U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Preliminary Techno-economic Analysis of Hydrogen Carriers

Dr. Ned Stetson, Program Manager, Hydrogen and Fuel Cell Technologies Office, Hydrogen Technologies Program

HTAC, Washington, DC

March 9, 2020


What are hydrogen carriers?

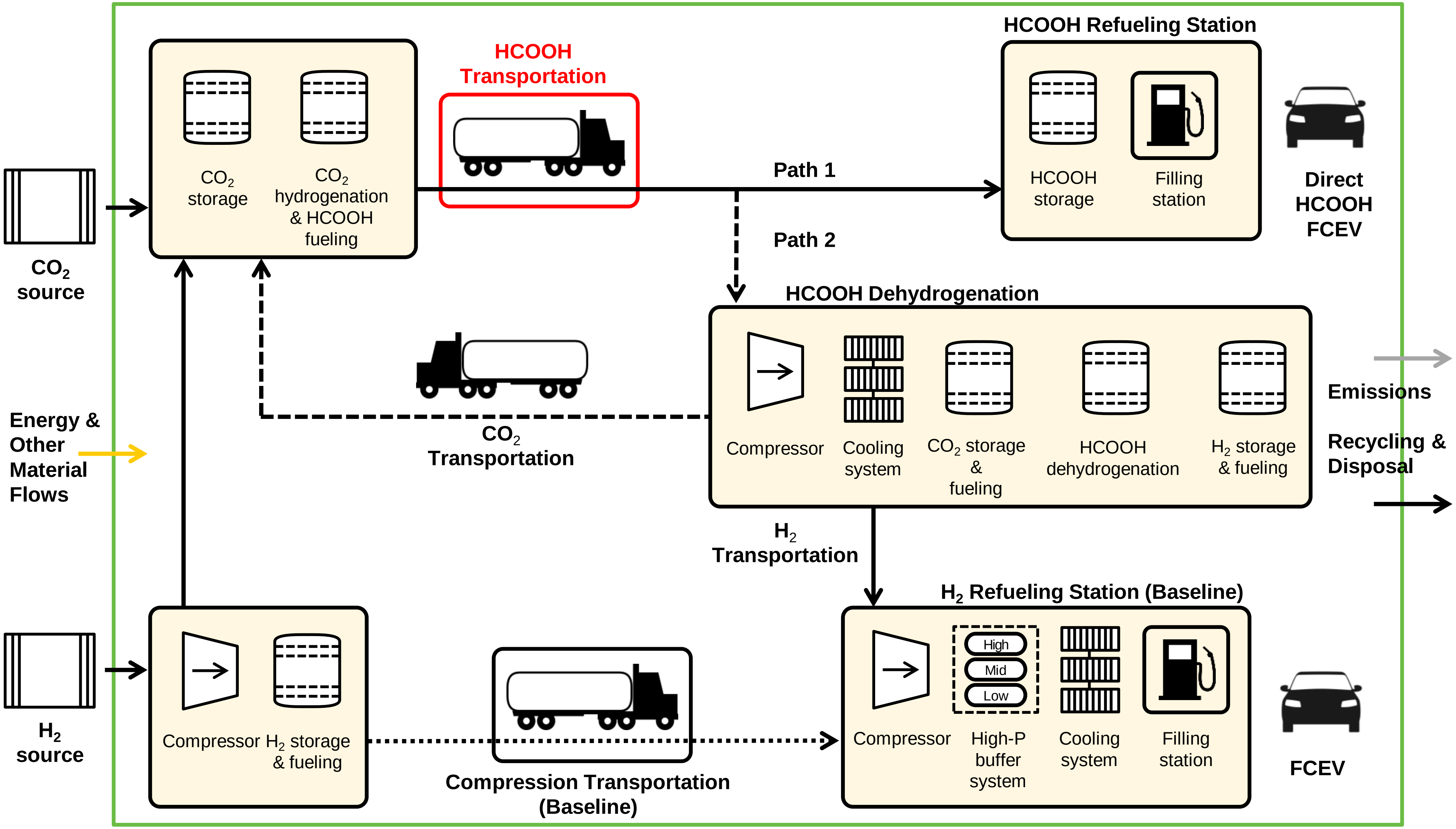
- Program's definition:
  - Hydrogen carriers are hydrogen-rich liquid or solid phase materials from which hydrogen can be liberated on-demand. Ideal hydrogen carriers have relatively high hydrogen densities at low pressure and near ambient temperature.

- Consensus from November workshop on hydrogen carriers:
  - Keep a broad definition of hydrogen carriers and let the requirements for specific applications narrow the scope of hydrogen carriers for consideration for those applications.

Examples of program activities on hydrogen carriers to date

- Prior to 2010 – supported Air Products and Chemicals to investigate heterocyclic materials as potential hydrogen storage materials, focused efforts on n-ethylcarbazole
- 2018 – Initiated techno-economic analysis at Argonne National Lab to establish a baseline comparison between conventional compressed and liquid hydrogen delivery with several commonly cited hydrogen carriers
- 2018 – Initiated preliminary efforts within HyMARC to investigate hydrogen carrier materials, with an emphasis on “additional” potential benefits (e.g., chemical compression)
- 2019 – included a topic in the FCTO FOA on hydrogen carriers, selected 4 projects to investigate and develop novel hydrogen carrier concepts
- Nov. 2019 – Held a hydrogen carrier workshop in Golden, CO - 74 participants representing industry, universities, and national labs, and from N. America, Europe and Asia

For Techno-Economic Analysis (TEA) – where system boundary is set and the pathway followed matters

