System Level Analysis of Hydrogen Storage Options

DOE W.B.S. Number 4.4.0.2

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Project ID: ST001

Argonne NATIONAL LABORATORY

Project Overview and Relevance

Timeline

- Project start date: Oct 2009
- Project end date: N/A
- Project continuation and direction determined annually by DOE

H_2 Storage Barriers Addressed

- A: System Weight and Volume
- B: System Cost
- C: Efficiency
- E: Charging/Discharging Rates
- J: Thermal Management
- K: Life-Cycle Assessments

Budget

- FY22 DOE Funding: $300K
- FY23 DOE Funding: $500K

Partners/Interactions

- National Renewable H_2 Production and Transmission Scenario: ANL-H2A, ANL-HDSAM, NREL,
- Hydrogen Carriers: PNNL, LBNL
- Hydrogen Storage: HMAT, LLNL, Sandia
- Cost Analysis: Strategic Analysis (SA)

Project Goals, Tasks and Milestone Status

Develop and use models to analyze renewable H_2 production and transmission, on-board and stationary bulk H_2 storage, and liquid H_2 carriers.

- Conduct independent systems analysis for DOE to gauge the performance of H_2 storage systems
- Provide results to material developers for assessment against system performance targets and goals and help them focus on areas requiring improvements
- Provide inputs for independent analysis of costs of on-board systems
- Identify interface issues and opportunities, and data needs for technology development
- Perform reverse engineering to define material properties needed to meet the system level targets

Type	Task	Due Date	% Complete
Progress Measure	Complete ammonia export study by including ammonia cracking, CO_2 sequestration for blue ammonia, and production of green ammonia using renewable wind and solar.	12/31/2022	100%
Progress Measure	Determine performance and cost of H_2 production with solar power and on-site storage options for selected sites in all contiguous states.	3/31/2023	100%
Progress Measure	Compare on-board LH_2 storage for Class-8 trucks with top fill and bottom fill. Prepare a report for journal publication.	6/30/2023	50%
Milestone / Deliverable	Extend national renewable H_2 production scenario to solar and pipeline transmission. Compare costs with wind scenario and transmission by trains, ships, and tube trailers relative to the target of $4/kg.	9/30/2023	25%

Project Impact

Solar Hydrogen Production and On-site Hydrogen Storage

- In a grid-independent scenario, H_2 can be produced at 2.26-3.37 $/kg including 1.13-1.76 $/kg for renewable plant, 0.75-1.09 $/kg for electrolyzer, and 0.38-0.57 $/kg for storage in carriers
- H_2 cost is 0.75-1.40 $/kg lower in grid-connected scenario
- 1.71-4.80 ¢/kWh credit for grid stabilization and grid balancing is needed to reach the target of \$1/kg-H_2

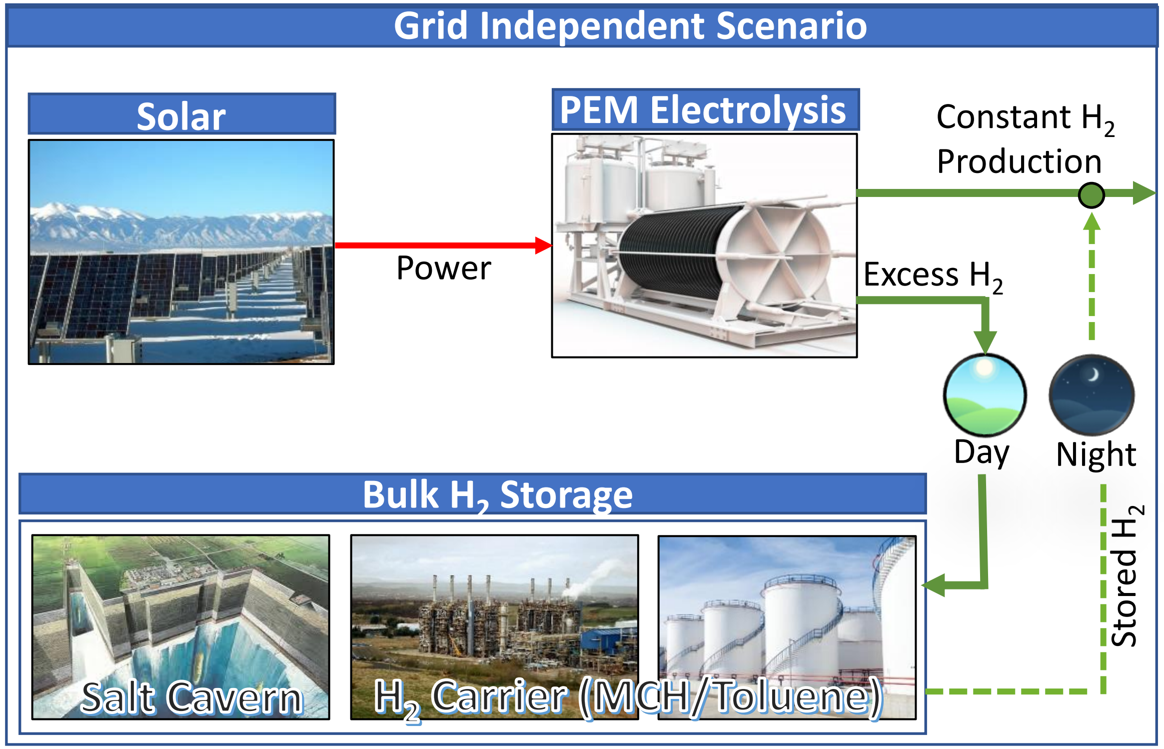
Ammonia Export

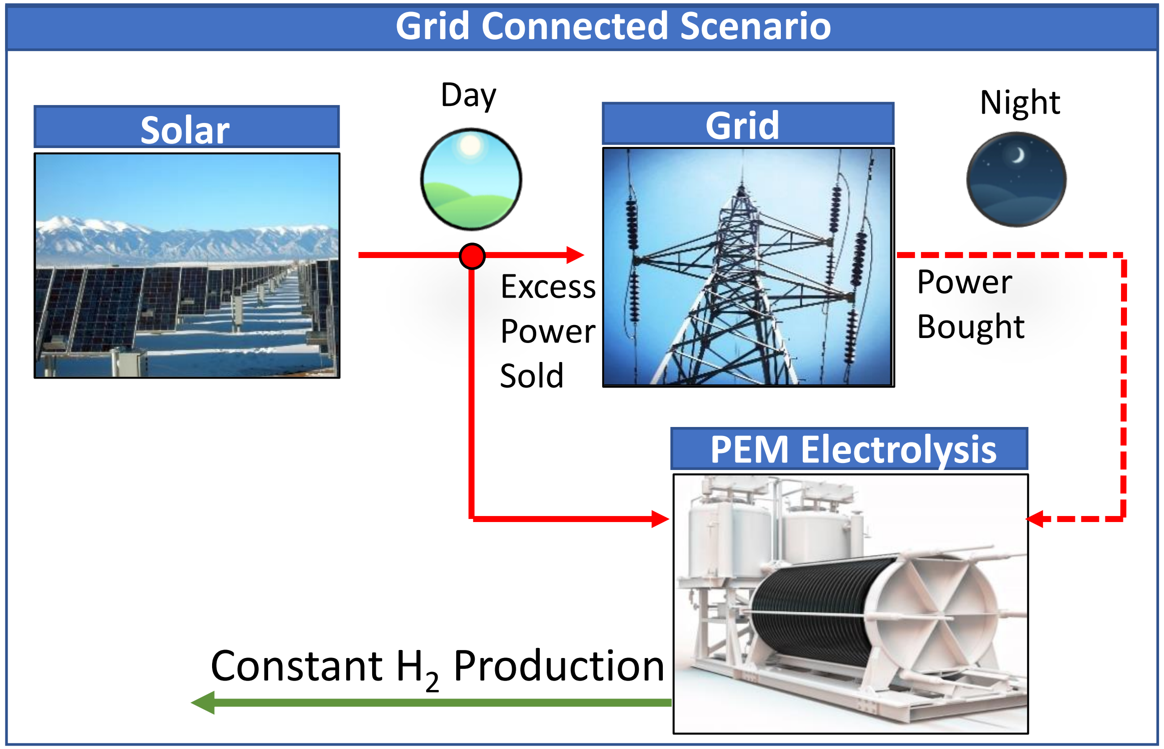
- Export cost of blue ammonia: 2.87-3.32 \$/kg-H_2
- Export cost of green ammonia: 0.66-1.10 \$/kg-H_2 higher than blue ammonia
- Export cost of LH_2: 0.88-1.61 \$/kg-H_2 higher than ammonia

On-board LH_2 Storage for Heavy Duty and Medium Duty Trucks

- At 32 - 45 g/L, cryo-compressed H_2 storage (CcH_2) has the highest system volumetric capacity:
  CcH_2 > sLH_2 > LH_2 > 700-bar cH_2 > 350-bar cH_2
- At 12 - 20 wt.%, liquid H_2 storage (LH_2) has the highest system gravimetric capacity:
  LH_2 > sLH_2 > CcH_2 > 350-bar cH_2 > 700-bar cH_2
- At 5 – 22 \$/kWh, liquid H_2 storage (LH_2) can be the least expensive option for heavy-duty applications:
  LH_2 < 700-bar cH_2 < 350-bar cH_2

Approach: National Renewable Hydrogen Production and Transmission Model: Solar Route





Metric

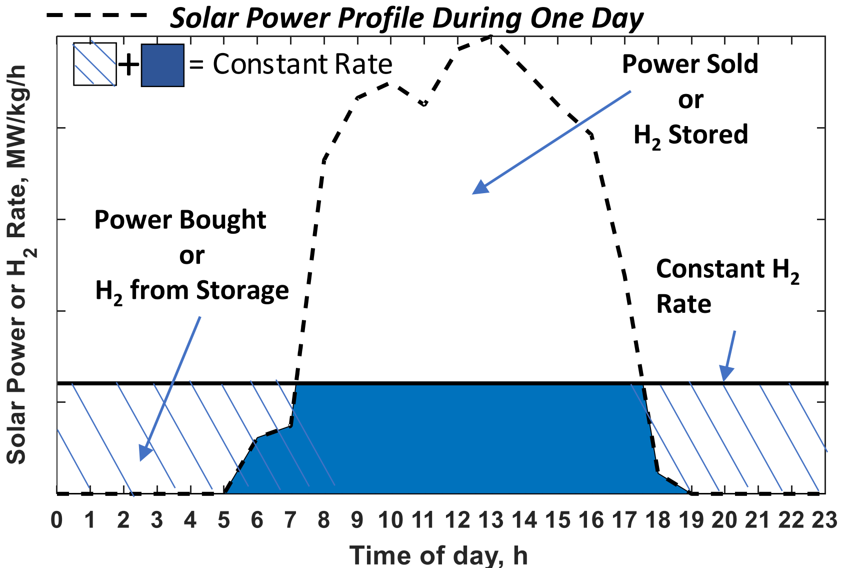
- Constant hourly H_2 production rate

Grid Connected Scenario

- Export excess power during the day and import power from grid during night to operate electrolyzer at constant power
- Zero net kWh to and from grid over the whole year
- Day time (peak hours): 6 am to 10 pm

Grid Independent Scenario

- Excess hydrogen produced during the day is stored as H_2 carrier or in a salt cavern to maintain constant rate throughout the day



