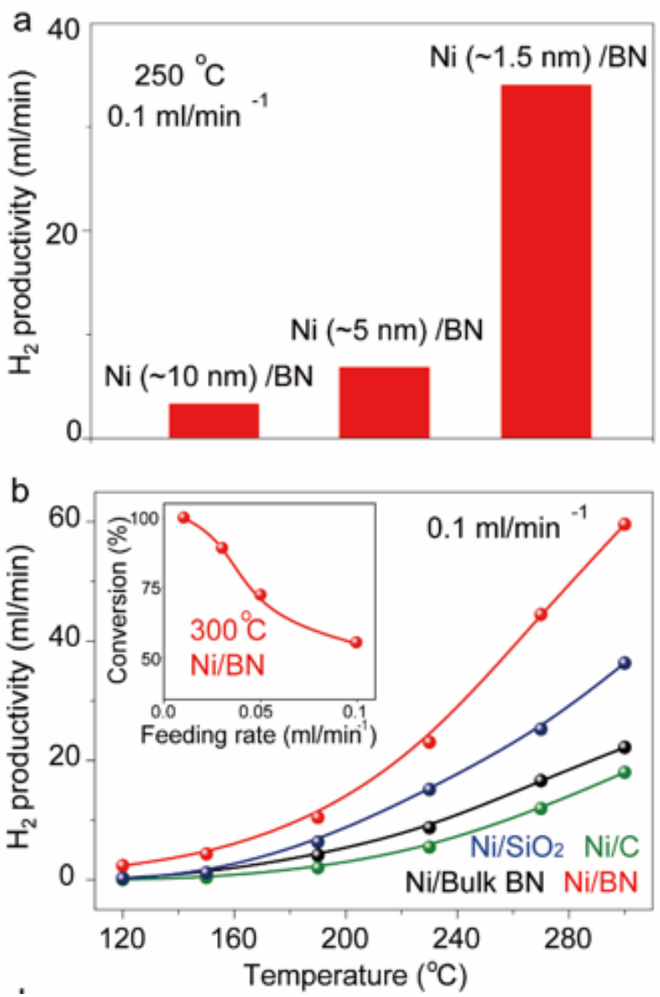


Figure. Schematic illustration of the formation of defective BN nanosheets and further deposition of Ni nanoclusters. The smaller nanoparticles (~1.5 nm) possess the capability of more localized electronic states for charge transfer. The defects help improve the binding energy of reactants at the surface of Ni nanoclusters, facilitating the catalytic reaction.