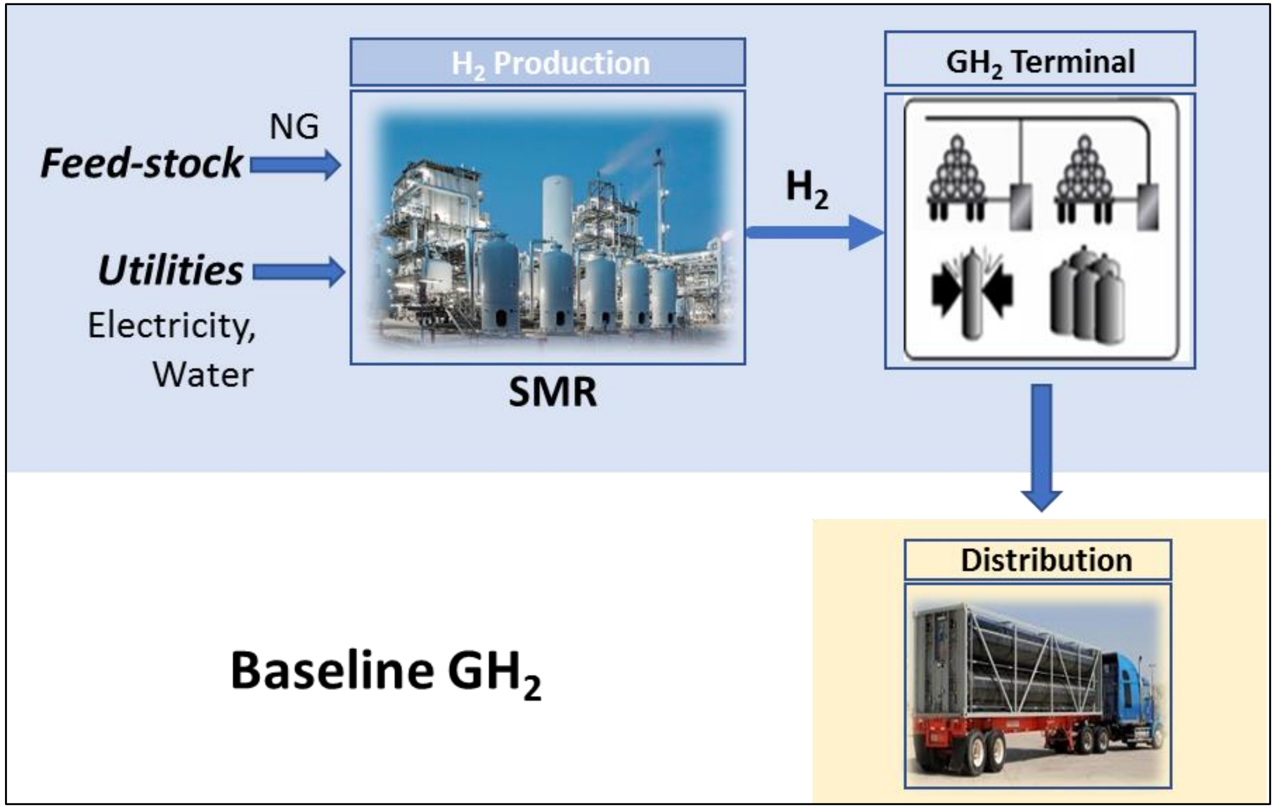


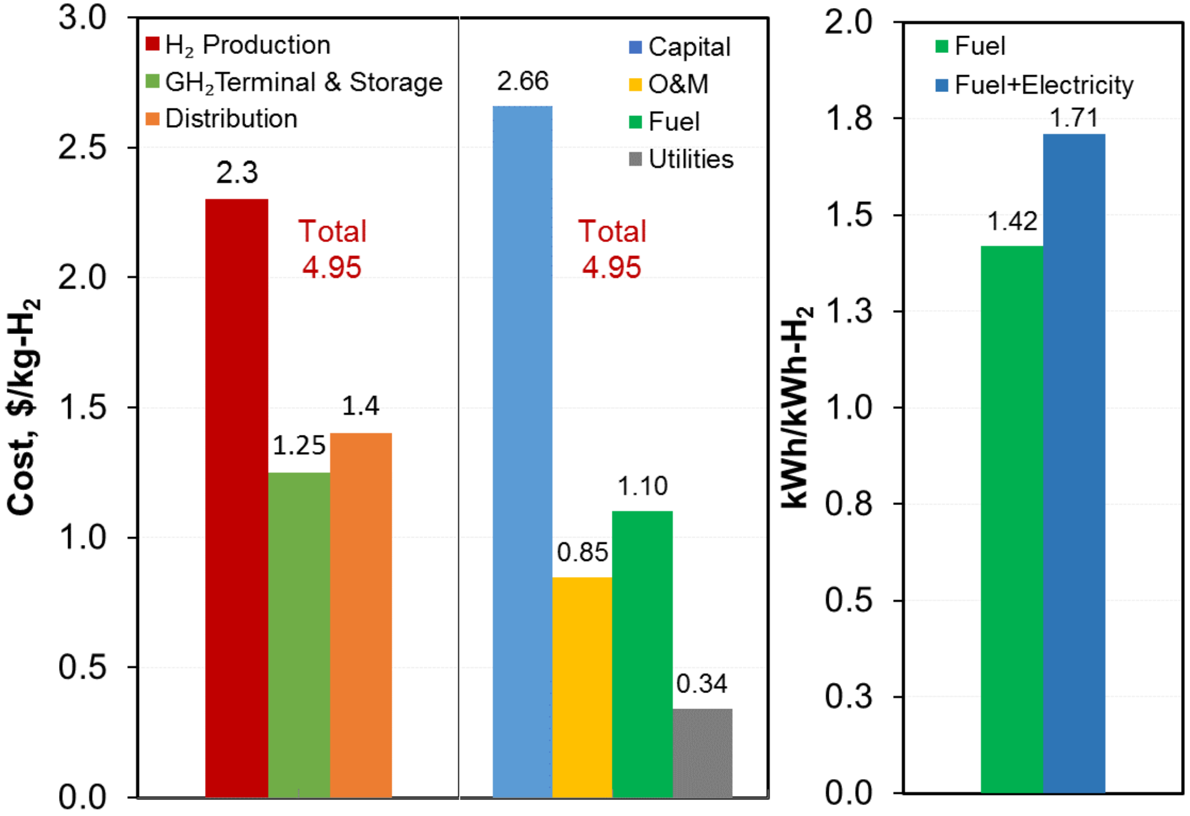
Baseline TEA of hydrogen carriers with compressed hydrogen

- All cases:
  - 50,000 kg H_2/day delivery to city gate terminal
  - Includes 10 days of storage at city gate terminal
- Hydrogen Carriers
  - Carriers transported from point of production to storage terminal
  - Carriers transported 150 km from storage terminal to city gate terminal
  - H_2 release at city gate terminal,
  - Local distribution as compressed gaseous hydrogen to refueling stations
  - Two-way carriers include transportation costs back to production site
- Gaseous Hydrogen case
  - H_2 production using SMR
  - Transmission as in trailer trucks for 150 km to city gate terminal
  - Local distribution to hydrogen refueling stations

Gaseous hydrogen baseline

$4.95/kg H_2 delivery to fueling station for gaseous hydrogen





50 tonne H_2 per day by SMR, 150 km from production site to terminal, trailer truck transport, transmission and distribution costs combined

Hydrogen carriers included in baseline study

Argonne NATIONAL LABORATORY

- One-way carriers
  - Ammonia (separate H_2 production step)
  - Methanol (direct with no separate H_2 production step)
- Two-way carrier
  - Methylcyclohexane/toluene

	MP	BP	H_2 Capacity		Production		Decomposition		
	^oC	^oC	wt%	g/L	P, bar	T, ^oC	P, bar	T, ^oC	ΔH kJ/mol-H_2
Ammonia									
	-78	-33.4	17.6	121	150	375	20	800	30.6
					Haber-Bosch Process Fe Based Catalyst		High-Temperature Cracking Ni Catalyst		
Methanol									
	-98	64.7	18.75	149	51	250	3	290	16.6
					$Cu/ZnO/Al_2O_3$ Catalyst		Steam Reforming		
MCH									
	-127	101	6.1	47	10	240	2	350	68.3
					Non-PGM Catalyst		Pt/Al_2O_3 Catalyst		

Factors to consider for hydrogen carriers

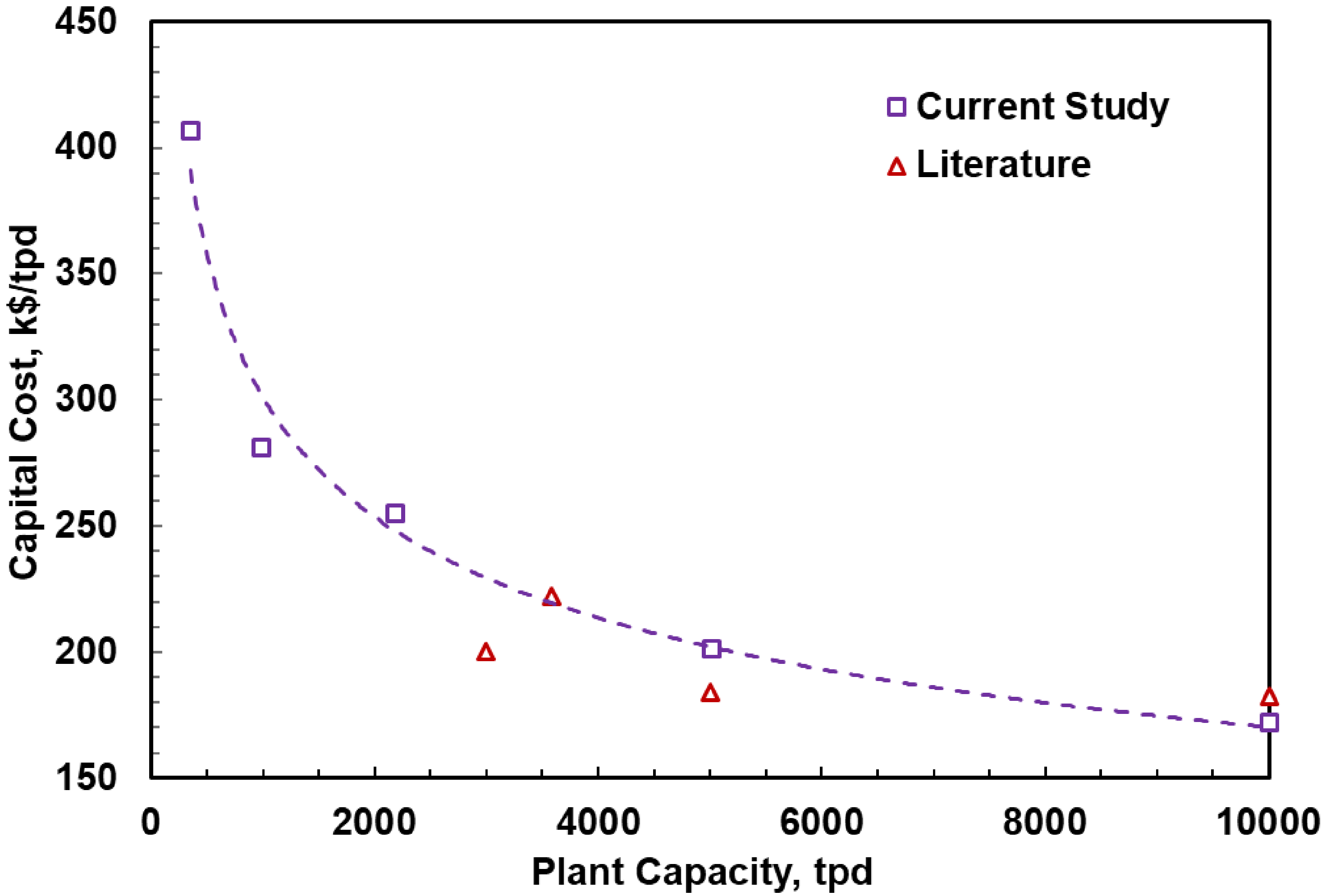
1. Capacity of carrier production/dehydrogenation plants:
   a. Production - assumed plants not built and sized just based on targeted H_2 delivery per day;
   b. Dehydrogenation - plants are sized for targeted hydrogen capacity
2. Production - cost and energy to produce hydrogenated carrier
3. Transmission – cost to delivery carrier from point of production to storage terminal (rail, ship, pipeline, etc.) and then to city gate (150 km by truck)
   a. For two-way carriers - includes cost to return dehydrogenated product to hydrogenation site
4. Dehydrogenation - cost and energy to dehydrogenate and release the hydrogen from the carrier at the city gate terminal
   a. Includes purification costs to clean-up the hydrogen
   b. For two-way carriers – includes replacement costs of lost carrier (e.g., evaporation, side reactions, etc.)

