HYDROGEN IN NORTH AMERICA

OCTOBER 2021

INTRODUCTION

Hydrogen is very clean burning fuel creating no GHG emissions when combusted. This has led to a rush of interest as more governments worldwide look for ways of reducing emissions. This paper will examine the cost of hydrogen and drivers for growth.

Creating hydrogen can result in GHG emissions depending on the process. Hydrogen can be produced via two processes:

- Using natural gas via steam methane reforming (SMR). This process results in carbon emissions as hydrogen is released from CH4 molecules.
  - Grey Hydrogen - hydrogen created via SMR with carbon released into the atmosphere.
  - Blue Hydrogen - hydrogen created via SMR with carbon captured and stored (CCS).
- Electrolyzing water utilizing a power source to release hydrogen from H2O.
  - Green Hydrogen – hydrogen created via electrolysis utilizing a non-carbon emitting power source (wind, hydro, solar, nuclear, or biofuel.

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HYDROGEN PROPERTIES

High diffusivity

Extremely low density in gas and liquid forms

Large flammability range relative to natural gas, NGLs, and Oil

Transportation:

- pressurized gas
- cryogenic liquid
- it can be combined in an absorbing metallic alloy matrix
- adsorbed on or in a substrate or transported in a chemical precursor form such as lithium, sodium metal, or chemical hydrides

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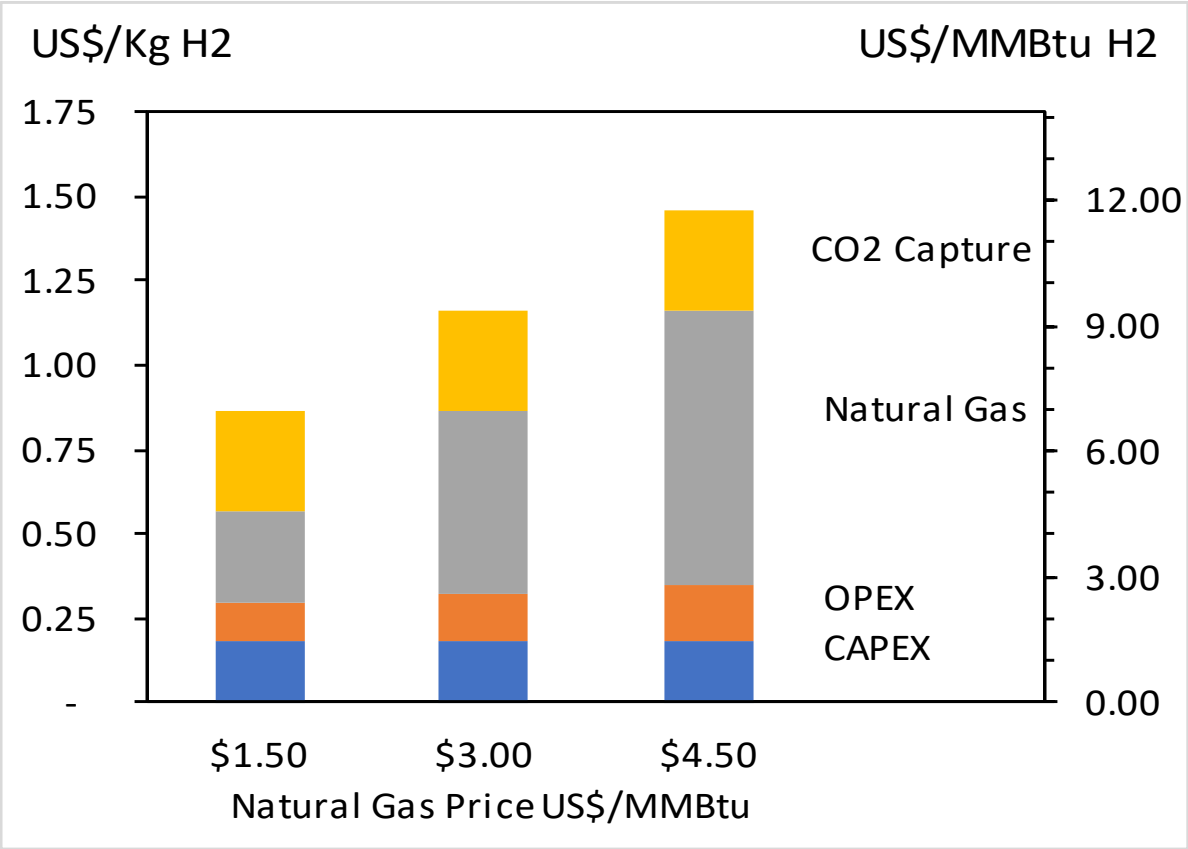
IMPACT OF NATURAL GAS COST ON HYDROGEN COST



- Natural gas is a major cost input into SMR Hydrogen production.
- SMR Hydrogen cost is very sensitive to natural gas pricing.
- Incorrys has assumed natural gas is used for SMR and CCS power inputs.
  - 75% natural gas input energy is converted to Hydrogen output
- US$3/MMBtu natural gas input price results in a US$9.35/MMBtu (US$1.15/Kg) Hydrogen equivalent at the plant gate.