Zhuolei Zhang, Jeff Urban

Catalytic Performance



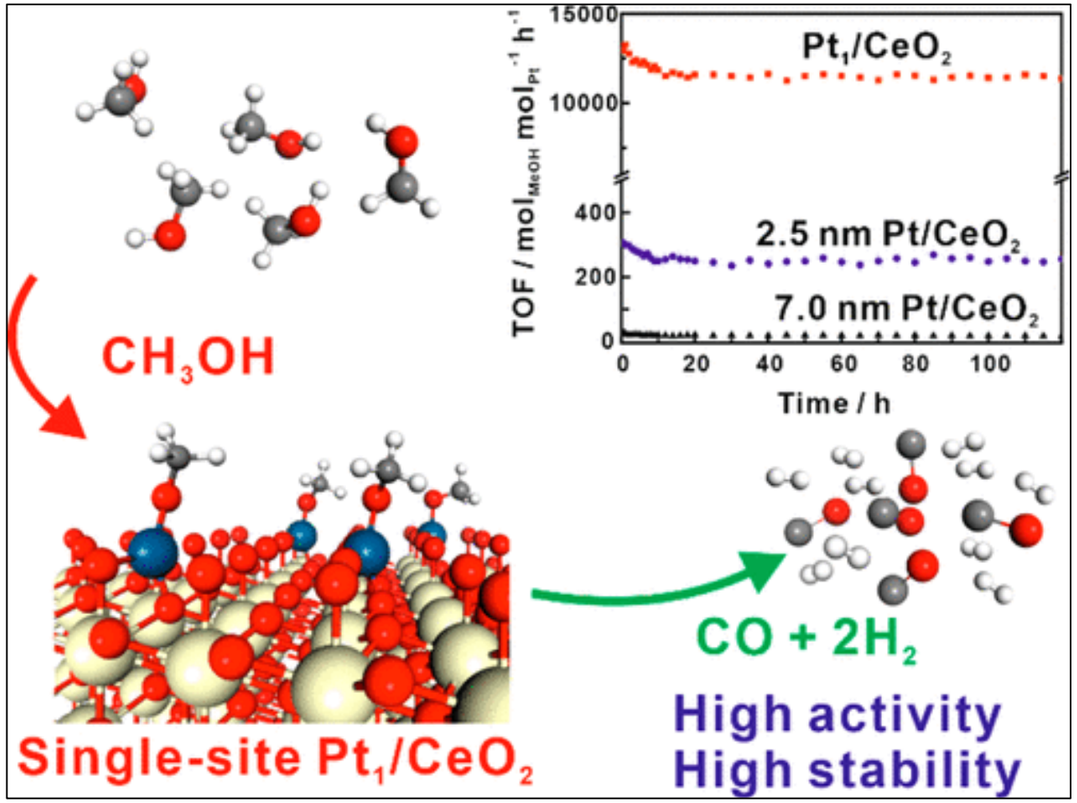
c

Catalysts	WHSV (g CH_3OH g^{-1} catalysts h^{-1})	TOF (mol CH_3OH mol^{-1}metal h^{-1})
1.5 nm Ni/BN (This work)	23.8	237.6
Pt/CeO2/Al_2O_3	15.7	946.1
Pd/CeO_2	1.0	123.4 (270 °C)
Rh/CeO_2	1.0	95.3
Ni/UDD	1.3	31.9
Commercial Cu/Cr	2.1	9.5
Co/CeO2	1.5	13.8
Ni/$N_{0.09}$CF	15	73.4
Ni/$N_{0.09}$CF	45	131.1

Figure. (a) Hydrogen productivity of Ni/BN nanocomposite with various Ni nanocluster sizes. (b) Temperature-dependent hydrogen productivity of Ni nanoclusters on various substrates. (c) Catalytic performance compared with that of some other catalysts.