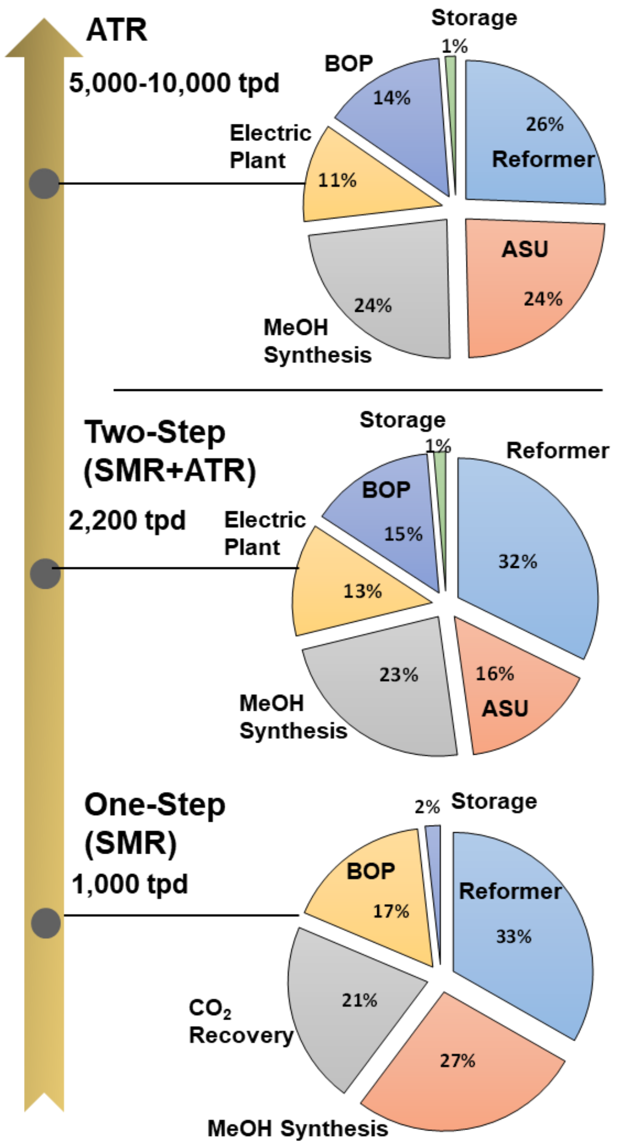
Production → Transmission → Dehydrogenation → Distribution

Plant capacity matters

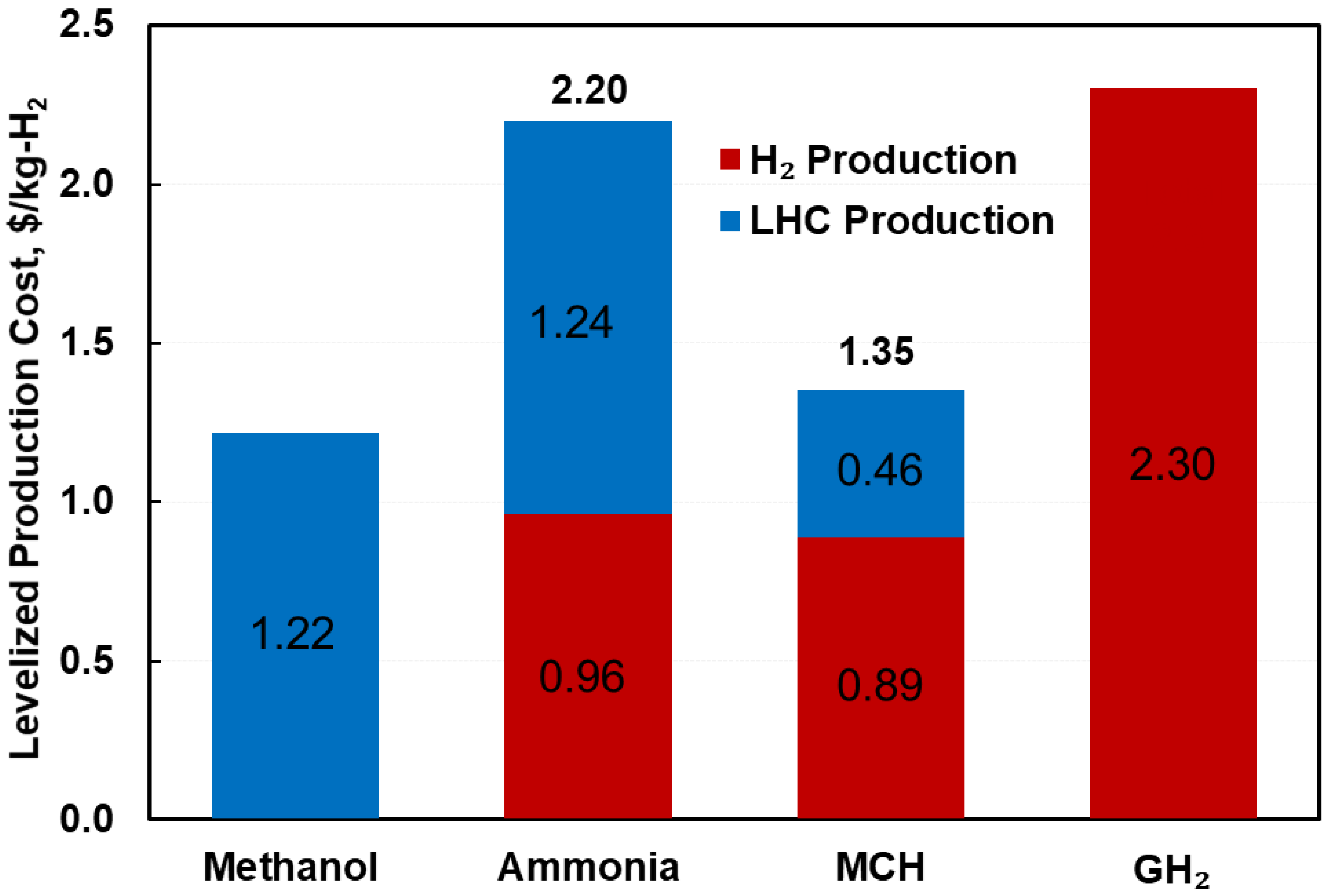
Argonne NATIONAL LABORATORY

Example – methanol – production method can change as plant capacity varies to reduce capital costs