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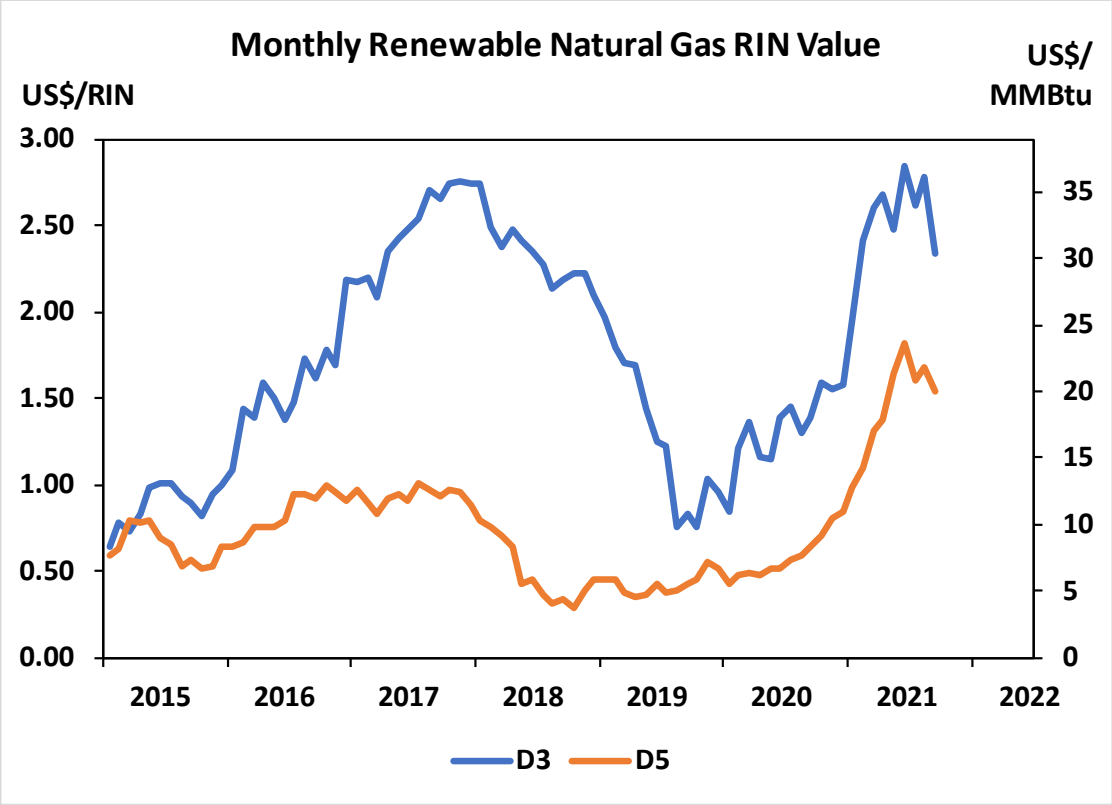
RIN PRICING



- Renewable Fuel Standard (RFS) program is administered by the EPA to increase renewable fuel in the transportation sector. Current 2022 target calls for 36 Billion gallons RFS by 2022.
- Renewable identification numbers (RIN) are tradable credits generated when a gallon of renewable fuel is produced. Cellulosic biofuel is classified as D-3 and advanced biofuel is assigned D-5.
- Hydrogen has historically been used in industrial processes: oil refining, ammonia production, methanol production and steel production. Grey Hydrogen is typically produced and consumed on-site.
- Currently hydrogen created from biogas pathways are classified as a D3 RIN. Although there is not a RIN for Blue or Green Hydrogen, Incorrys believes as regulations are developed, it can be used as a substitute for natural gas or as renewable gas.
- To generate RINs, the renewable gas must be used for transportation purposes. However, RIN pricing is instructive for broader renewable gas markets being enacted by various states and provinces.
- EPA conversion for biogas:
  - 77,000 Btu = 1 gallon equivalent = 1 RIN.

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PIPELINE BLENDING

- Hydrogen blending into natural gas pipelines is considered an option to grow hydrogen capability without the large upfront costs and time of developing a dedicated hydrogen pipeline network.
- Hydrogen as a renewable gas, with associated credits, could be important in utilising the North American natural gas pipeline grid.
- SMR in combination with CCS could utilise the North American pipeline grid to provide low/no carbon option.
- Economic incentive for converting excess curtailed energy from renewable sources (wind, solar) into hydrogen.
- Safety is the most important factor for operators of natural gas pipelines throughout North America.
- 2013 NREL study* concluded low concentrations (<5-15% hydrogen by volume) of hydrogen blending in Natural gas pipelines was viable.
- Enbridge Gas received permission from the Ontario Energy Board to blend up to 2% hydrogen** from Electrolysis in Markham, Ontario.
- Hydrogen is lower density than natural gas therefore, requires 30% more pipeline space to delivery the same energy (Btu basis).

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* Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues
** OEB Decision EB-2019-0294

EXPORT OVERVIEW HYDROGEN AND HYDROGEN INDUSTRIAL FEEDSTOCK

HYDROGEN PROPERTIES

Hydrogen has high energy per weight, however, has low density therefore; low energy per volume.

Having low boiling point (-253 degrees C) and low-density results in challenges in storage and transportation.

Can be shipped as pure Hydrogen or utilizing a Hydrogen carrier, via ammonia (NH_3) and Methylcyclohexane (MCH).

HYDROGEN TRANSPORT PATHS

Pure Hydrogen

- Similar to Natural gas transportation

Ammonia (NH_3)

- Similar to Natural Gas Liquid Transportation

Methylcyclohexane (MCH)

- Similar to Crude Oil transportation

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INPUT COST ASSUMPTIONS

This section provides the capital and operating cost assumptions for the three cases: Hydrogen, Low-Carbon Ammonia, and Methylcyclohexane-Toluene Hydrogenation. Estimates for Transportation costs to the Westcoast and Marine competitiveness to Asia (Japan as a proxy) are also shown.