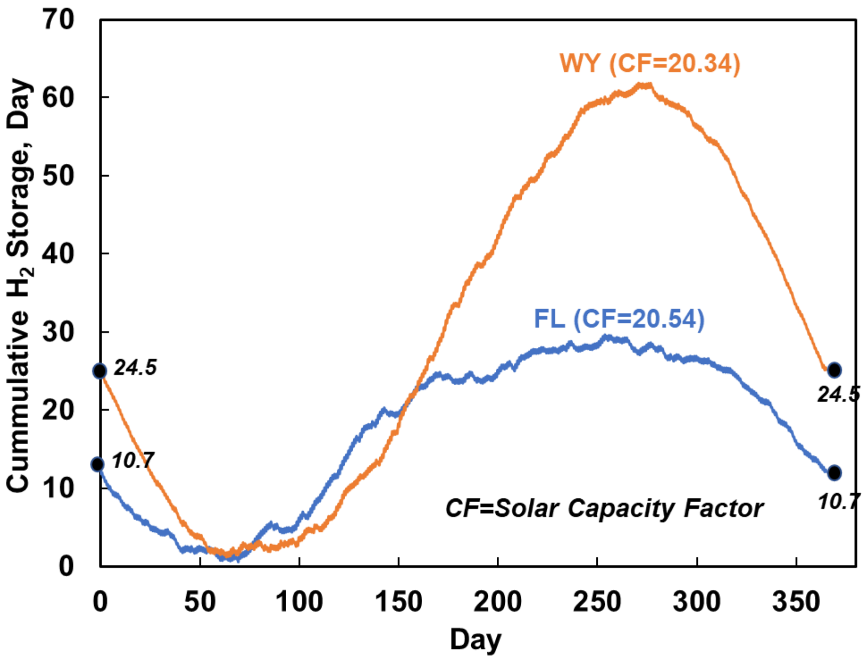
Grid Independent

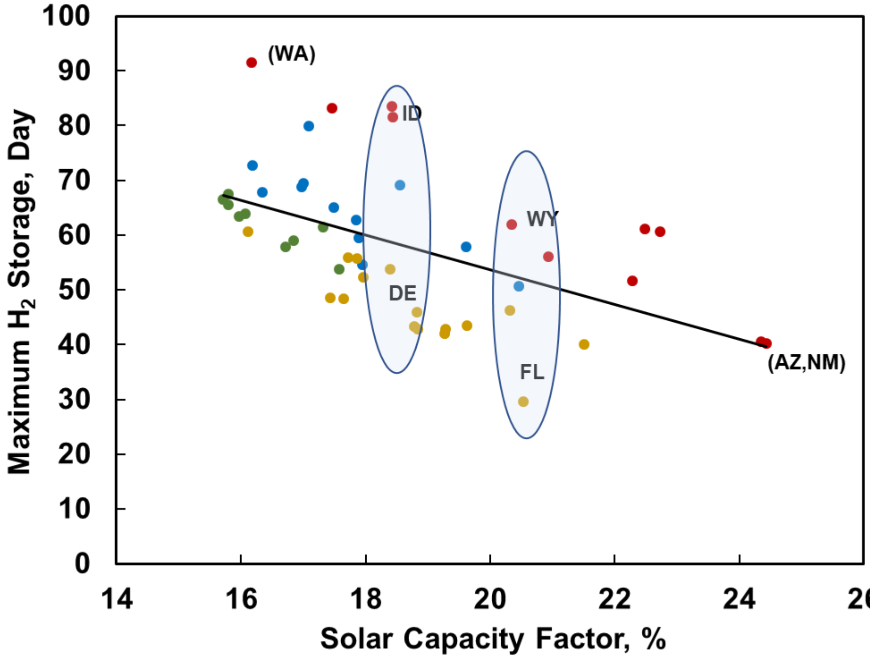
Electrolyzer load-follows solar power

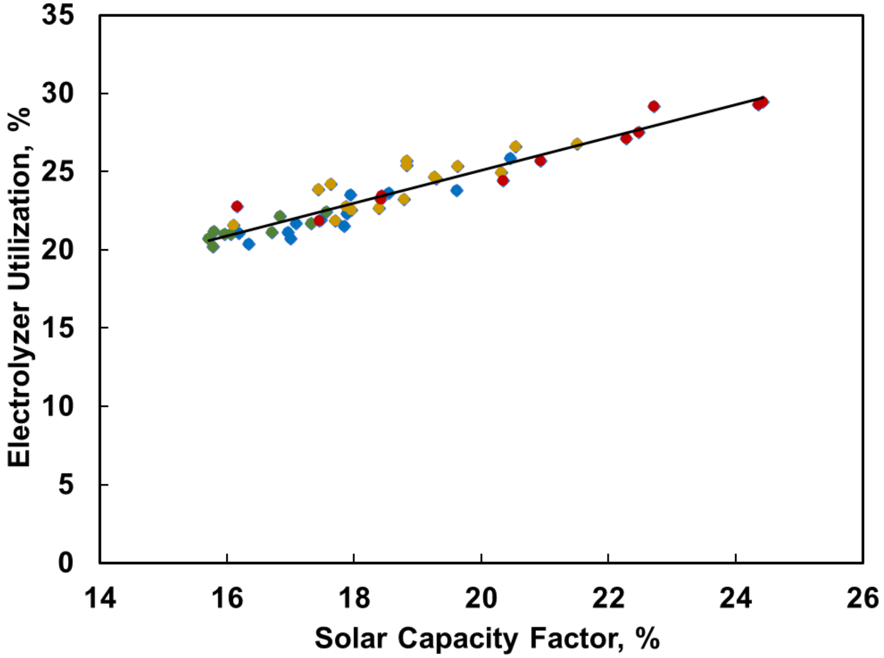
Grid Dependent

Electrolyzer operates at constant power

Accomplishments: Grid Independent Solar H_2 Production Scenario – Performance







Storage Constraint

- Hydrogen storage at the first day of the year must equal the amount on the last day of the year

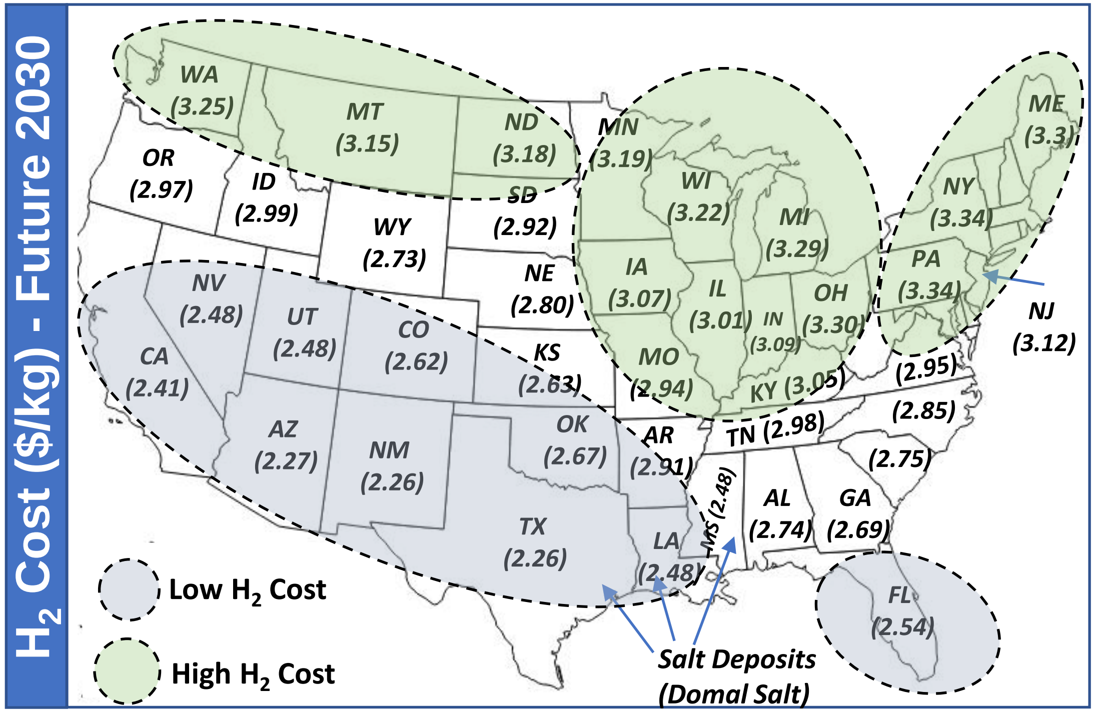
Storage Capacity

- Storage amount is strongly affected by the seasonal variations of solar power and correlates weakly with solar capacity factor

Electrolyzer Utilization

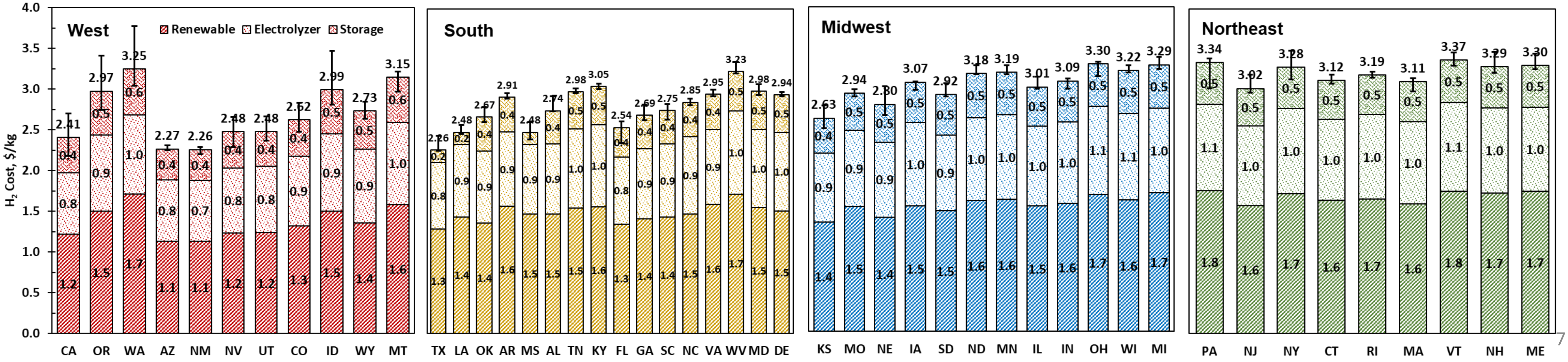
- Electrolyzer load follows solar power and leads to a low utilization factor (20-30%) that correlates with the solar capacity factor

Grid Independent Solar H_2 Production Scenario – Cost



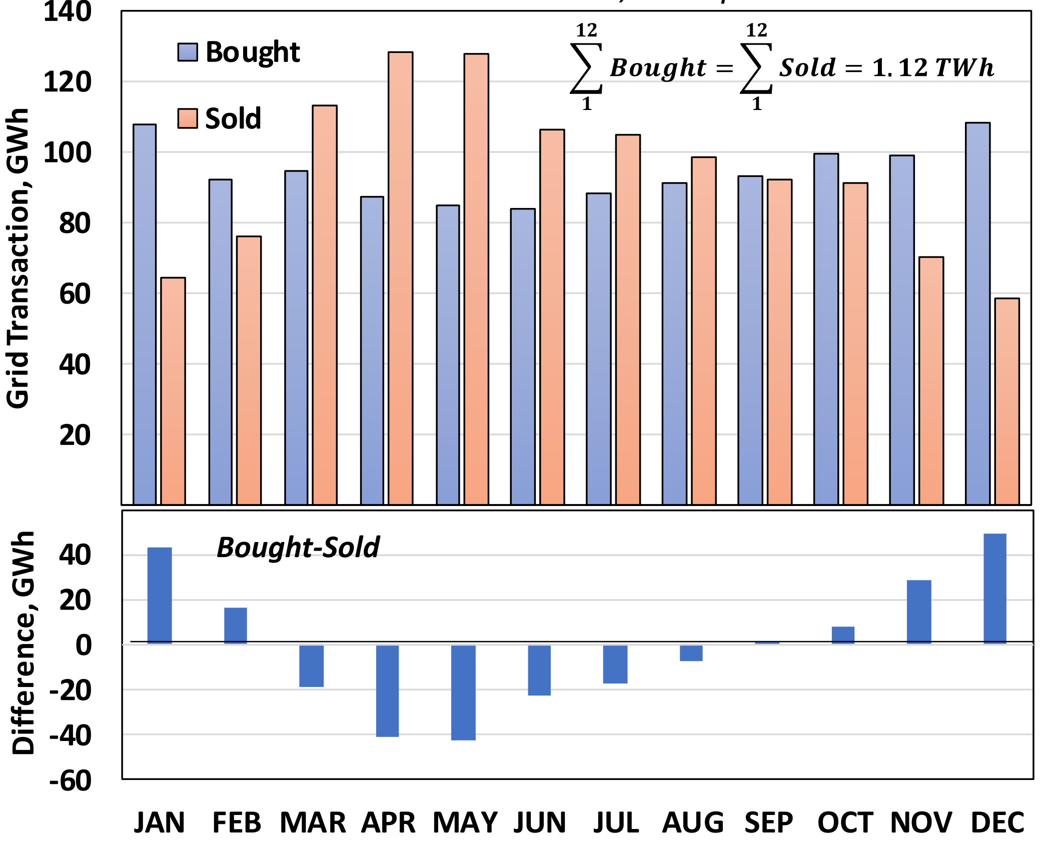
H_2 cost is lowest in southwest and highest in mid-west, northeast and northwest

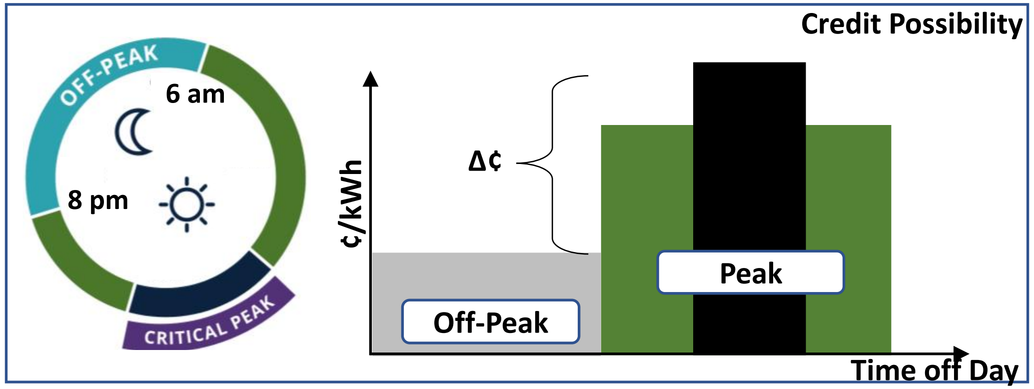
- Total H_2 cost: 2.26-3.37 \$/kg
- Renewable cost: 1.13-1.76 \$/kg
- Electrolyzer cost: 0.75-1.09 \$/kg
- Storage cost: 0.38-0.57 \$/kg with carriers, ~0.15 \$/kg with salt caverns