Levelized cost for production

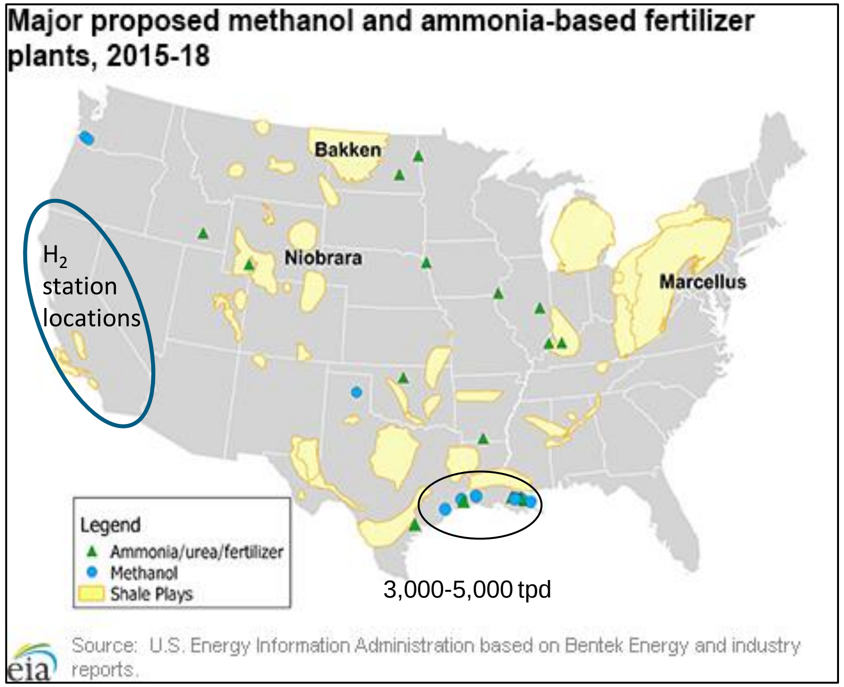


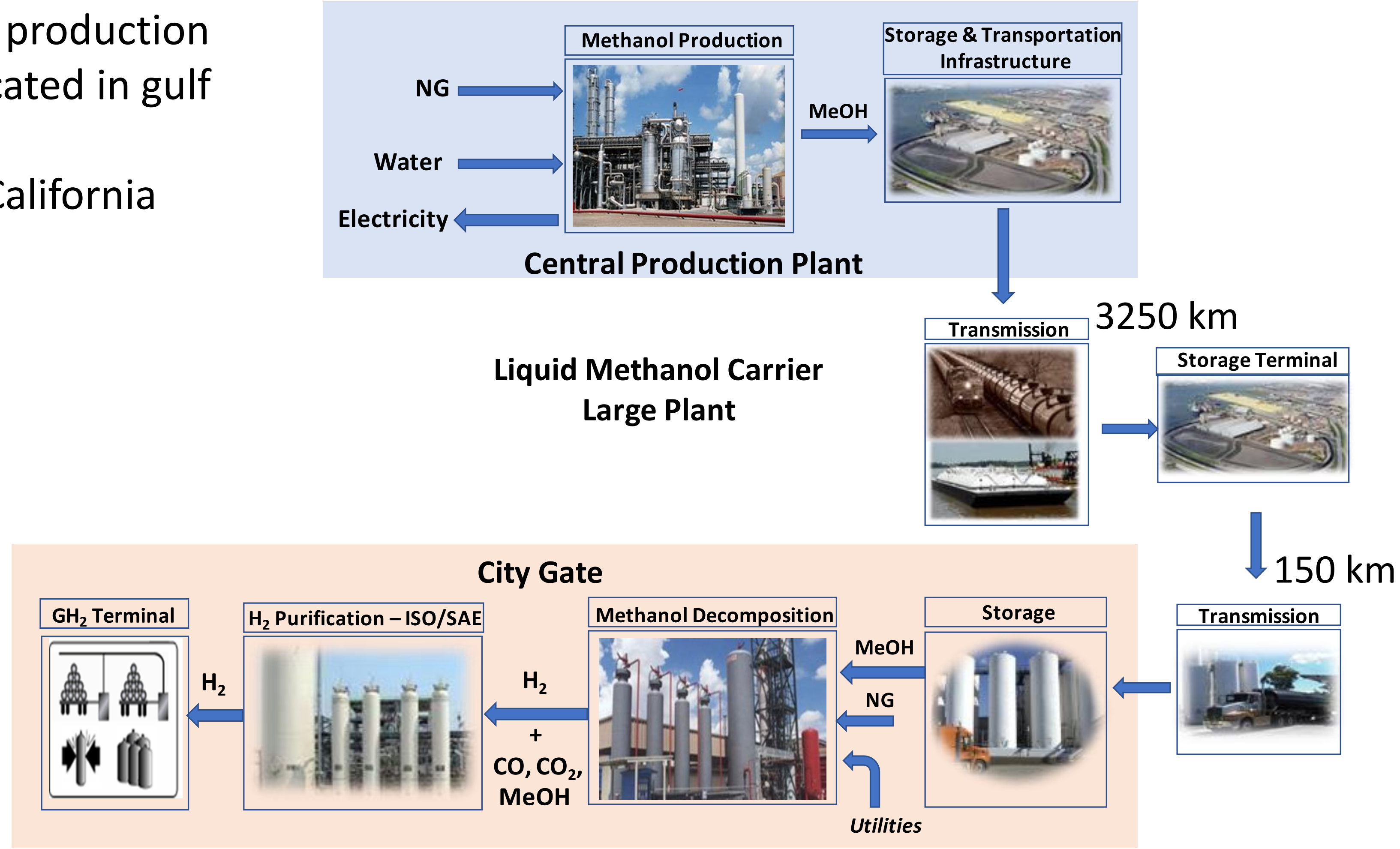
- Levelized production cost for methanol the lowest when produced in high capacity plants (10k ton/day)
- Methylcyclohexane production through hydrogenation of toluene competitive with methanol levelized production cost
- Ammonia production highest on a levelized production cost, plants more capital intensive than methanol plants

Production | Transmission | Dehydrogenation | Distribution

Transmission from point of production to city gate

- Large-scale methanol and ammonia production planes, with low-cost natural gas located in gulf coast region
- H_2 refueling stations are located in California





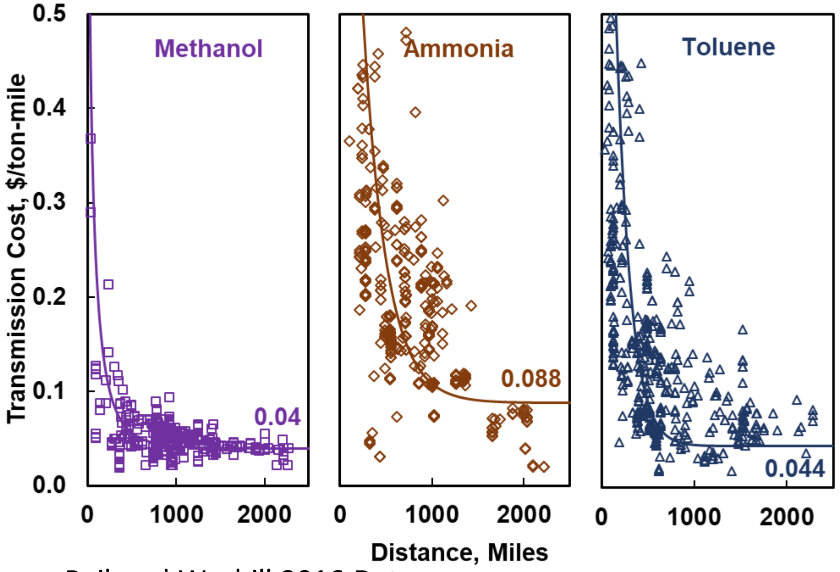
Production | Transmission | Dehydrogenation | Distribution