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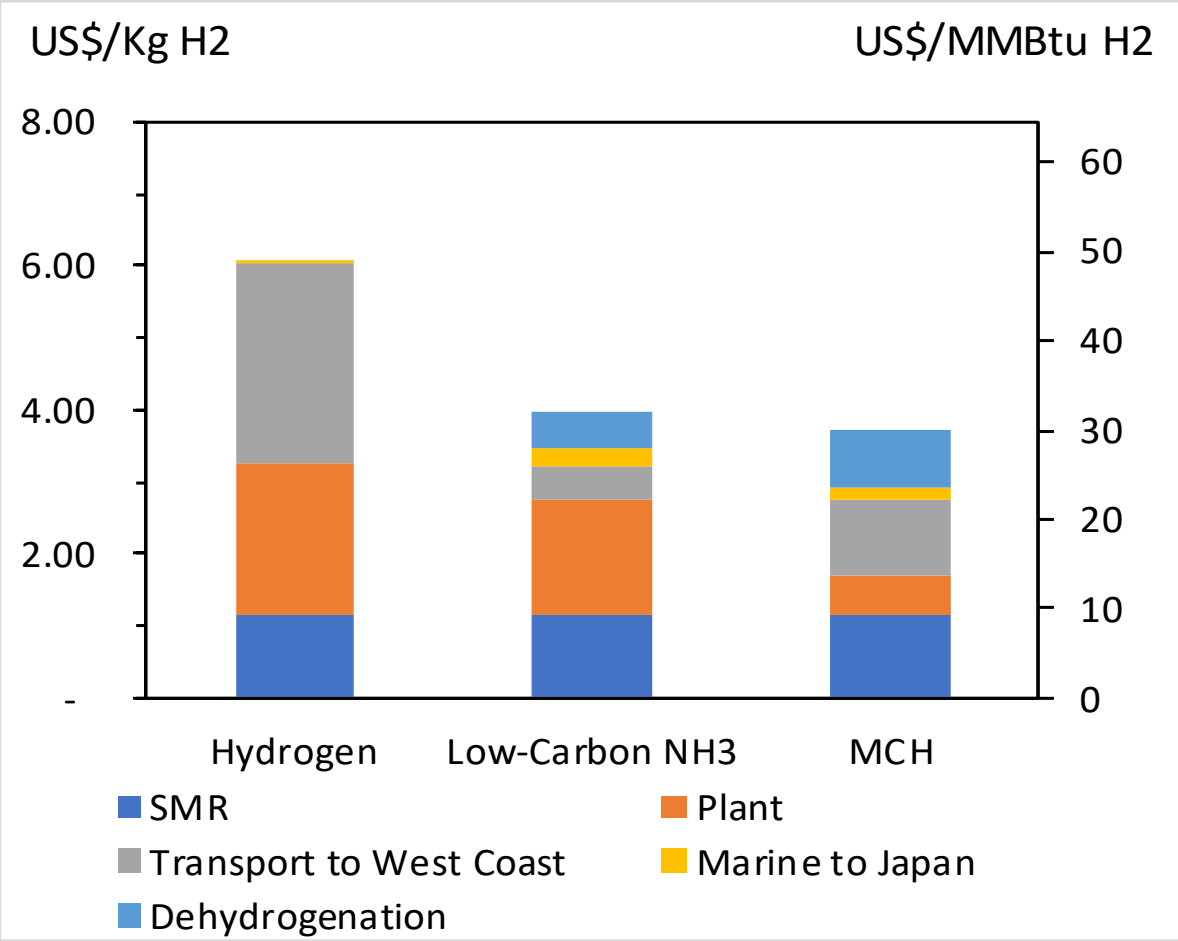
SUMMARY



- Hydrogen is assumed to be produced in Edmonton area utilising the Steam Methane Reformer (SMR) process with carbon sequestration.
- **Hydrogen case** assumes gas from the SMR process is shipped via pipeline (1,150 km) to the west coast where it is liquefied and shipped via cryogenic tanker to Asia.
- **Low Carbon Ammonia (NH_3) case** assumes hydrogen is converted to NH_3 in Edmonton where it is railed to the west coast and transported to Asia via LPG type rail cars/tanker. USD$3.15/Kg H2 equivalent to USD$568/t NH3 pre-dehydrogenation process.
- **Methylcyclohexane (MCH) case** assumes hydrogen is converted to MCH in Edmonton where it is railed to the west coast and transported to Asia via crude oil type rail cars/tanker.
- The ability to convert natural gas and sequester carbon near tidewater would improve overall economics.

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OBSERVATIONS

- **SMR costs are directly correlated with natural gas input pricing**.
  - USD$6.90/Mcf input price (cost to bring Canadian gas to Asia via LNG) would result in USD$1.95/kg H2 versus USD$1.16/kg H2 @ USD$3.00/Mcf.
- **SMR output USD$1.16/kg H2 is equivalent to USD$9.40/MMBtu or about 4 times 2020 Henry Hub price.**
  - However, SoCal Gas in California has PUC approval to deliver 20% renewable natural gas (RNG) by 2030 to its franchise area. RNG has traded around USD$20-33/MMBtu over the past year (based on DC-3 RINS).
- **Hydrogen from electrolysis is currently 3 times more costly than SMR.** Companies such as Plug Power are investigating mass modular production via high tech robotic manufacturing (~Tesla Gigafactory) to drive down costs.
  - Aiming to reduce cost by 50% which could deliver the ability to compete with SMR when combined with wind/solar off peak power optimisation.