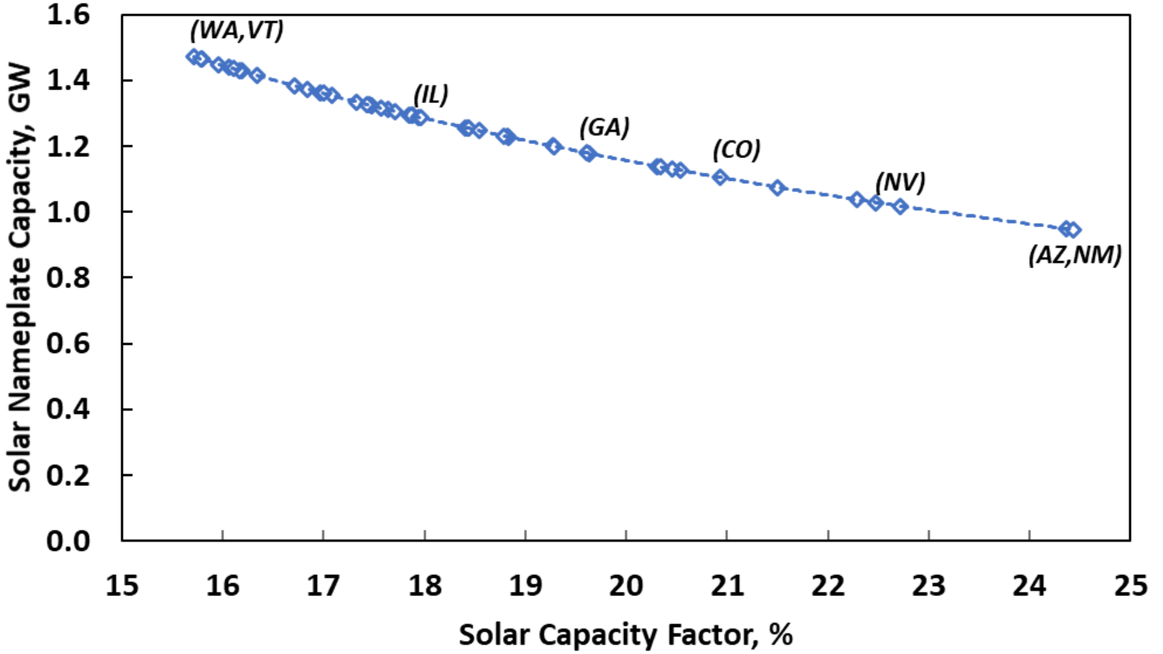
Grid Connected Solar H_2 Production Scenario – Performance

100 TPD Production Rate, Example FL





100 TPD Production Rate



Grid Connected Scenario Constraint

- kWh sold to and bought from the grid are equal on annual basis

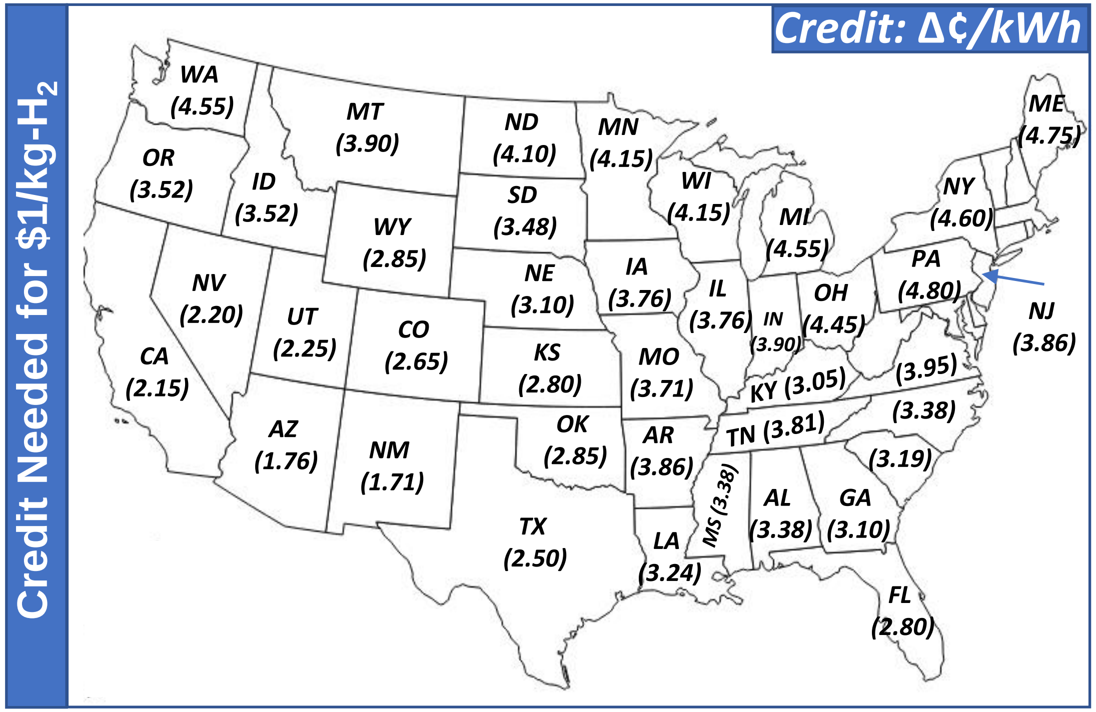
Solar and Electrolyzer Capacity

- Solar nameplate capacity correlates with the capacity factor
- Electrolyzer operates at constant power throughout the year with nearly 100% utilization

Potential Additional Revenue

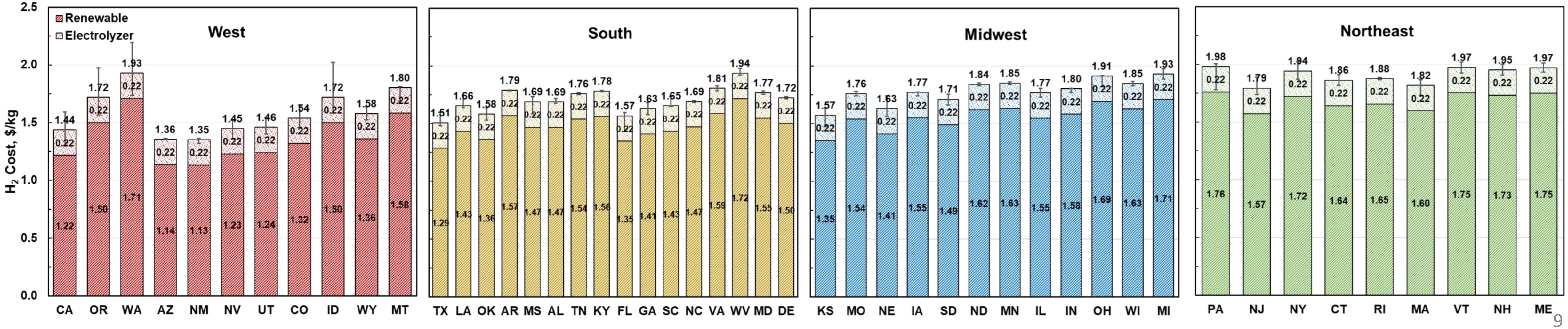
- Energy credit: Difference between the cost of electricity sold during peak hours and bought during off-peak hours
- kWh sold at peak = 100%, kWh bought off-peak = 67%

Grid Connected Solar H_2 Production Scenario – Cost

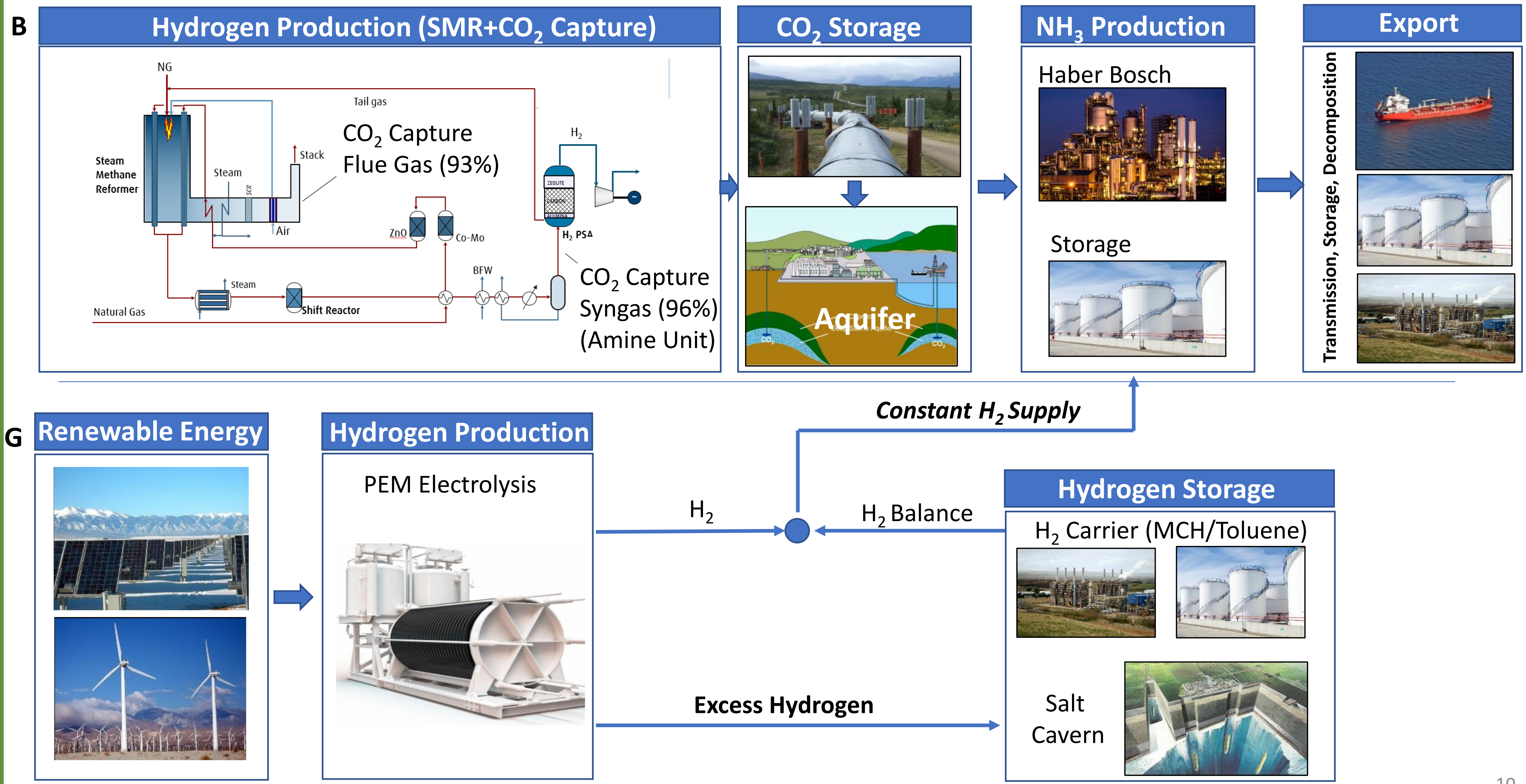


H_2 cost is 0.75-1.40 $/kg less than in grid-independent scenario

- Total H_2 cost: 1.35-1.98 $/kg
- Renewable cost: 1.13-1.76 $/kg, same as in grid-independent scenario
- Electrolyzer cost: 0.22 $/kg
- Storage cost: 0
- Credit needed to reach $1/kg-$H_2$: 1.71-4.80 ¢/kWh