Task 3: Single-Site Catalyst for Efficient Hydrogen Generation with Alcohols

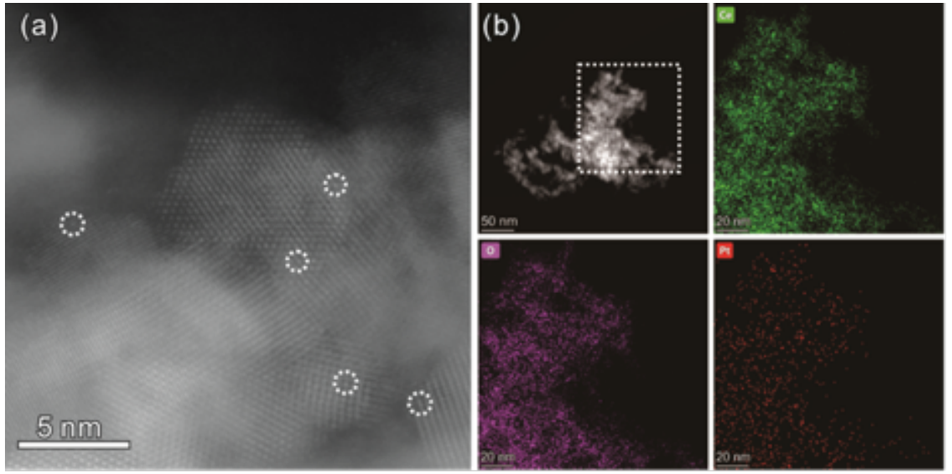
*JACS **141**, 17995 (2019)*

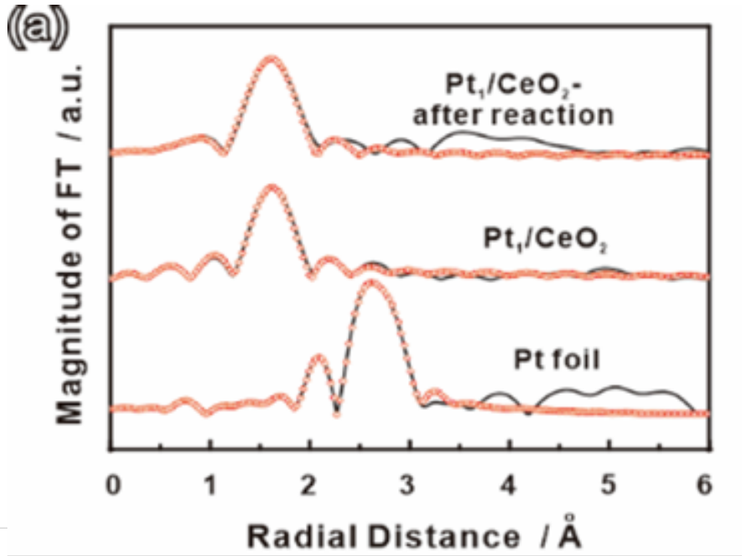


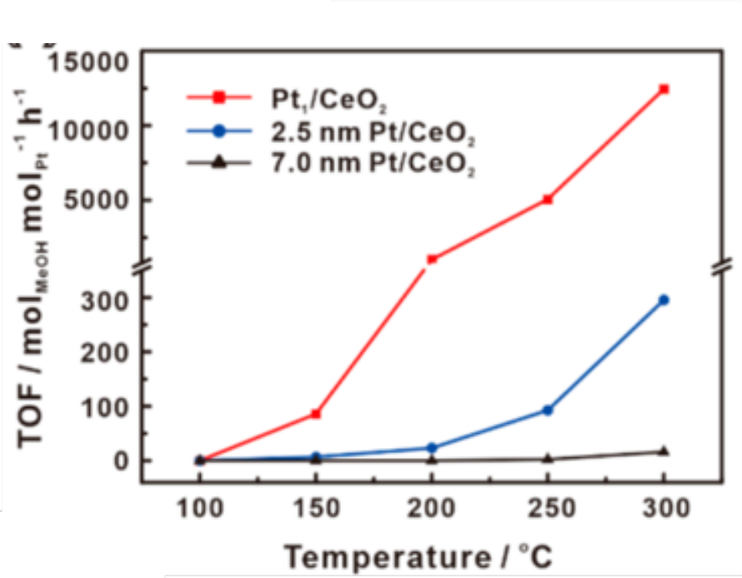
- In direct methanol dehydrogenation, the reaction rate of atomic Pt could reach **12000-14000 $mol_{methanol}/mol_{pt}/hour$**: **40 times** that of Pt nanoparticles of 2.5 nm diameter, and more than **800 times** that of 7nm Pt NPs.
- Furthermore, the atomic Pt catalyst has a high reaction stability (**120 hours**).