TRANSPORTATION PATHWAYS TO HYDROGEN EXPORT

Transport From Edmonton to the West Coast

- Hydrogen Gas Pipeline
  - Used the Northern Gateway 1,150 km Right of Way as a proxy to deliver Hydrogen Gas to Kitimat.
- NH_3 by rail requires slightly pressurized tanks like NGLs. CN Rail tariff to Prince Rupert used as a proxy with cost assumed at USD$0.09/tonne-mile for NH_3.
- MCH by rail can be shipped simply in crude oil tanks. CN Rail tariff to Prince Rupert used as a proxy with cost assumed at USD$0.10/tonne-mile for MCH.
  - CN Rail to Prince Rupert (1,460) or Lower Mainland (1,100 Km)
  - CP Rail to Lower Mainland (1,300 Km)
- Government of Canada mandates minimum liability insurance coverage under *Safe and Accountable Rail Act*.
  - USD$192M for 100,000 – < 1.5 million tonnes of oil per year
  - USD$0.77B for >= 1.5 million tonnes of oil per year
- Act creates a supplementary shipper-financed fund to be used in the event of accident. Shippers would have to pay > USD$1.35 per tonne of crude oil. In addition, the railway may increase service fees in case of high insurance premiums.

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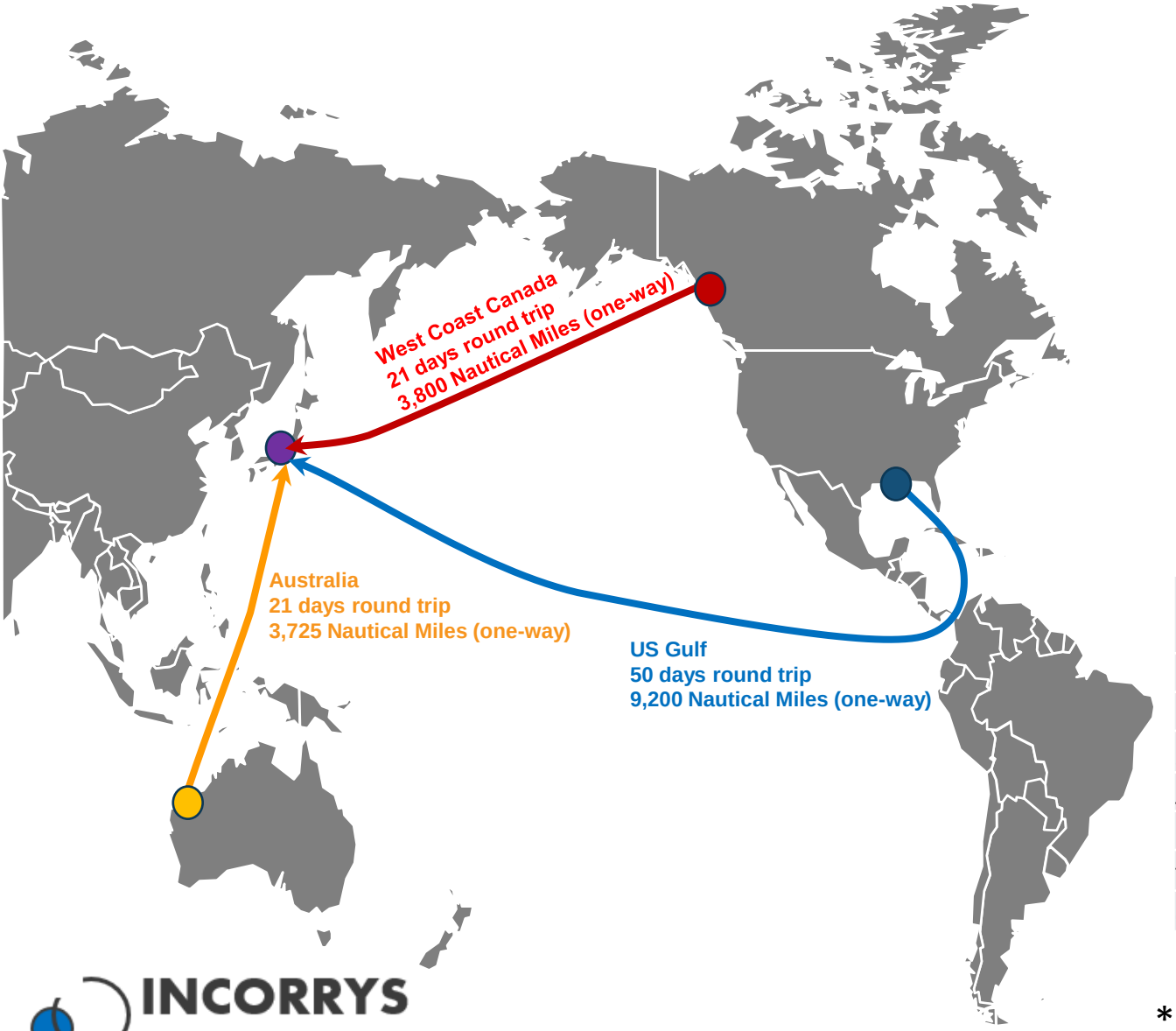
MARINE TRANSPORTATION COMPETITIVENESS TO ASIA



- Generally, cost of marine transportation is a function of shipping distance and vessel capacity.
- Hydrogen content of liquid hydrogen (100%), ammonia (18%), and MHC (6%*) also impacts cost per kg of H2.
- Shipping from the West Coast of Canada or Australia would be similar.
- US Gulf costs for MCH, NH_3, and H2 would be more than double Canada/Australia costs.