Transmission cost comparison through various means

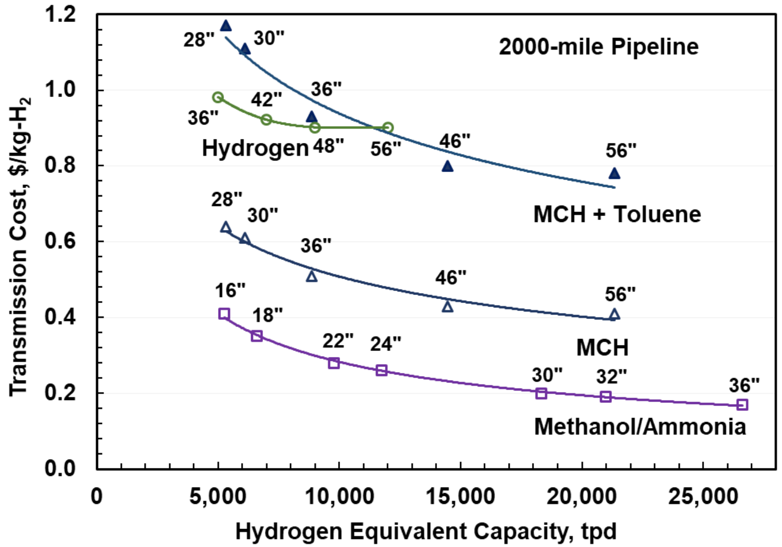
Argonne NATIONAL LABORATORY

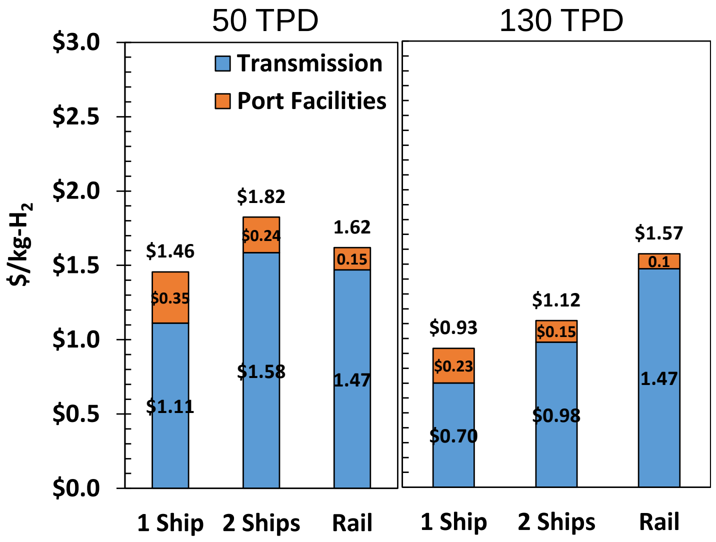
- H_2 capacity of the carrier is an important factor in determining the transmission cost by rail
  - Toluene has nearly the same train transmission cost as methanol on tpd basis, but is >3X costlier on kg-H_2 basis
- Toxicity and handling are also important factors in determining rail transmission costs
  - Ammonia has nearly the same H_2 capacity as methanol but is >2X costlier to move by train
- Long H_2 or carrier pipelines (>1000 mile) do not offer significant cost savings
  - Pipelines may not be economically viable for two-way carriers

Comparison costs: by rail **by pipeline** **by ship for MCH/toluene**



Railroad Waybill 2016 Data



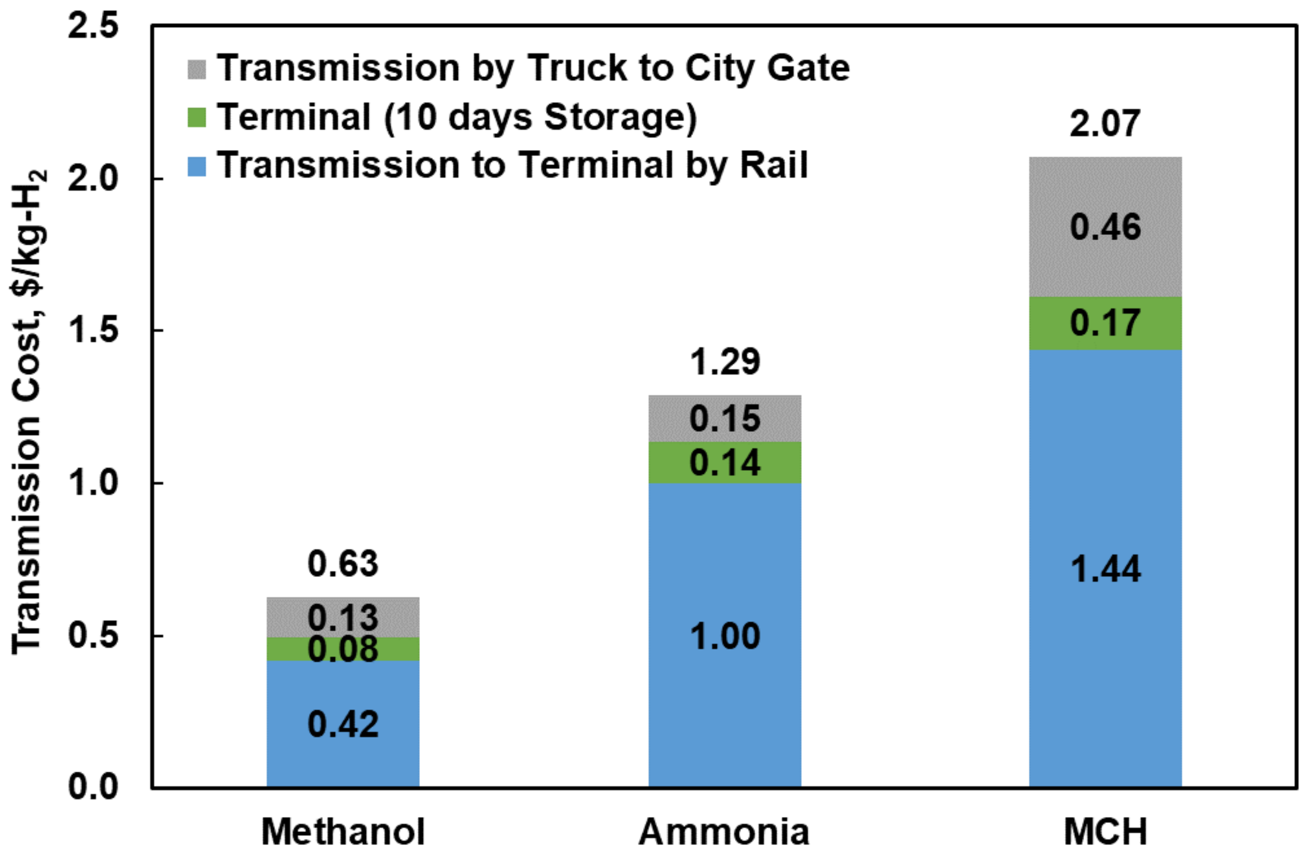


Levelized transmission cost comparison

Argonne NATIONAL LABORATORY

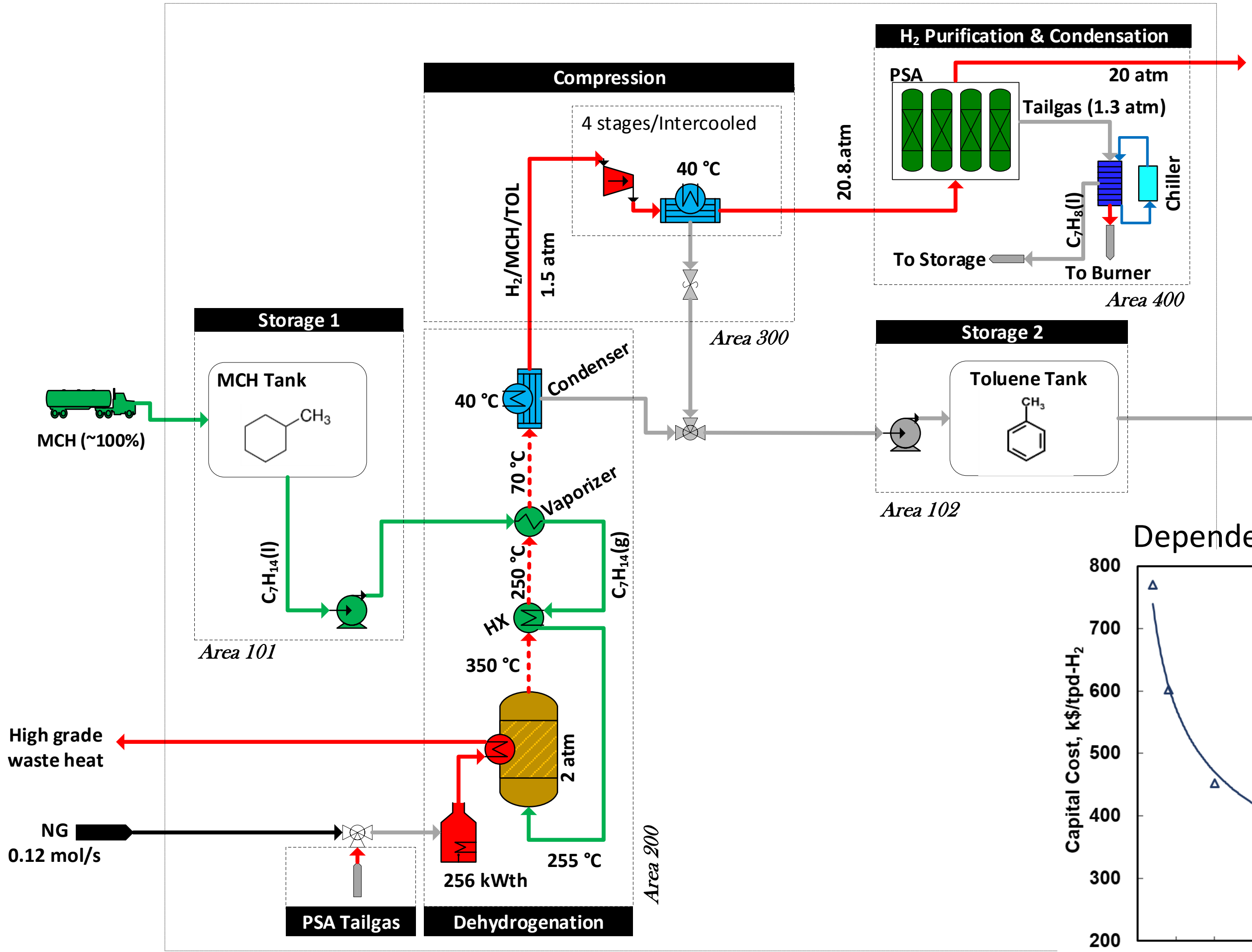
Methanol transmission lowest, methylcyclohexane more costly due to return leg