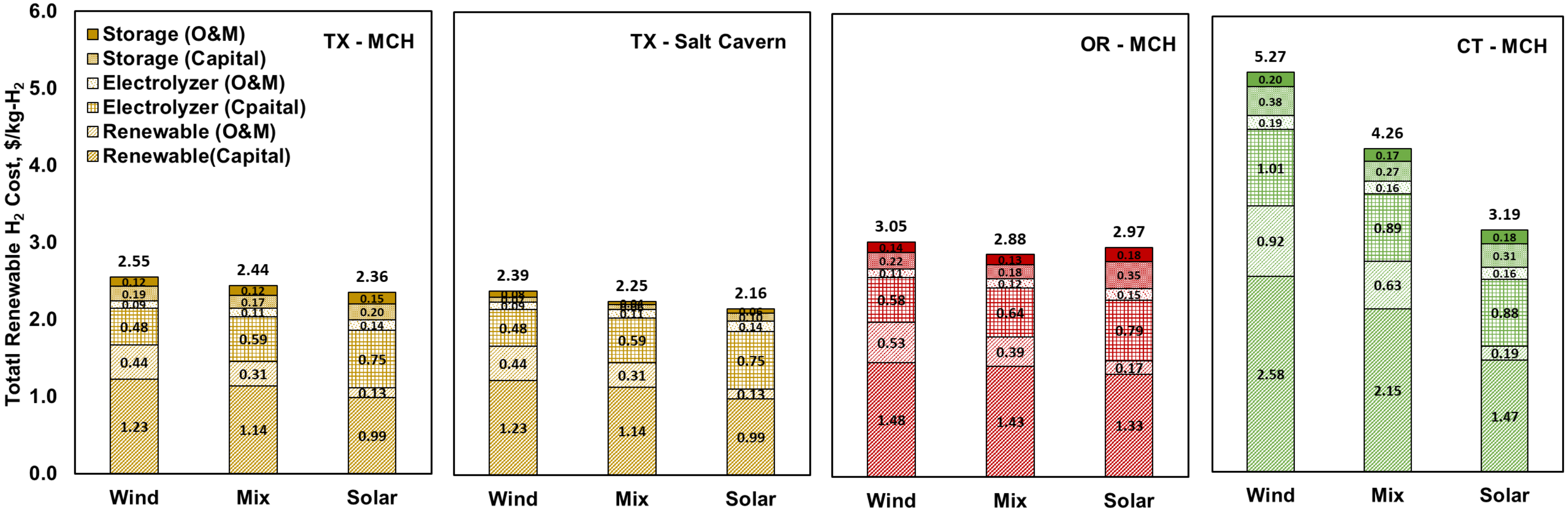


Approach: Blue (B) and Green (G) Ammonia Export

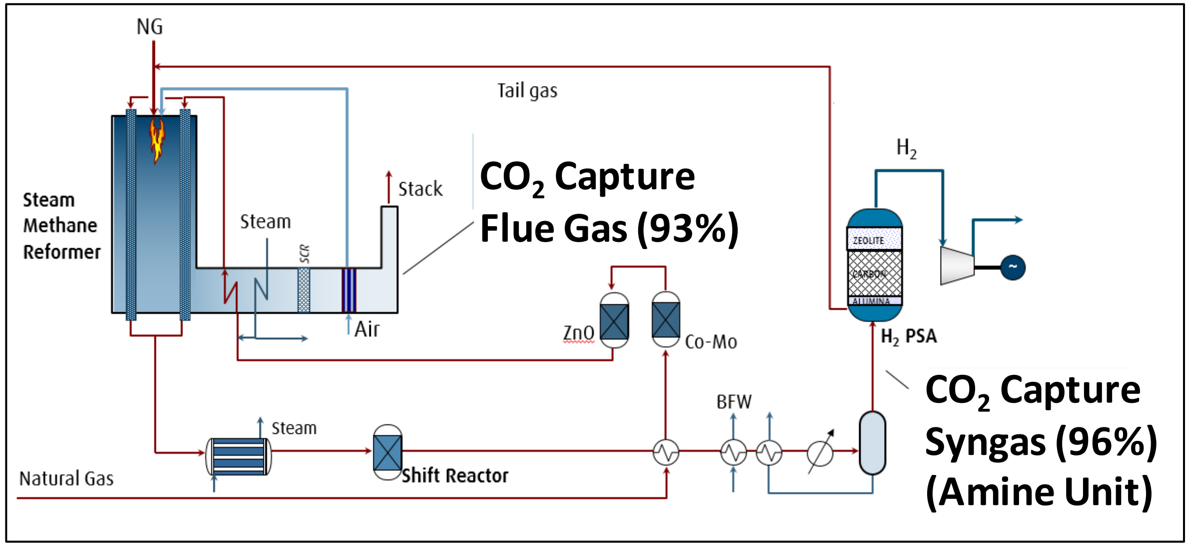


Accomplishments: Green Hydrogen Production Cost

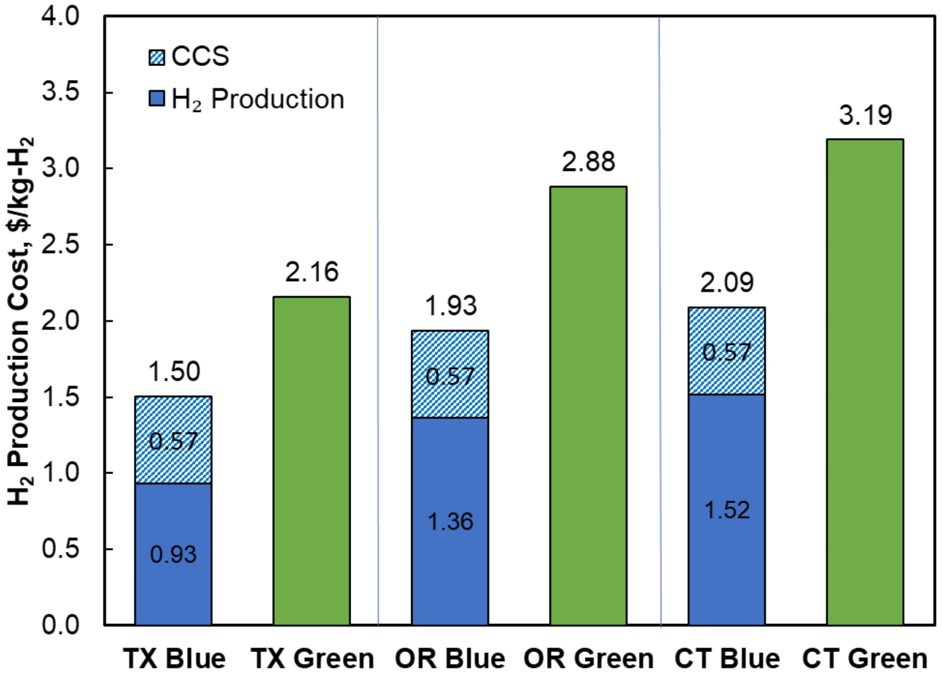
- Except CT, the green H_2 production costs are similar for wind, mix and solar, but lowest for solar
- H_2 cost: TX < OR < CT
- Cost contributors: Renewable plant > electrolyzer plant > storage



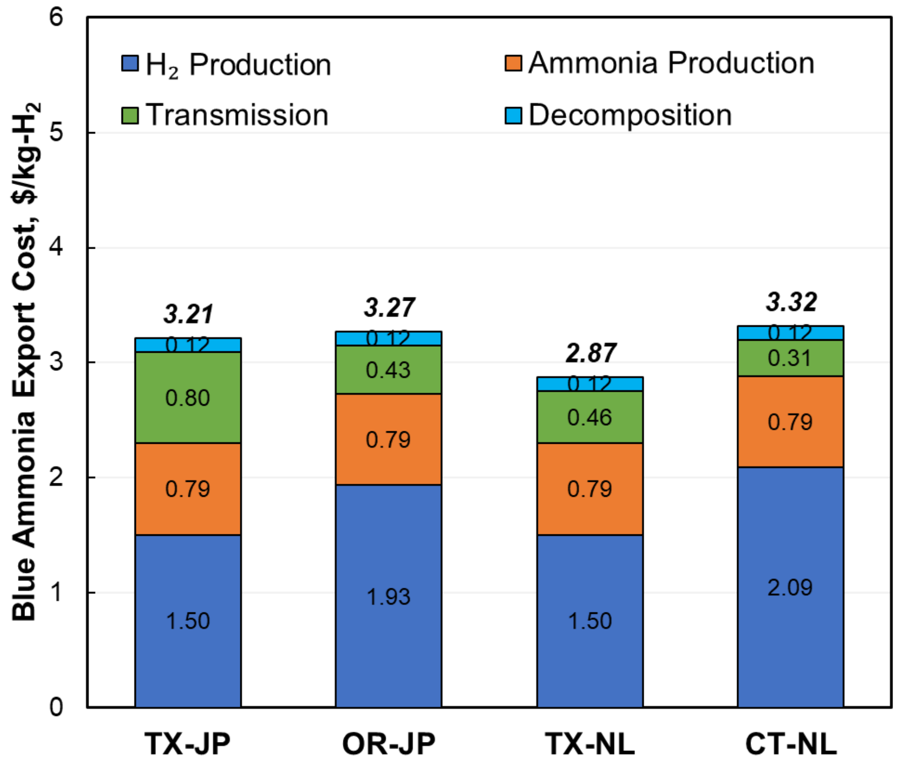
Blue Hydrogen Production Cost

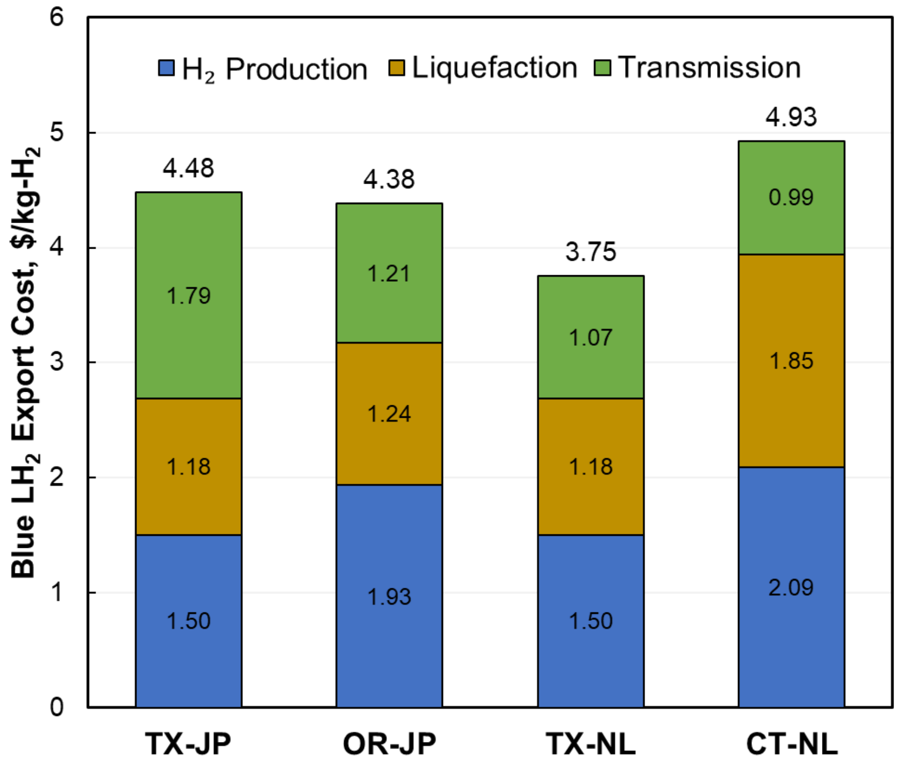


- NG demand: 0.029 MBtu/kg-NH_3
- CO_2 capture by amine solution
- CO_2 piped 300 km, captured in amine solution and stored in saline formations (FECM/NETL CO_2 Transport and Sequestration Cost Model)
- Blue H_2 cheaper than green H_2 by 0.66-1.10 \$/kg-H_2