Marine Transport Assumptions

	MCH (Oil Tanker)	NH_3 (LPG Tanker)	H2 (LNG Tanker)
Port Charge USD$	$ 153,846	$ 153,846	$ 153,846
Day Rate USD$/d	$ 25,000	$ 60,000	$ 100,000
Ship Capacity, kg	100,000,000	45,500,000	63,000,000
Japan-Canada Cycle, days	21	21	21
Cost per kg per day	$ 0.01	$ 0.03	$ 0.04
Tonnes/d product output per 380 Tonnes/d H2	6,250	2,115	380
Cost per kg per day H2	**$ 0.14**	**$ 0.19**	**$ 0.04**

* MCH %H content less Toluene %H content = 6.1%

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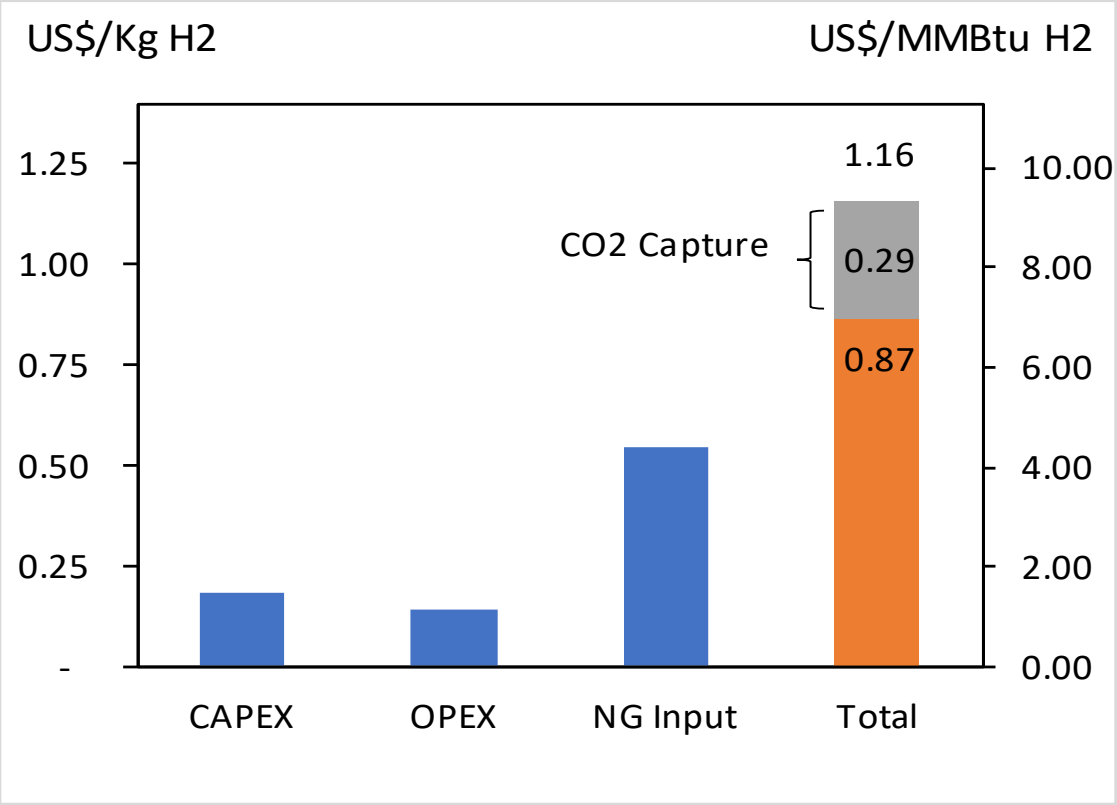
HYDROGEN STEAM METHANE REFORMING



- Blue hydrogen is created when using natural gas via steam methane reforming (SMR), results in carbon emissions as hydrogen is released from CH4 molecules, is combined with carbon capture and storage.
- Modeling Parameters:
  - 380 Tonnes H2/day plant output or 47.3 MMcf H2/d
  - 62 MMcf/d natural gas input @ USD$3.00/Mcf
  - CAPEX USD$170 MM
  - 90% load factor
  - 35:65 Equity to Debt
  - 15% Equity return
  - 7% Debt cost
  - USD$100/tonne CO_2 value