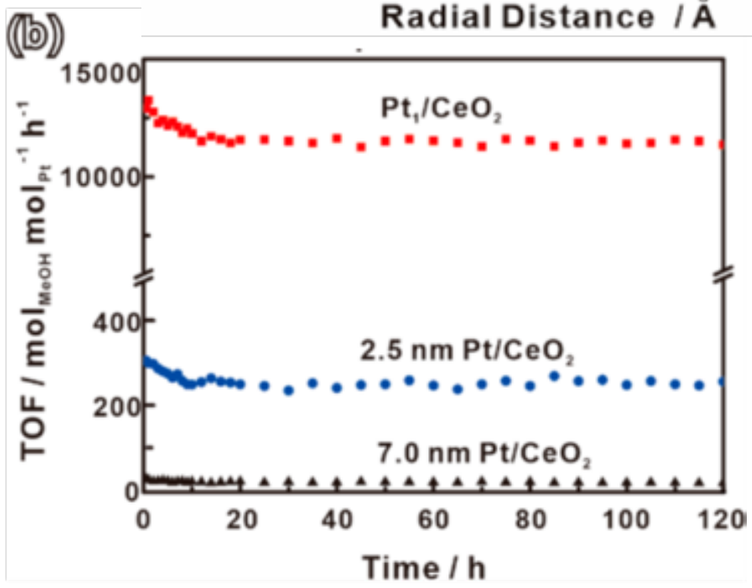
Ji Su, Gabor Somorjai

Single-Site Catalyst for Efficient Hydrogen Generation with Methanol



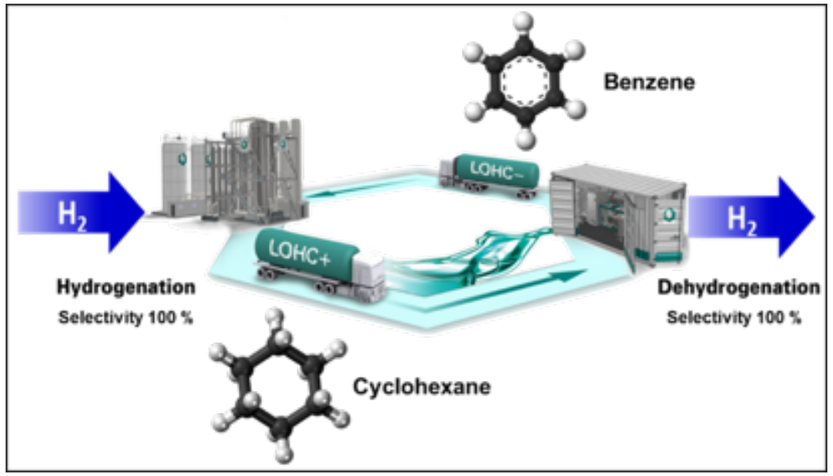






Ji Su, Somorjai, Liu, Guo, Prendergast, Klebanoff, Stavila, Allendorf

Reversible Hydrogen Generation/Storage Process Development: with Cyclohexane/Benzene and Single-Sites Catalyst (Pt_1/CeO_2)



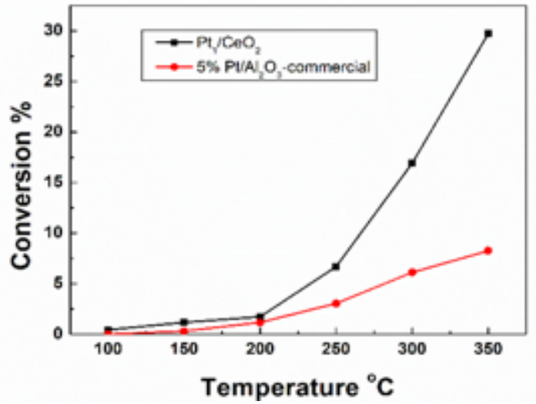
- **Ji Su and Gabor Somorjai (MSD/LBNL):** Catalytic process development
- **Mark Allendorf and Vitalie Stavila (SNL):** Catalytic materials development
- **Yi-Sheng Liu and Jinghua Guo (ALS/LBNL):** XAS characterization
- **Pragya Verma, David Prendergast (TMF/LNBL):** DFT calculations
- **Tom Autrey (PNNL):** H_2-carriers

Single Pt sites catalyst VS Pt NPs

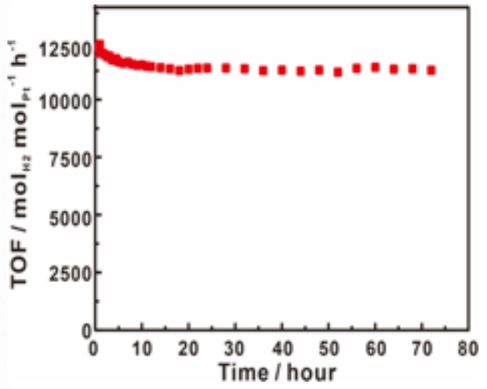
Reaction condition:

1 atm, 350°C, 100 mg catalysts;
Gas flow: N_2 30ml/min.

Cyclohexane Dehydrogenation



Single Site Catalyst Stability



Manuscript for Nature Catalysis

Target: produce 1 kg H_2/min from cyclohexane

Catalyst	Reaction conditions	Catalyst Required (for 1 kg H_2/min)	Pt loading
Pt_1/CeO_2 (0.15 wt %)	Cyclohexane 0.05 ml/min Conversion: 29.7 %	121 kg	**181.5 g**
Pt_1/CeO_2 (0.15 wt %)	Cyclohexane 0.02 ml/min Conversion: ~ 80 %	113 kg	**169.5 g**
Pt/Al_2O_3	Cyclohexane 0.05 ml/min	434 kg	**21700 g**