Ammonia Export Cost





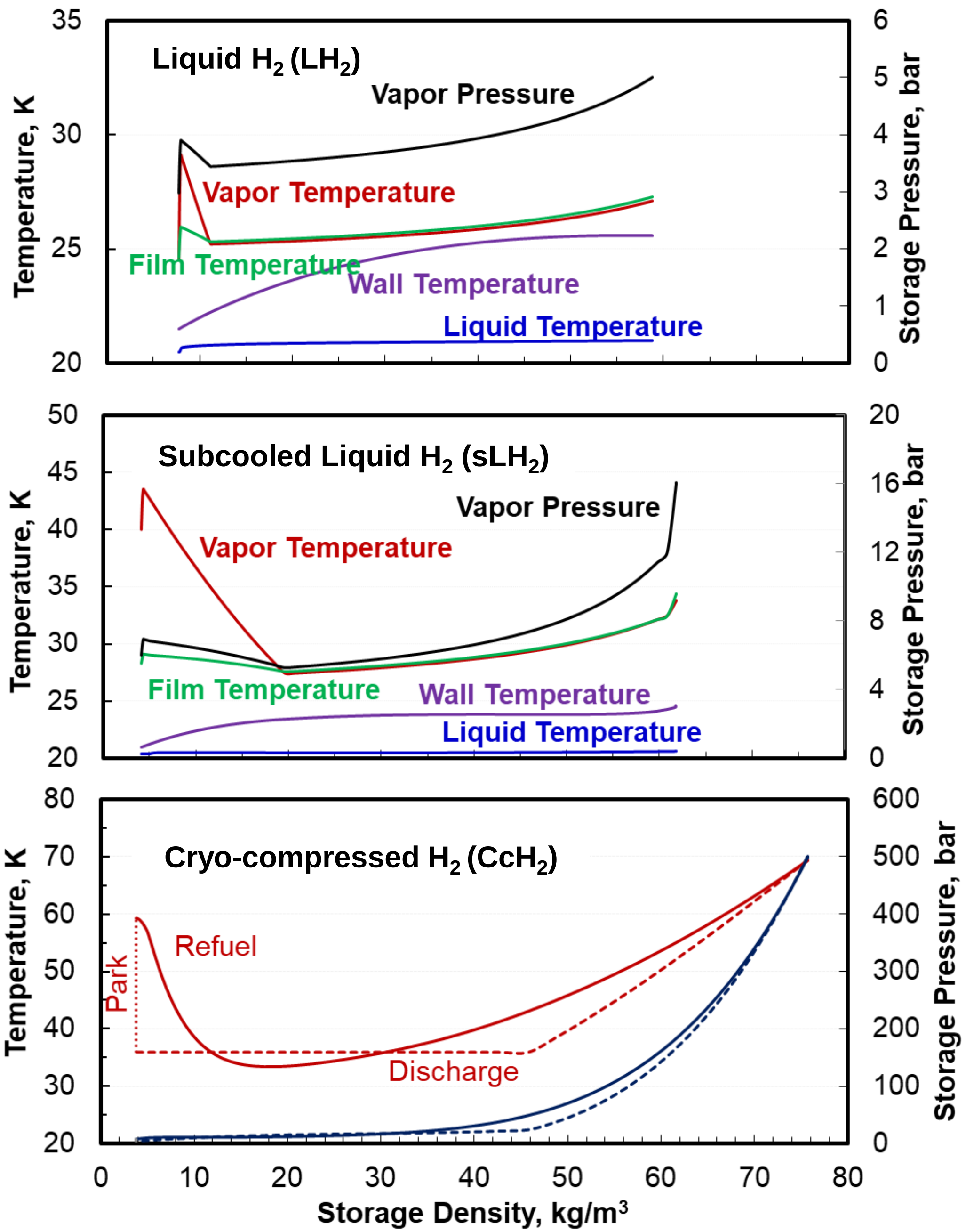
Ammonia Export Cost

- Export cost of blue ammonia: 2.87-3.32 \$/kg-H_2
- Export cost of green ammonia: 0.66-1.10 \$/kg-H_2 higher than blue ammonia
- Export cost of LH_2: 0.88-1.61 \$/kg-H_2 higher than ammonia
- Despite longer transmission route, ammonia export is cheaper from TX due to low NG price (blue ammonia) and higher solar capacity factor (green ammonia)

Approach: On-board Hydrogen Storage for Medium-Duty and Heavy-Duty Vehicles

Packaging Options[1]

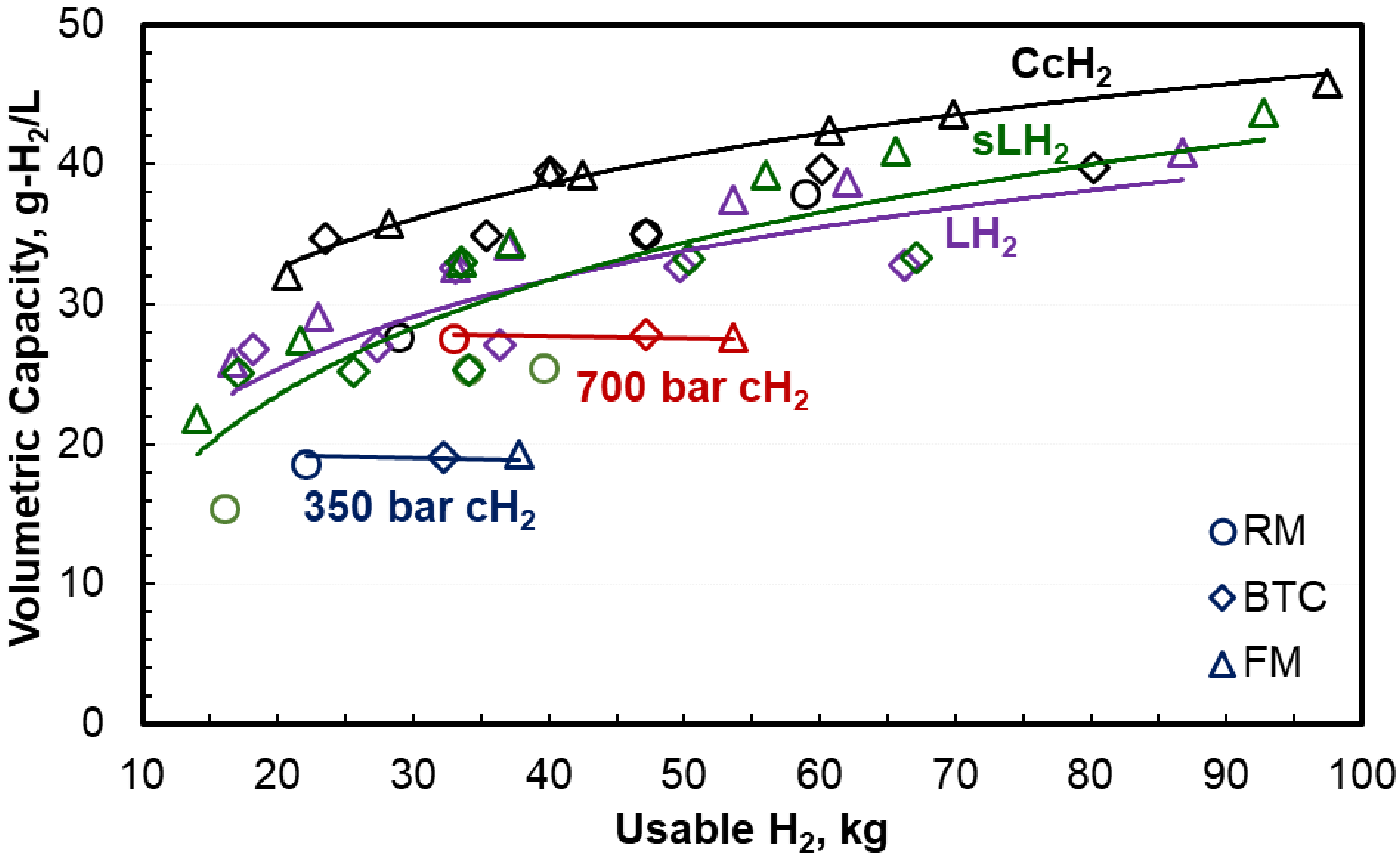
Baseline Packaging Options Outer Diameter (cm) X Outer Length (cm)		
Frame Mounted, FM	**Roof Mounted, RM**	**Behind the Cab, BTC**
2 Tanks	4 Tanks	2, 3 or 4 Tanks
53 X 152	41 X 203	41 X 203
53 X 203	41 X 246	53 X 203
53 X 120	30 X 246	
66 X 152		
66 X 203		
66 X 229		
66 X 305		



Accomplishments: Volumetric Capacity

Cryo-compressed H_2 storage has the highest system volumetric capacity

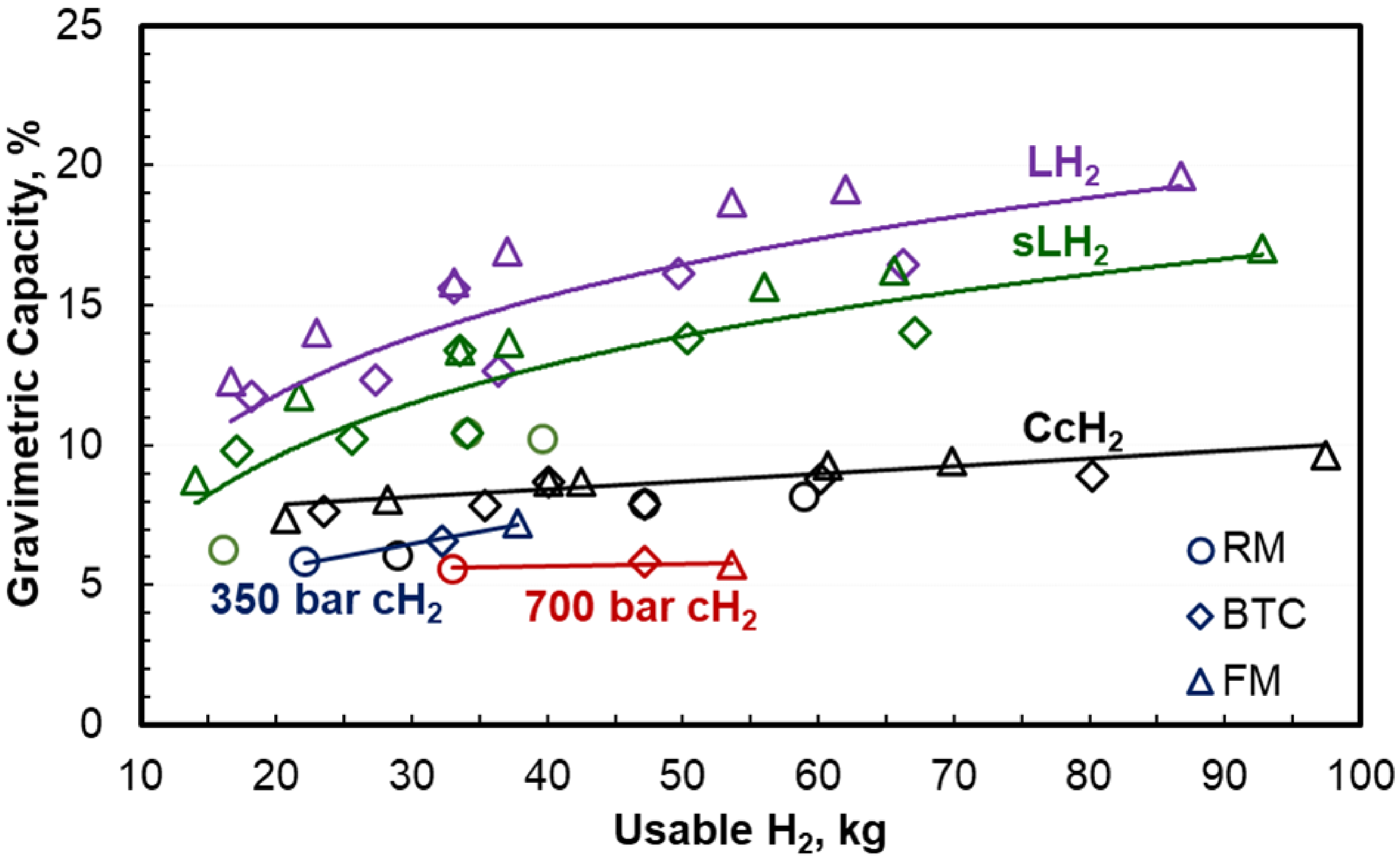
- System volumetric capacity: CcH_2 > sLH_2 > LH_2 > 700-bar cH_2 > 350-bar cH_2



Gravimetric Capacity

Liquid H_2 storage has the highest system gravimetric capacity

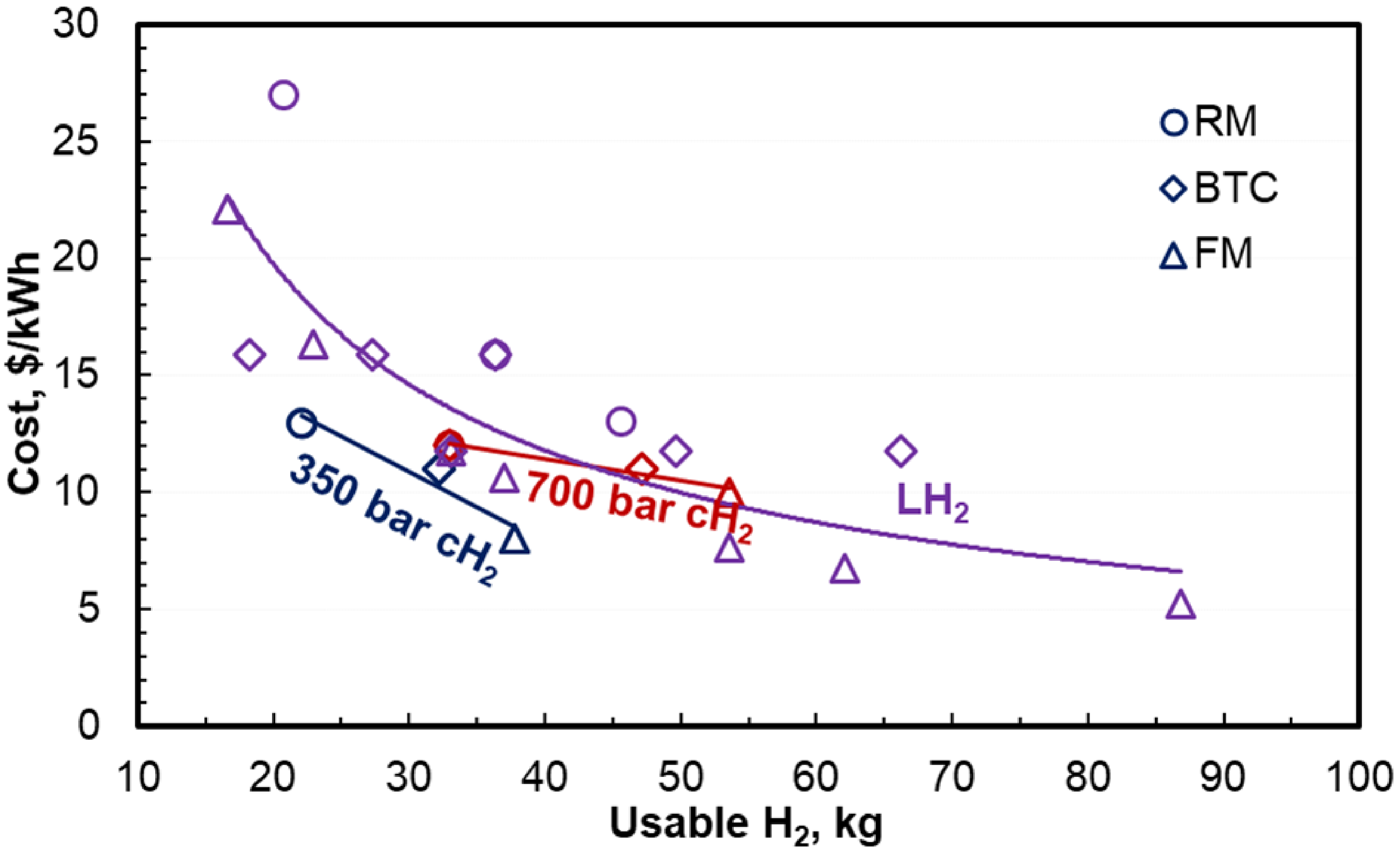
- System gravimetric capacity: LH_2 > sLH_2 > CcH_2 > 350-bar cH_2 > 700-bar cH_2