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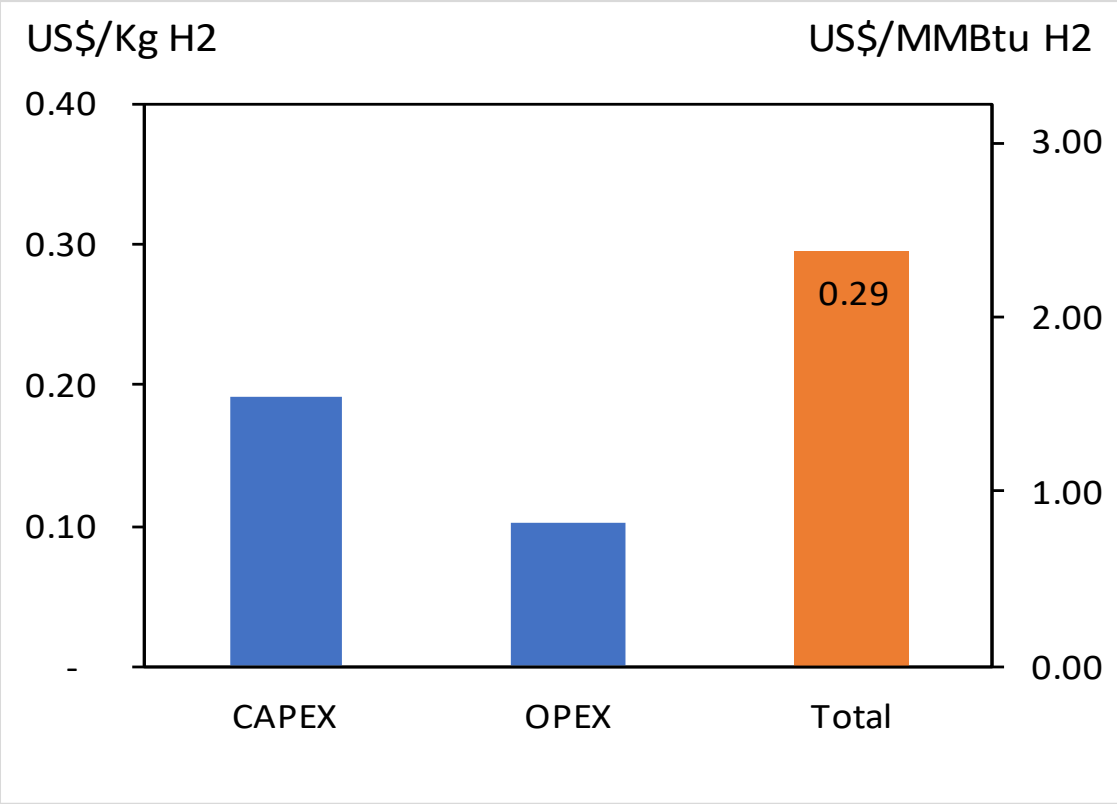
CARBON CAPTURE AND STORAGE



- Carbon Capture and Storage (CCS) the process of capturing and storing carbon dioxide from industrial processes thereby preventing released into the atmosphere.
- Modeling Parameters:
  - 380 Tonnes H2/day plant output or 47.3 MMcf H2/d
  - 916 Tonnes/d CO2 Output
  - CAPEX USD$180 MM
  - 90% load factor
  - 35:65 Equity to Debt
  - 15% Equity return
  - 7% Debt cost
  - USD$120/tonne CO_2

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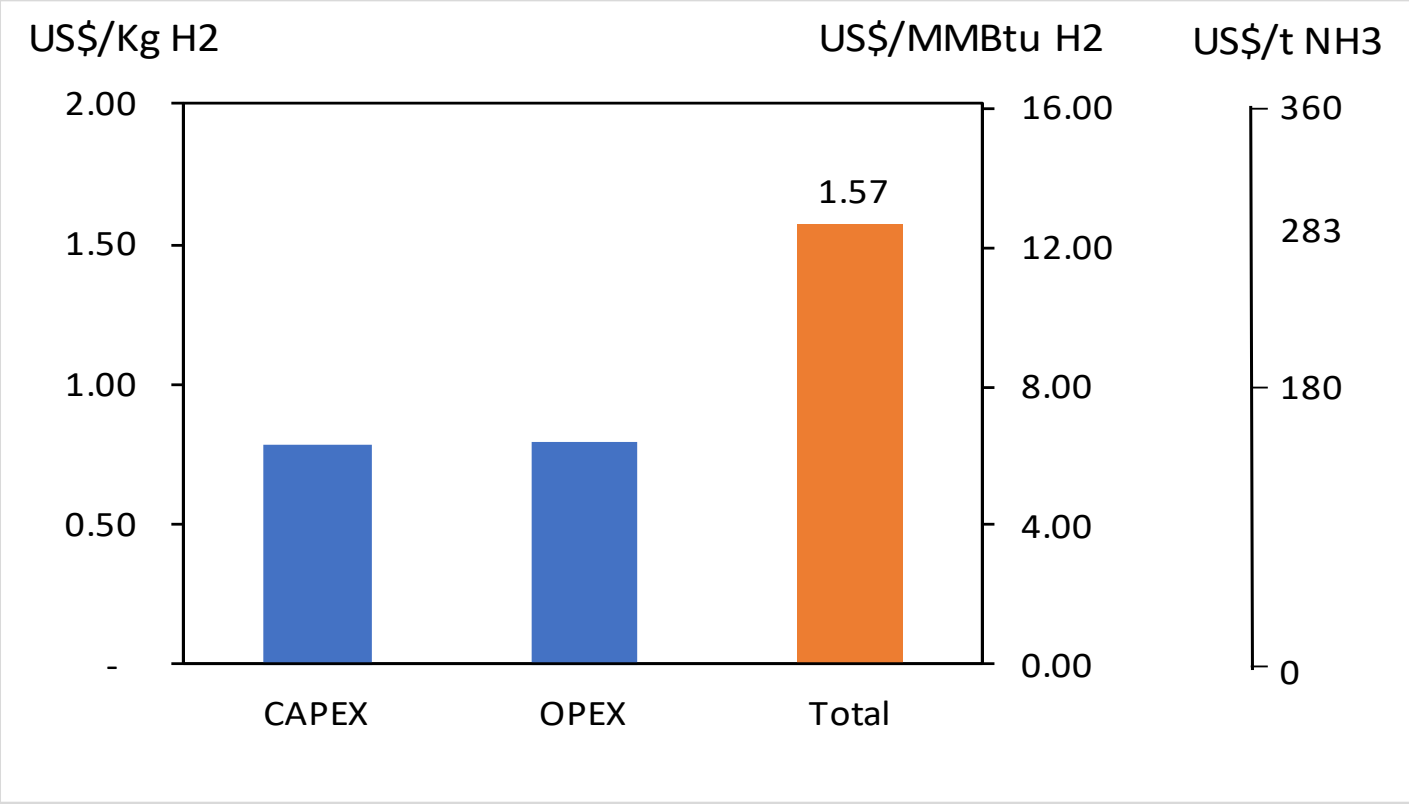
LOW CARBON AMMONIA PLANT