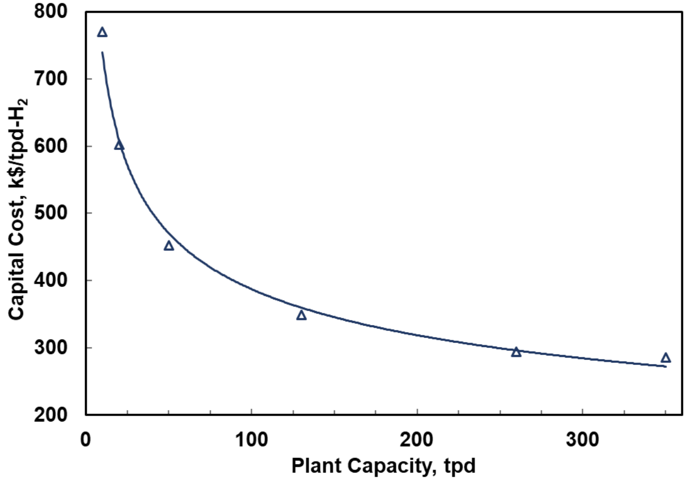
- Unit train (once every 10 days) to storage terminal in California (3250 km);
- Local transmission by truck (150 km) to city gate terminal
- Similar case for both methanol and ammonia, methylcyclohexane includes return leg for toluene



Production | Transmission | Dehydrogenation | Distribution

Capital cost of methylcyclohexane dehydrogenation plant





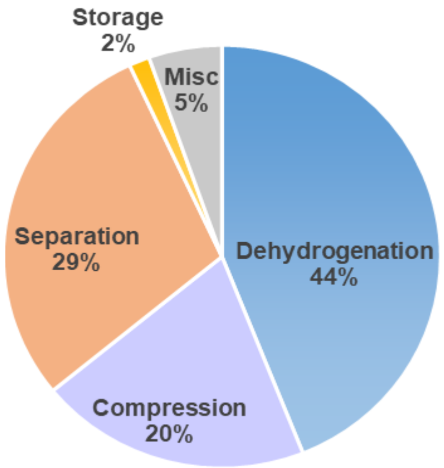
Losses

- Toluene+MCH: 0.84%
- Hydrogen: 10%
- Heat: 0.36 $kWh_{th}/kWh_{th}\text{-}H_2$

Feedstock/Utilities

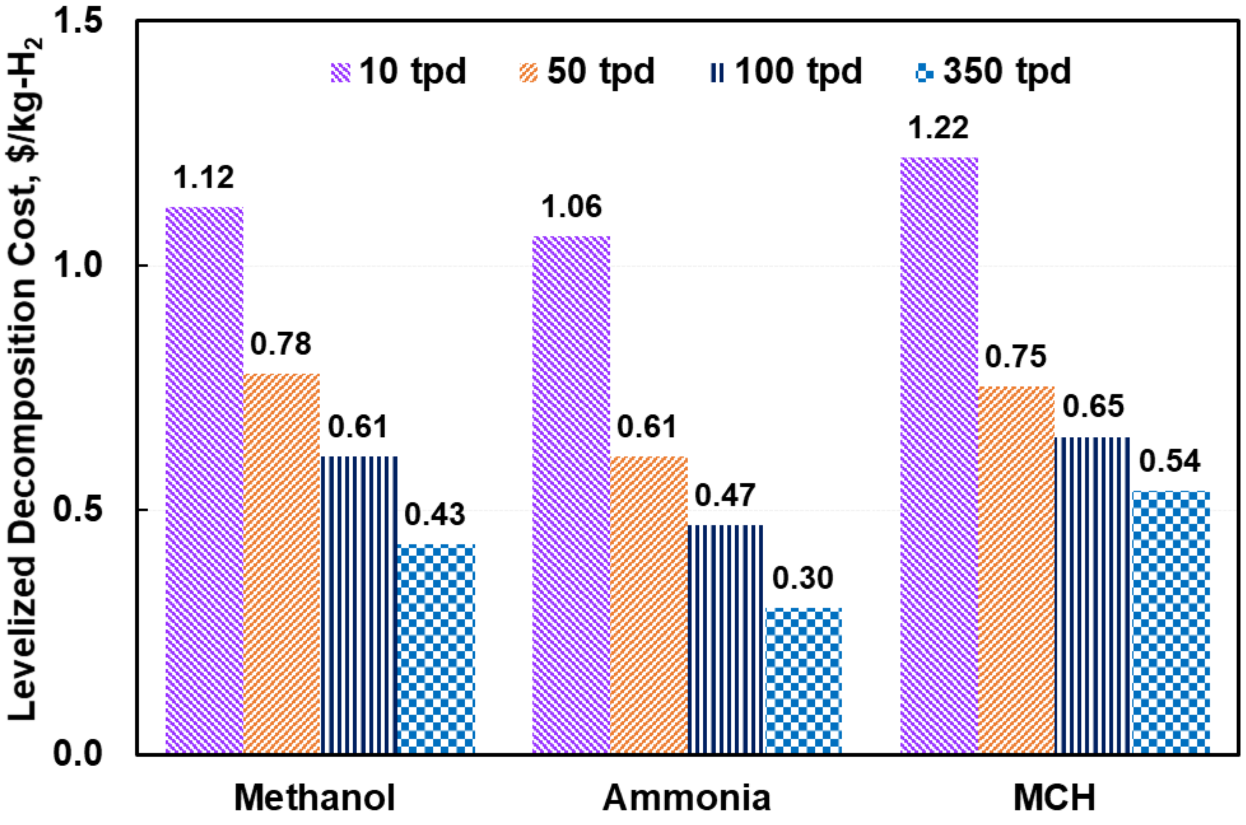
- NG: 0.22 $kWh_{th}/KWh_{th}\text{-}H_2$
- Electricity: 0.04 $kWh_e/KW_{th}\text{-}H_2$

Capital Cost Factors: 50 tpd-H_2



Production | Transmission | Dehydrogenation | Distribution

Levelized decomposition cost comparison



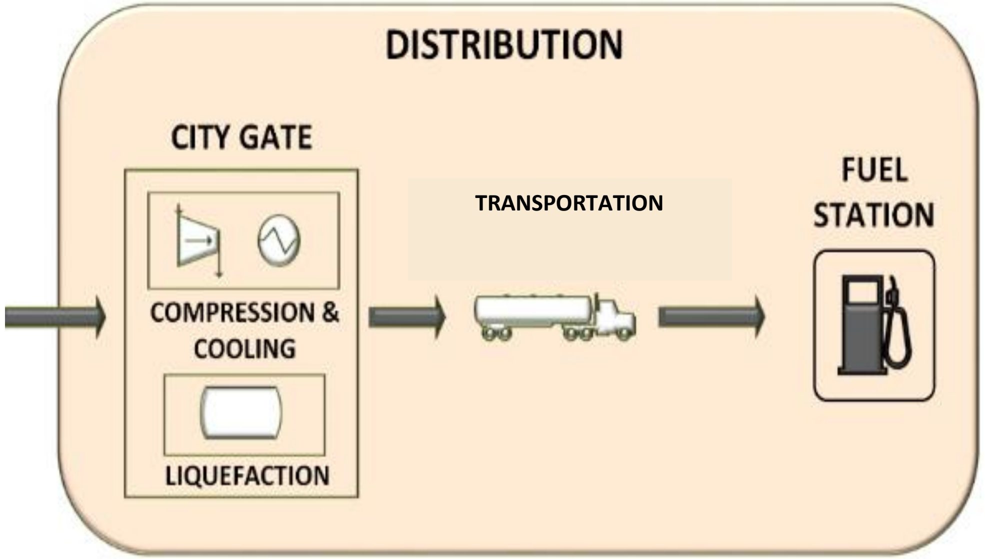
Levelized decomposition costs (LDC) are comparable for the three carriers: 0.61-0.78 \$/kg-H_2 at 50 tpd-H_2