Cost

Liquid H_2 storage can be the least expensive option for heavy-duty applications

- Cost: LH_2 < 700-bar cH_2 < 350-bar cH_2



FY2023 Collaborations

Hydrogen Carriers	HyMARC: PNNL, LBNL
Bulk Storage	ANL (H2A Group), ANL (HDSAM), H2IT Taskforce, PNNL
Compressed Hydrogen (cH_2) Storage for Trucks	SA Team: SA, ANL, PNNL; Ford
Cryo-Compressed Hydrogen (CcH_2) Storage for Trucks	LLNL, PNNL, SNL
Liquid Hydrogen Storage (LH_2) for Heavy Duty Applications	Chart Industries, Universal Hydrogen, General Electric, LLNL, SNL
Off-Board Cost	ANL (H2A Group), ANL (HDSAM), H2IT Taskforce
On-Board Cost	Strategic Analysis Inc (SA)

Major Collaborating Projects

1. Strategic Analysis (SA): Hydrogen Storage Cost Analysis, ST235
2. Analysis of Hydrogen Export Potential, SA177
3. Integrated Onsite Waste-Heat Driven Hydrogen Carrier System for Steel and Renewables, ST227
4. Liquid Storage Lab Call Project, ST223

Future Work

National Renewable H_2 Production and Transmission Scenario

- Extend scenario to on-shore and off-shore wind, solar, and nuclear
- Compare pathway costs considering transmission by trains, ships, tube trailers and pipelines relative to the target of \$4/kg-H_2

On-board Storage for On-Road and Off-Road Heavy-Duty Applications

- LH_2 Dispensing: Develop and validate LH_2 dispensing model
- LH_2 On-board Storage: Performance of LH_2 on-board storage systems for heavy duty applications
- LH_2 Scenario: 1) LH_2 trailer defueling, 2) Dewar storage, refueling and discharge, 3) LH_2 dispensing, 5) Vehicle refueling
- Compressed gas storage

Bulk Storage of LH_2

- LH_2 Transfer: Evaluate LH_2 losses with pressure transfer vs. pump transfer
- LH_2 Bulk Storage: LH_2 storage at different scales including refueling station, liquefaction plant, ports
- Boil-off Mitigation: Helium refrigeration, vapor shielding, insulation materials
- LH_2 Transmission: LH_2 transmission and distribution in LH_2 trailers and LH_2 ships
- LH_2 Scenario: 1) Liquefaction and LH_2 storage at plant, 2) LH_2 trailer refueling, 3) LH_2 trailer transmission and delivery, 4) LH_2 trailer defueling, 5) LH_2 trailer return to liquefaction plant

Hydrogen Carriers

- Renewable Carriers: Production of hydrogen carriers using renewable sources
- Liquid carriers for bulk storage and transmission

Summary

Relevance:	Independent analysis to evaluate on-board and off-board performance of hydrogen production, storage and transmission methods and systems
Approach:	Develop and validate physical, thermodynamic and kinetic models of hydrogen production, storage and transmission. Address all aspects of on-board and off-board targets including capacities, rates, efficiencies, and costs
Progress:	Developed and analyzed a national solar H_2 pathway to show that H_2 can be produced at 1.35-1.98 $/kg in a grid-connected scenario which is 0.75-1.40 $/kg less than in a grid-independent scenario. Showed that blue ammonia can be produced at 0.60-1.0 $/kg-$H_2$ less than green ammonia. Determined that the cost of exporting blue ammonia on selected international routes is 0.88-1.61 $/kg-$H_2$ less than liquid H_2. Demonstrated the possibility of exceeding 40 g-H_2/L volumetric density and 15 wt.% gravimetric capacity by storing >85 kg of LH_2 in two frame mounted tanks in Class 8 trucks. Projected the high-volume manufacturing cost of on-board LH_2 storage in Class-8 trucks below the target of $8/kWh.
Collaborations:	Organizations: Ford, HyMARC, LLNL, PNNL, SA, Delivery Team Projects: ST100, SA177, ST223, ST227
Proposed Future Work:	Develop models for national renewable H_2 production and transmission pathway. Complete analysis of stationary hydrogen storage for different scales, duration and applications. Validate results for hydrogen storage on-board HDVs and MDVs.

TECHNICAL BACKUP AND ADDITIONAL SLIDES

Technology Transfer Activities

Private Industry Consulted

1. Chart Industries (LH_2 Storage)
2. Universal Hydrogen (LH_2 Storage)
3. General Electric (LH_2 Storage)
4. Ford (Type 4 Tanks)
5. FIBA Technologies, Inc. (Type 2 Tanks)

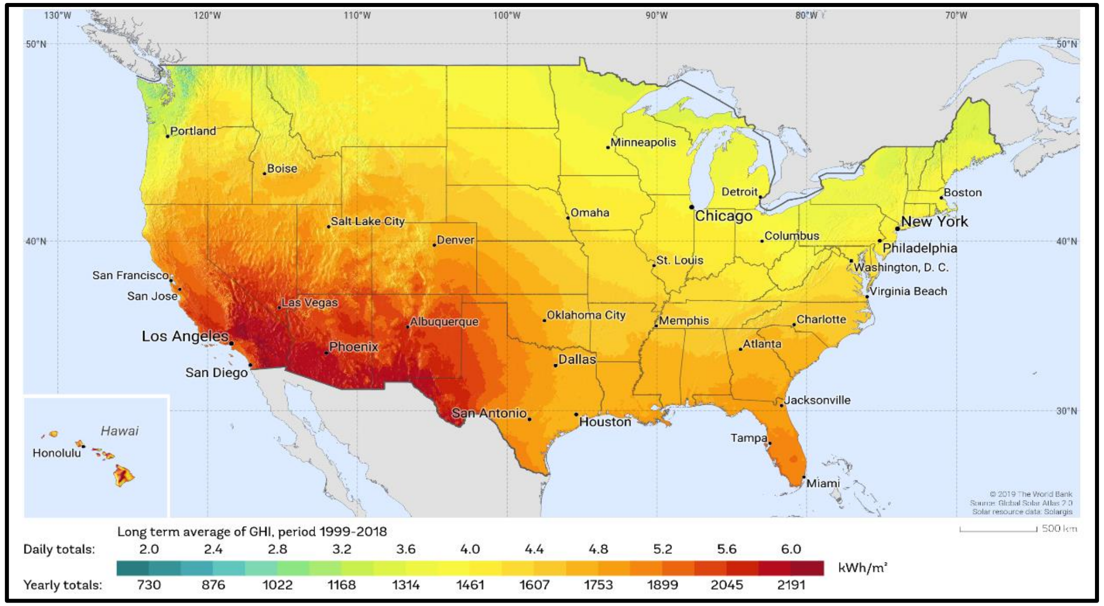
Major Collaborating Projects and Initiatives that Originated from this Work

1. Strategic Analysis (SA): Hydrogen Storage Cost Analysis, ST100
2. Analysis of Hydrogen Export Potential, SA177
3. Integrated Onsite Waste-Heat Driven Hydrogen Carrier System for Steel and Renewables, ST227
4. Liquid Storage Lab Call Project, ST223

Publications and Reports

1. Dionissios D. Papadias, Jui-Kun Peng, and Rajesh K. Ahluwalia, "Hydrogen Carriers: Production, Transmission, Decomposition, and Storage," International J. Hydrogen Energy, 46, 47 (2021) 24169-24189.
2. D. D. Papadias and R. K. Ahluwalia, "Bulk Storage of Hydrogen," International J. Hydrogen Energy, 46, 70 (2021) 34527-34541.
3. R. K. Ahluwalia, H. S. Roh, J-K Peng, and D. Papadias, "On-board Liquid Hydrogen Storage for Long-Haul Trucks," Liquid Hydrogen Technologies Workshop (Virtual), Hosted by DOE-EERE-HFTO and NASA's Cryogenics Technical Discipline Team, Feb. 22-23, 2022.
4. R. K. Ahluwalia, H-S Roh, J-K Peng, D. Papadias, A. R. Baird, E. Hecht, B. D. Ehrhart, A. Muna, J. A. Ronevich, C. Houchins, N. J. Killingsworth, and S. M. Aceves, "Liquid Hydrogen Storage System for Heavy Duty Trucks: Configuration, Performance, Cost, and Safety," International J. Hydrogen Energy, 48, 35 (2023) 13308-13323.
5. R. K. Ahluwalia, J-K Peng, H-S Roh, D. Papadias, X. Wang, and S.M. Aceves, "Liquid Hydrogen Storage System for Heavy Duty Trucks: Capacity, Dormancy, Refueling, and Discharge," Submitted to International J. Hydrogen Energy, February 2023.

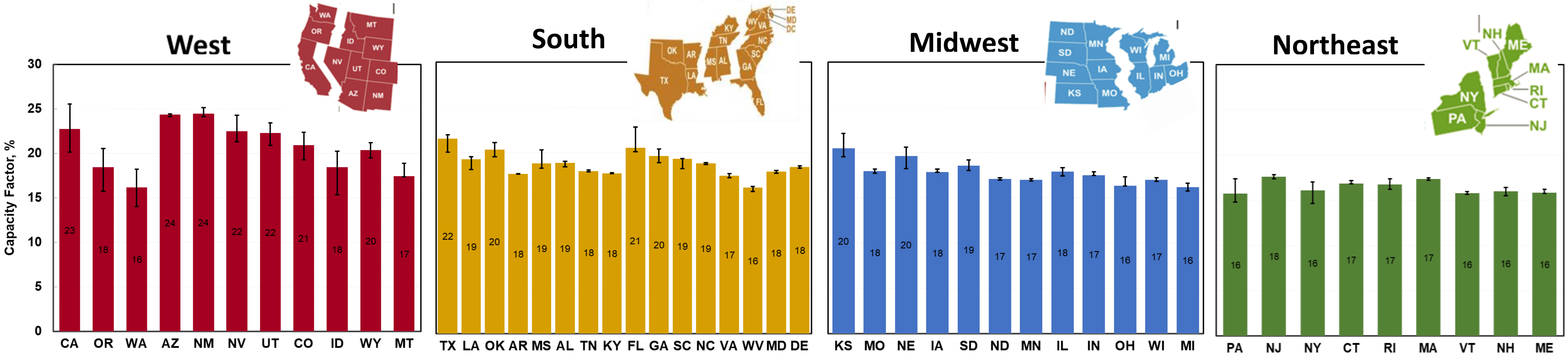
Solar Potential – Yearly Capacity Factor



Global Horizontal Irradiation - https://solargis.com/maps-and-gis-data/download/usa

Single Axis Photovoltaic Solar System

- Solar net capacity factor includes system losses and is highest in south-western states and lowest in north-east
- Difference between extremes: AZ,NV,NM,CA (~24%), NY,PA,CT,MI (~16%)