- Low Carbon Ammonia utilises blue hydrogen to create NH3, which than can be used in fertilizer production, as a hydrogen carrier, or directly as fuel.
- Modeling Parameters:
  - 380 Tonne H2/day plant input
  - 2,115 Tonnes/d NH_3 output
  - CAPEX USD$740 MM
  - 90% load factor
  - 35:65 Equity to Debt
  - 15% Equity return
  - 7% Debt cost
  - Cost of USD$283/Tonne NH_3

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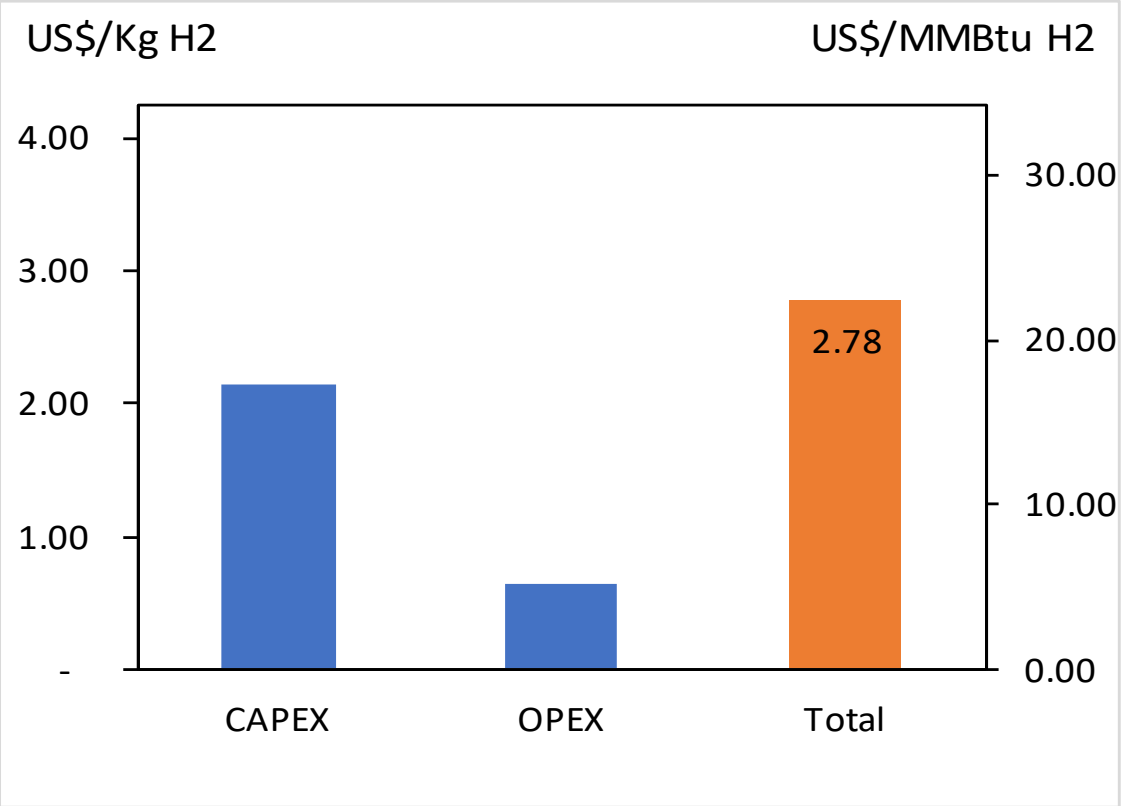
HYDROGEN PIPELINE



- 380 Tonne H2/day pipeline input
- 1,150 km, 16 inch pipeline
- CAPEX USD$2,020 MM
- 90% load factor
- 35:65 Equity to Debt
- 15% Equity return
- 7% Debt cost
- Natural Gas Compression

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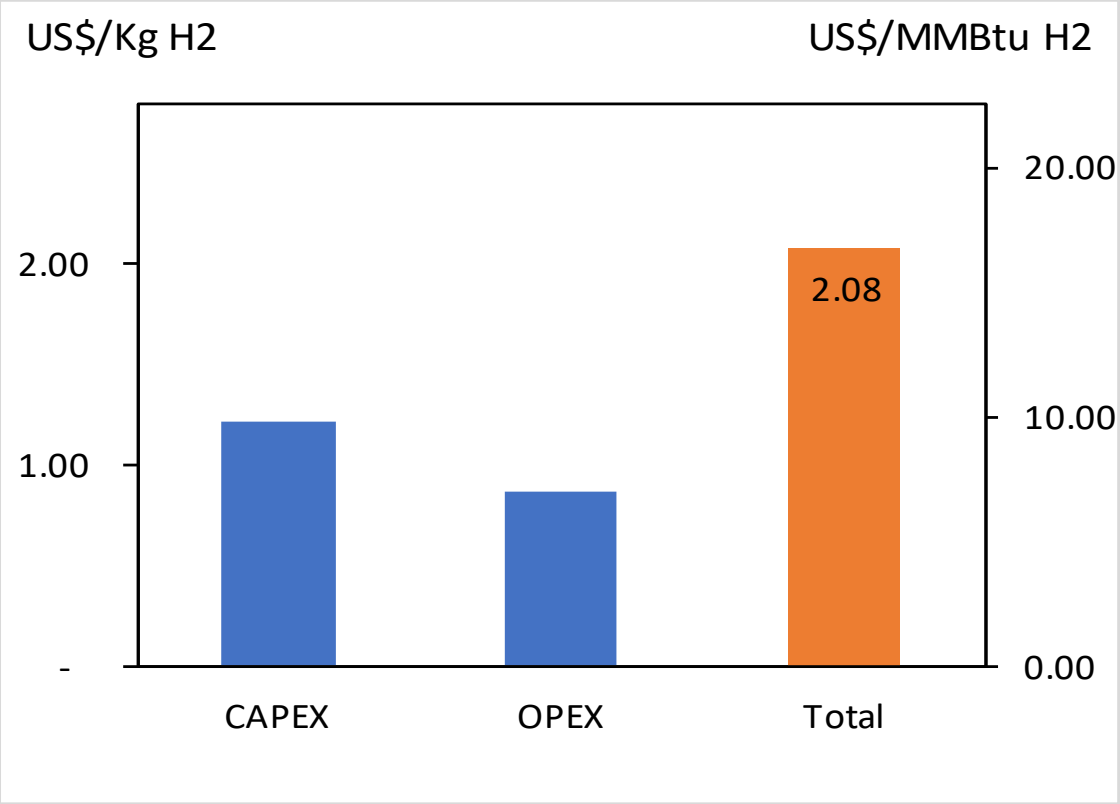
HYDROGEN LIQUEFACTION