- At high throughput, LDC decreases most for ammonia. However, ammonia decomposes at a high temperature (800^{o}C) using a catalyst (Ni) that may require further development and field testing
- Methanol decomposition method well established but requires steam reforming and water gas shift catalysts. Cost may decrease if methanol reformed at >3 atm.
- MCH decomposes at 2 bar using a PGM catalyst (Pt/Al_2O_3) and requires a large compressor

Production | Transmission | Dehydrogenation | Distribution

Distribution costs

City-Gate Terminal to Refueling Station "Last-Mile" Distribution



Comparing distribution as 350 & 500 bar compressed H_2 and liquid H_2 for various distances

Some key initial findings:

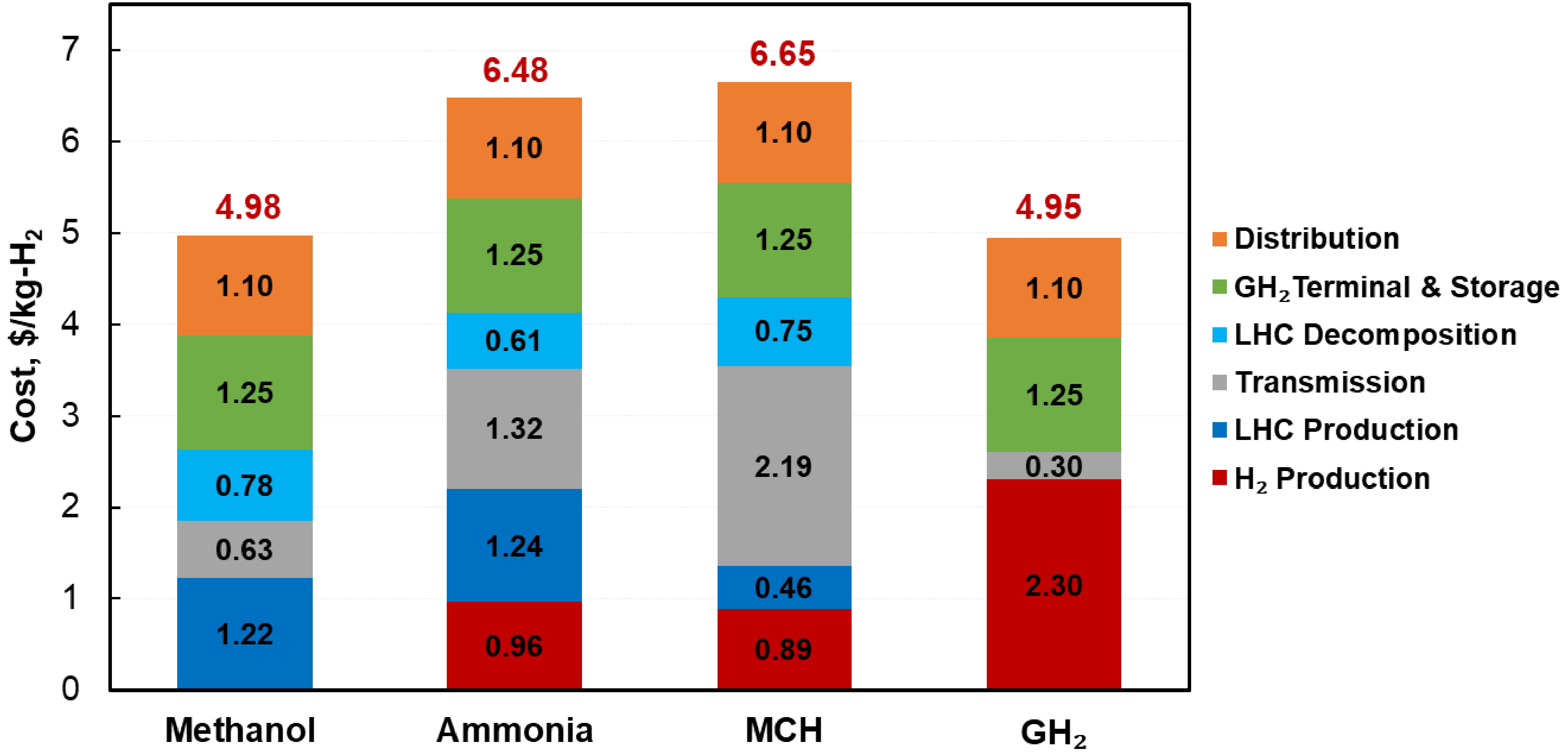
- Cost savings for cH_2 do not scale at higher pressures,
- The number of cH_2 trucks required increases rapidly with distance.
- LH_2 costs dominated by liquefaction cost and energy penalty (32%).

For baseline analysis, all cases kept constant:

- **400 kg H_2/day dispensing rate at fueling station**
- **Trailer capacity of 1024 kg, 36 m^3 volume**

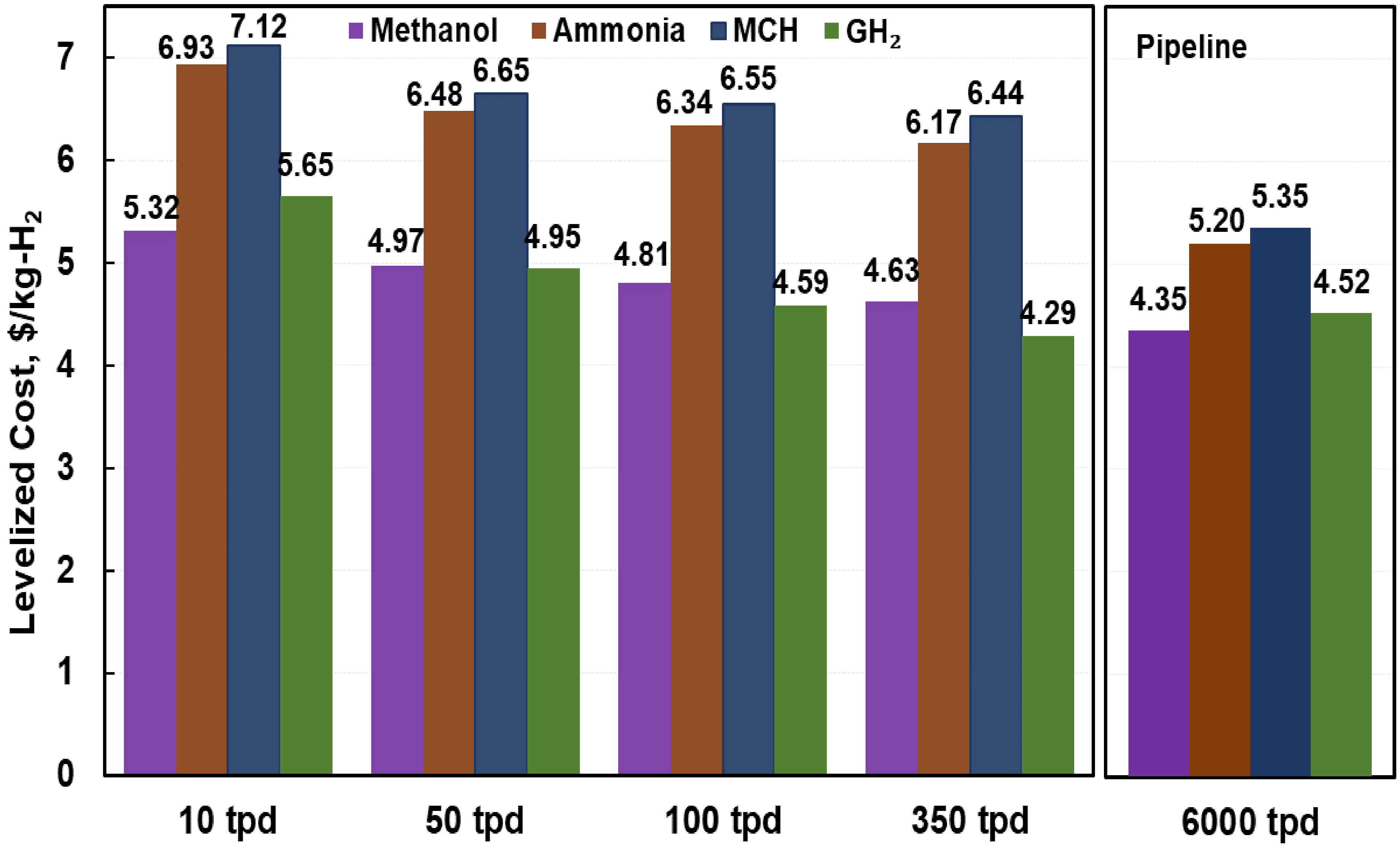
Production → Transmission → Dehydrogenation → **Distribution**