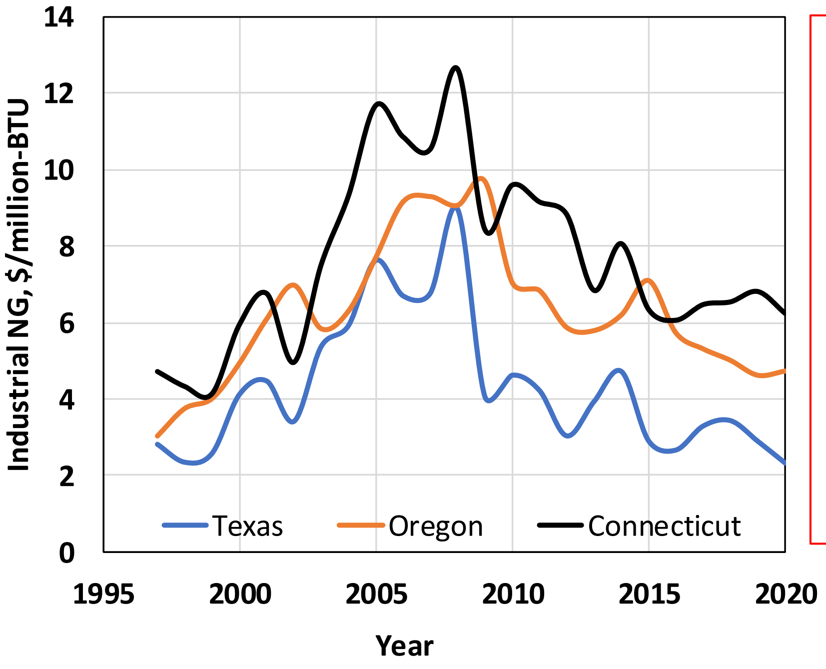
Ammonia Export Cost Study – Blue Hydrogen

1. Ammonia Production
- Production Method: SMR + CCS + Haber Bosch
- Plant Capacity: 2x2,500 TPD[1] NH_3
- H_2 equivalent throughput with losses[1]: 665 TPD H_2 equivalent
- CapEx: $994 million (each plant)
- OpEx: $47 million
- Feedstock: Natural Gas
- Fuel Cost: 3.02-6.45 $/million-Btu

2. Storage at Port
- Storage Method: Refrigerated tanks
- Storage Capacity: 58,200 Tonnes (NH_3)
- Storage Cost: $50 million (satellite + plant)
- Days of Storage: 15

3. Port Infrastructure
- Infrastructure: $76.7 million
- Pipeline: $3.3 million
- Total CAPEX: $130 million (incl. storage)
- Port Fees: $130,000 (per roundtrip)
- Canal Crossing Fees: $460,000 (per roundtrip)

4. Tanker
- Type: Refrigerated chemical tanker, -33°C storage temperature
- Maximum Capacity: 85,000 m^3
- Propulsion Power: 12 MW at 16 kts (NM/hr.) cruise speed
- Fuel: Low sulfur marine gas-oil
- Bunkered Fuel Cost: $650/tonne, 2018 data
- Specific Fuel Consumption: 170 g/kWh.
- Crew Complement: 4 officers, 3 engineers, 25 deckhands.
- CAPEX: $130 million
- OPEX: $2.6 million (per roundtrip)



Industrial Natural Gas (NG) Price
- Data Source: EIA.gov
- 5-year average (2015-2019) NG gas price

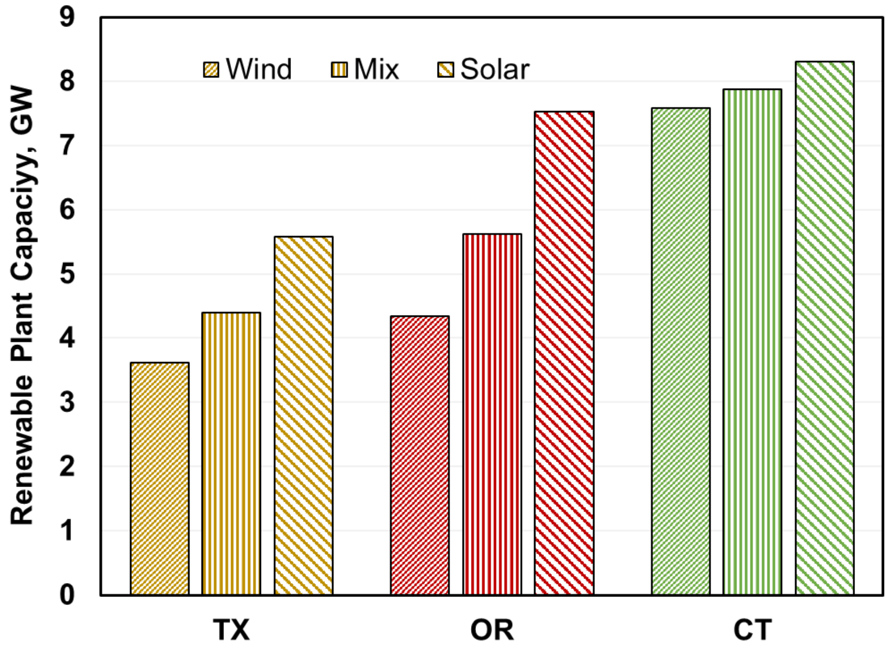
- TX: $3.02/million-BTU
- OR: $5.55/million-BTU
- CT: $6.45/million-BTU

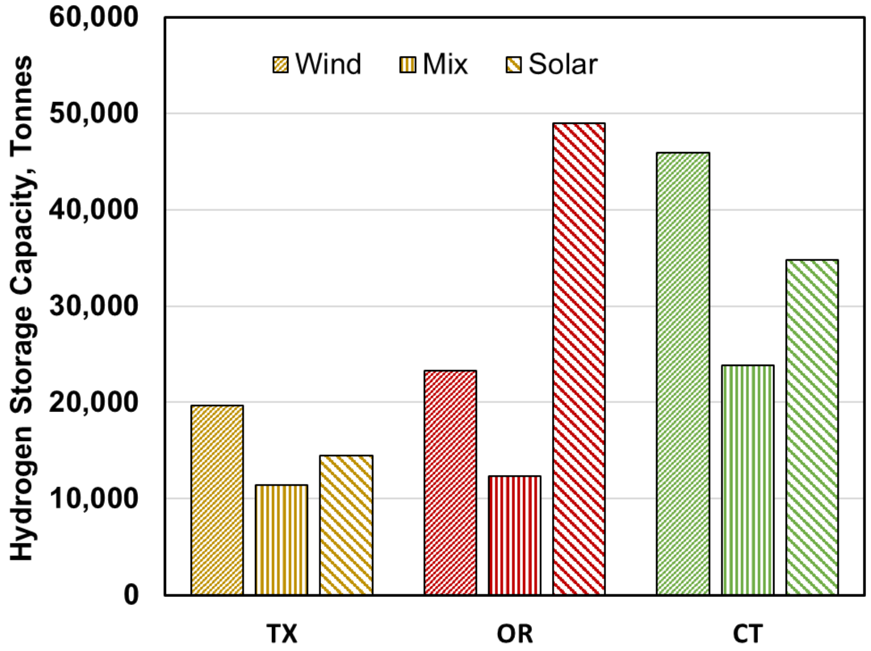
[1]TPD=Tonnes per Day *[2]Losses are 25% due to ammonia decomposition (H_2 separation)*

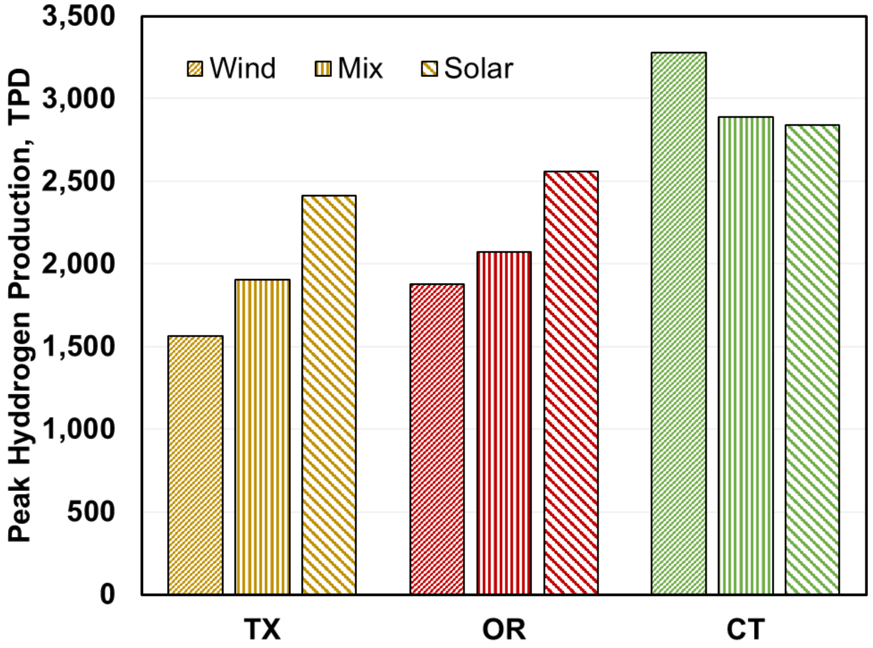
Green Hydrogen Production: Cost Factors

	Current (2020)	Future (2030)	Comments and References
Wind Plant (On-Shore)			
CAPEX, $/kW	1,436	1,050	1. www.energy.gov/eere/solar/articles/2030-solar-cost-targets
OPEX, $/kW	46	26	2. IRENA (2019) - ISBN 978-92-9260-156-0
Solar Plant (PV)			3. Stehly et al. (2019). Cost of Wind Energy Review
CAPEX, $/kW	1,080	550	4. Feldman et al. (2021). U.S. Solar Photovoltaic System and
OPEX, $/kW	8.7	4.8	Energy Storage Cost Benchmark: Q1 2020. NREL
Electrolyzer (PEM)			1. Cost estimates by Strategic Analysis, PEM electrolysis central
Stack, $/kW	342	143	production. James B.D. et al. "Analysis of Advanced H_2
Mechanical BOP, $/kW	36	23	Production and Delivery Pathways", DOE 2019 AMR, P112
Electrical BOP, $/kW	82	68	April 30th, 219
Total, $/kW	460	234	2. H2A Current and Future Central PEM Electrolysis, V. 3.2018
Liquid Hydrogen			
Max Liquefier Unit, kg/day	100,000		1. Connelly et al. (2019). DOE Hydrogen and Fuel Cells
Electricity Consumption, kWh/kg	10		Program Record #19001, September 9, 2019
CAPEX, $/kg-day	2,520		2. Majumdar et. al. (2007). Numerical Modeling of Propellant
Max LH_2 storage (spherical), m^3	10,000		Propellant Boiloff in Cryogenic Tank. NASA-215131
Financials			
Analysis Period, y	30		
Depreciation	MACRS		H2A Assumptions
Equity Financing, %	40		www.nrel.gov/hydrogen/h2a-production-models.html
Tax Rate, %	25.74		
Inflation, %	1.9		
After Tax Real IRR, %	10		

700 TPD Green Hydrogen Production – Performance Factors

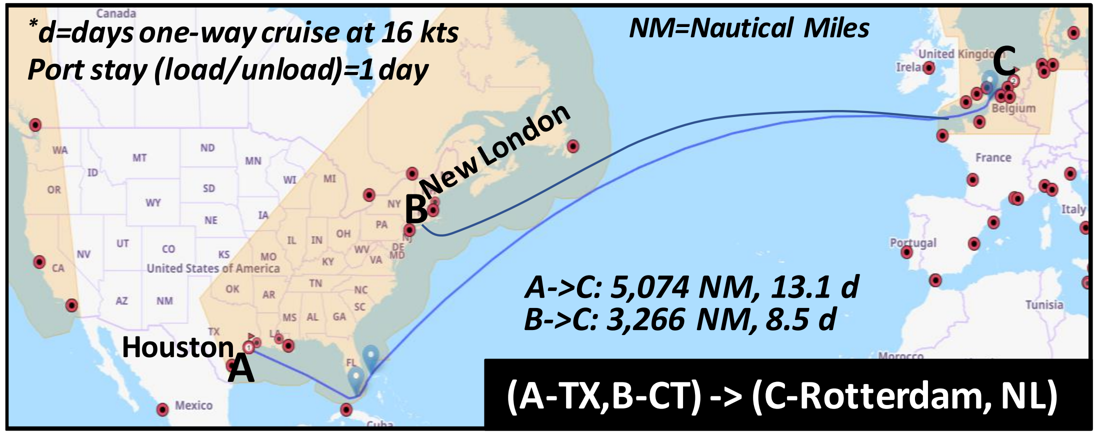


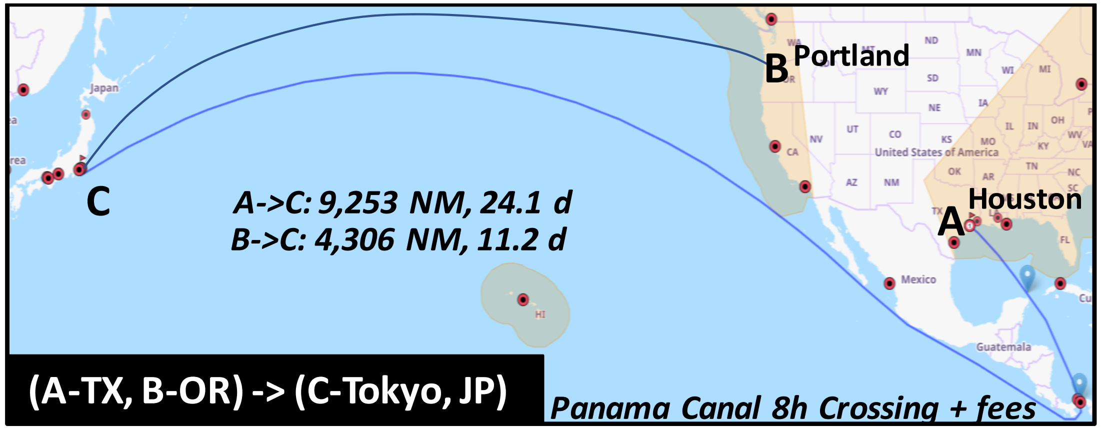




- Renewable plant capacity: CT>OR>TX, increases as solar displaces wind
- Storage capacity lowest for mix wind/solar (50%). Larger requirements in CT/OR than TX
- Peak hydrogen production (and electrolyzer cost) increases as solar displaces wind. Lowest peak production rate in TX

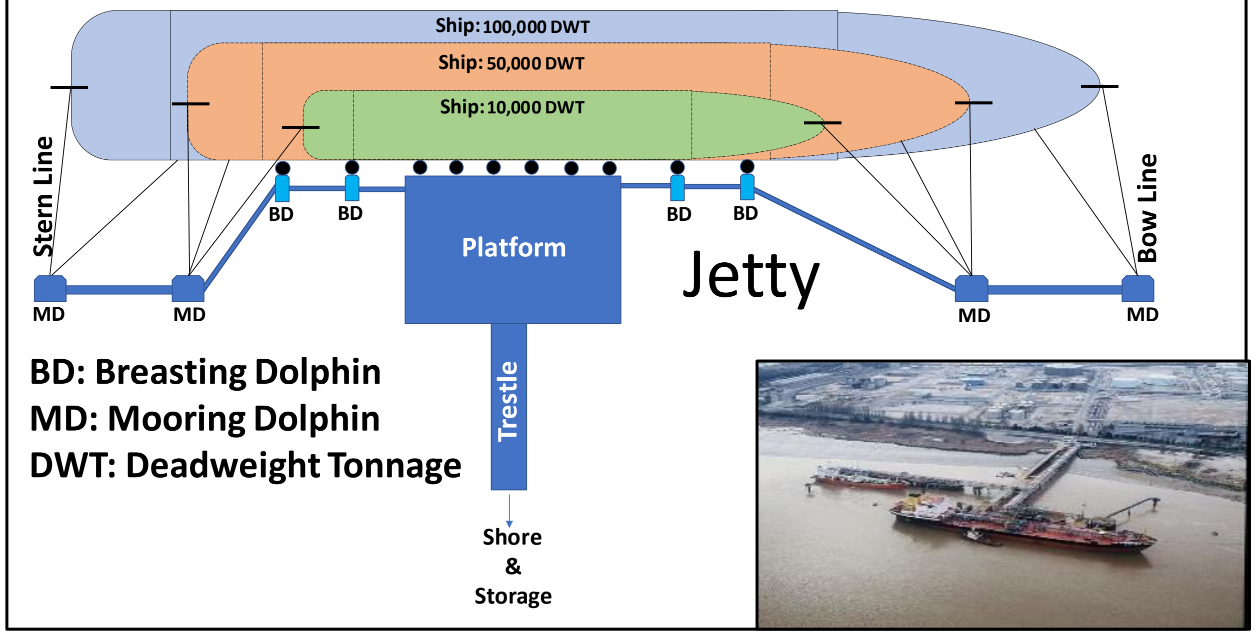
Transmission Routes and Port Infrastructure

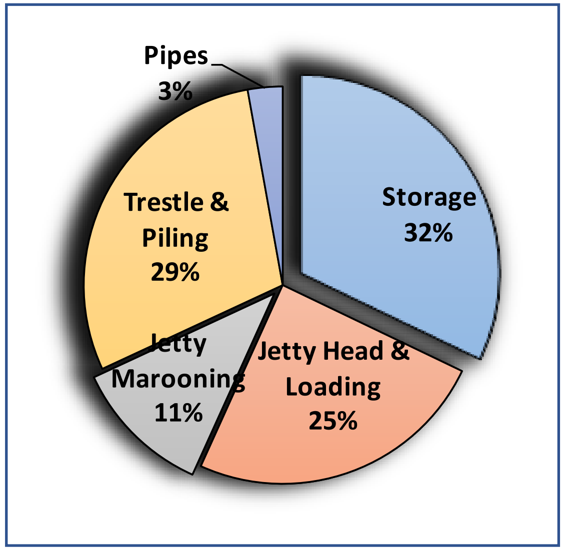




	TX-JP	TX-NL	OR-JP	CT-NL
Sail distance – one way, nm	9,253	5,074	4,306	3,266
Number of ships on route	5	3	3	2
Storage, days	15	15	15	15
Liquid ammonia cargo, Tonnes, m^3	51,000	41,700	48,300	50,000
Tanker cargo (H_2 equivalent), Tonnes	6,800	5,500	6,440	6,670
Tanker water displacement, DWT	84,460	69,000	80,100	82,100
Tanker CAPEX, $Million	130	118	127	130

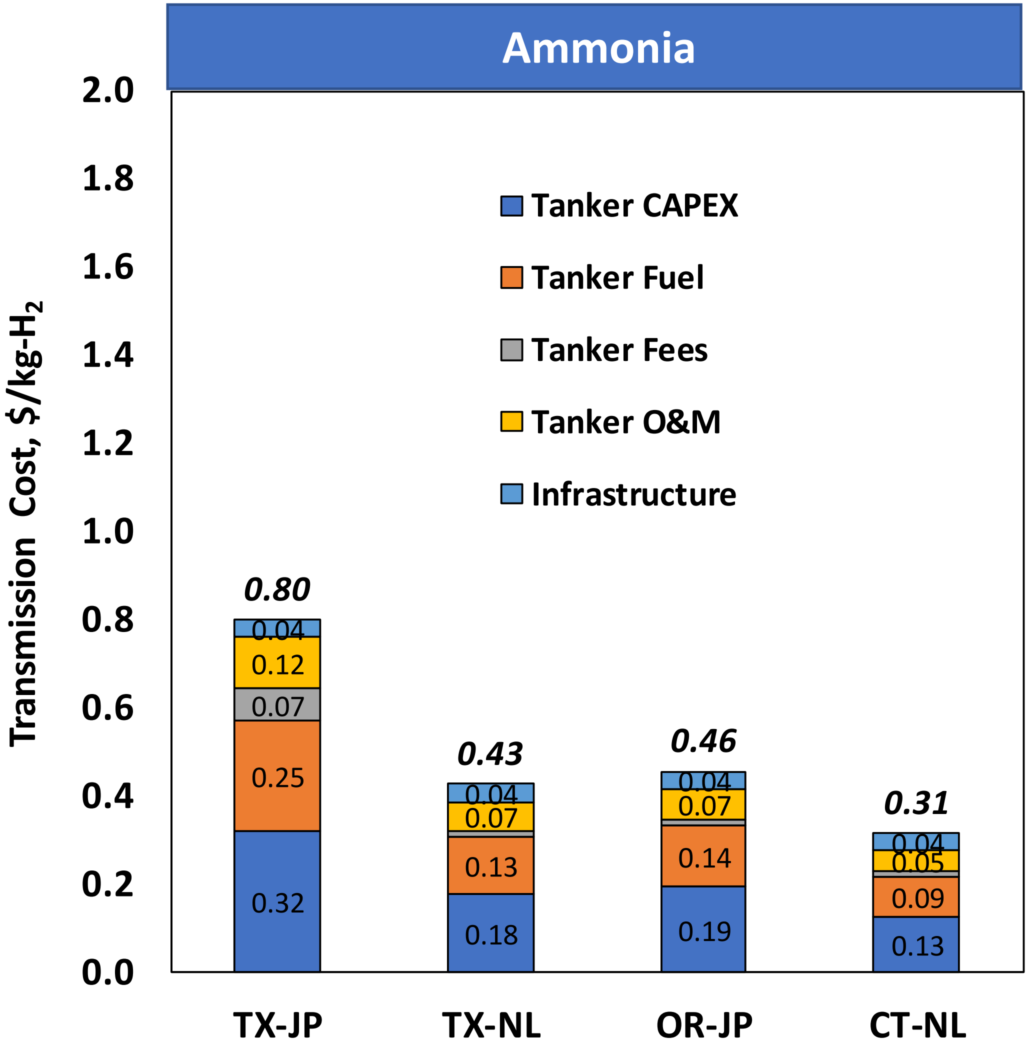
Tanker Port infrastructure



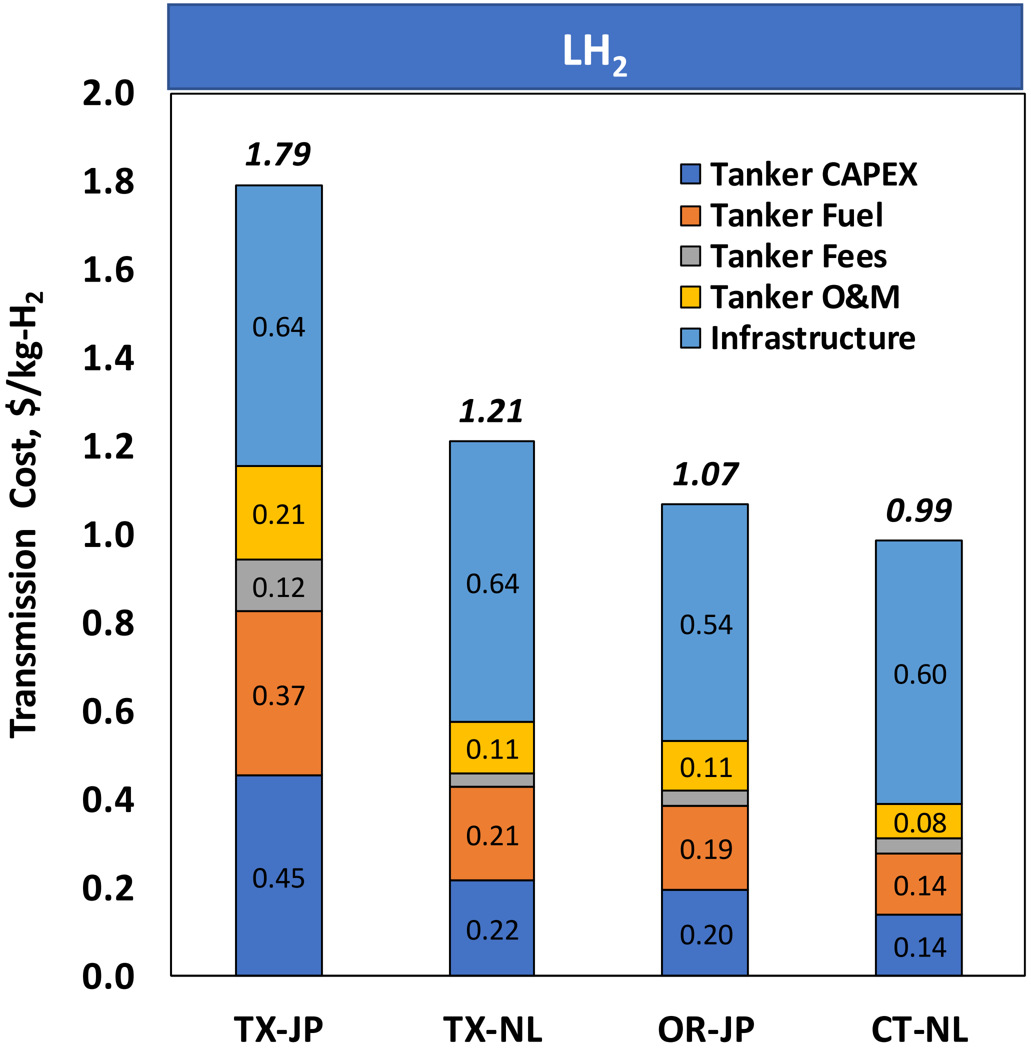


- Tankers close to 90,000 DWT – requires a large Jetty system
- 130 million in CAPEX
- Storage accounts for ~32% of the infrastructure cost

Ship Transmission Cost



- Transmission cost: 0.31-0.80 $/kg-$H_2$ (47-130 $/Tonne-$NH_3$)
- Storage only a small fraction of infrastructure cost (0.02 $/kg-$H_2$)



- Transmission cost: 0.99-1.79 $/kg-$H_2$
- Storage accounts for the majority of infrastructure cost (0.50-0.60 $/kg-$H_2$)

Carbon Fiber Usage

Cryo-compressed H_2 storage uses least amount of carbon fiber composite

- Carbon fiber usage: CcH_2 < 350-bar cH_2 < 700-bar cH_2