Baseline levelized cost of H_2 at 50,000 kg per day



- At 50,000 kg H_2 per day, methanol produced at high volume in the gulf coast area, and transport to California can be cost competitive with "locally" produced gaseous hydrogen.
- Ammonia and methylcyclohexane have a cost premium over "locally" produced gaseous hydrogen

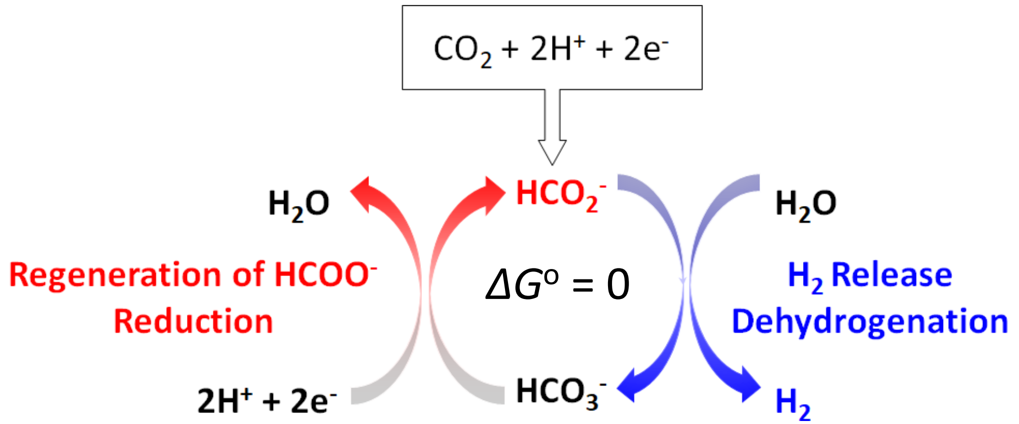
Levelized costs of H_2 at various daily demands



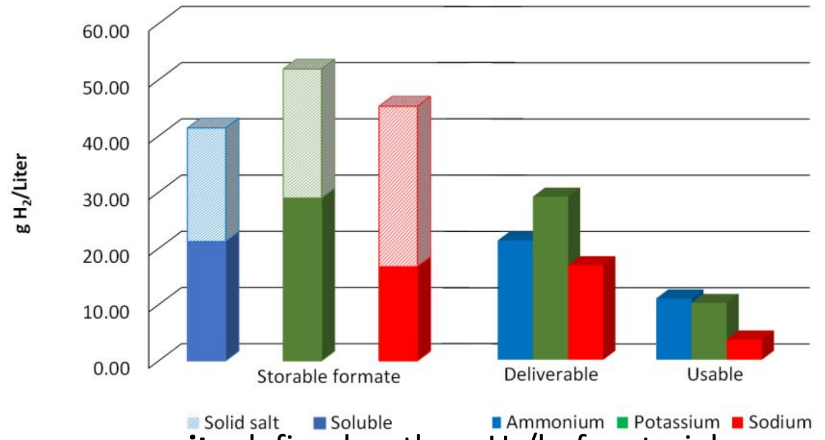
Analysis of formate salts as hydrogen carriers

Pacific Northwest NATIONAL LABORATORY

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

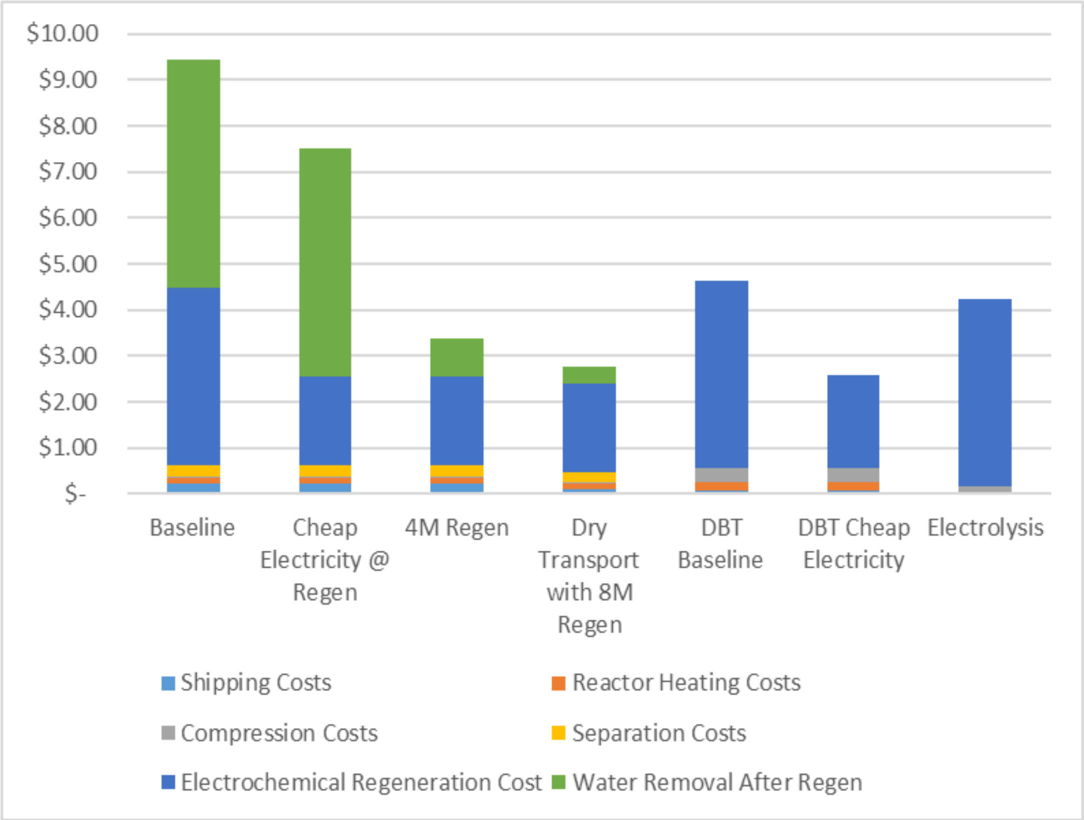


Volumetric capacity



Storage capacity defined as the g H_2/l of material
Deliverable capacity limited by the solubility of formate at 20 °C
Usable capacity limited by the solubility of bicarbonate at 60 °C

Preliminary TEA suggests water removal is the most expensive process



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

Summary

- Hydrogen carriers can be cost competitive with gaseous hydrogen production
  - Production capacity can influence cost competitiveness
  - Transmission costs can vary depending on nature of the hydrogen carrier
  - Two-way carriers are disadvantaged by two-way transportation costs and replacement costs
- Application specific requirements need to be considered when determining suitability of a hydrogen carrier
- Boundary conditions should be considered when comparing different TEAs

- Future activities
  - Including comparison with liquid hydrogen transmission and distribution
  - Expand analysis of other types of hydrogen carriers (e.g., formate salts)
  - Investigation of impact of yield, cycle life, energy use, etc.
  - Consider other potential benefits (e.g., chemical compression)

Acknowledgements

- Argonne National Laboratory
  - Rajesh Ahluwalia
  - D.D. Papadias
  - J-K Peng
- Lawrence Berkeley National Laboratory
  - Hanna Breunig
  - Aikaterini Anastasopoulou
- Pacific Northwest National Laboratory
  - Tom Autrey
  - Kat Grubel
  - Kriston Brooks

Thank you for your attention

Dr. Ned Stetson
Program Manager – Hydrogen Technologies
Hydrogen & Fuel Cell Technologies Office
Ned.Stetson@ee.doe.gov

www.hydrogen.energy.gov