- 380 Tonne H2/day pipeline input
- 1,150 km, 16 inch pipeline
- CAPEX USD$1,150 MM
- 90% load factor
- 35:65 Equity to Debt
- 15% Equity return
- 7% Debt cost
- Natural gas used for plant power.

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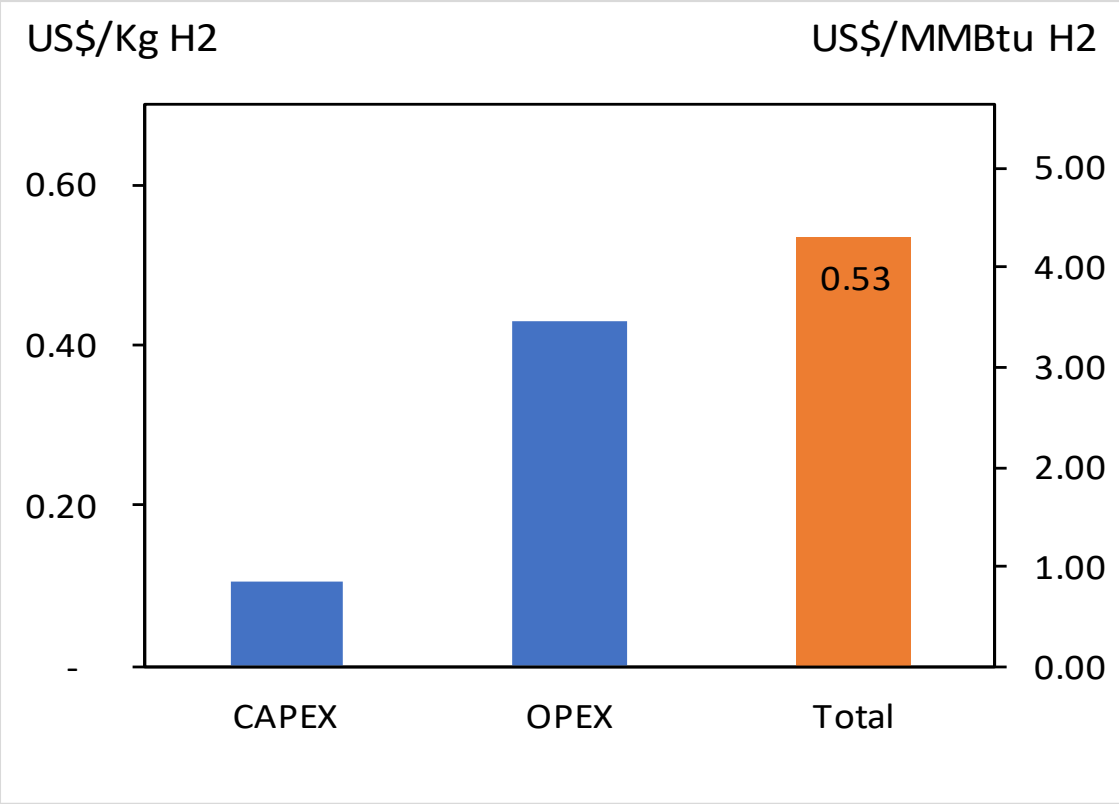
METHYLCYCLOHEXANE-TOLUENE HYDROGENATION



- Toluene Hydrogenation creates Methylcyclohexane (MCH). MCH can then be shipped similar to NGLs to where it will undergo a dehydrogenation process resulting in hydrogen and Toluene – MCH is sometimes referred to as a hydrogen carrier.
- Modeling Parameters:
  - 380 Tonne H2/day input
  - 6,250 Tonnes/d MCH output
  - CAPEX USD$100 MM
  - 90% load factor
  - 35:65 Equity to Debt
  - 15% Equity return
  - 7% Debt cost
  - Toluene USD$0.57/kg and 2.5% losses

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CONCLUSIONS

- Hydrogen provides clean burning scope 3 emissions. Large scale adoption of hydrogen in transportation and power would result in increased natural gas demand.
- Approximately 25% of Energy is lost through the SMR conversion of natural gas to hydrogen. A US$3.00/MMBtu natural gas price results in a US$10.50/MMBtu Hydrogen breakeven equivalent at the SMR/CCS plant gate.
- Potential for blue hydrogen to utilize current natural gas infrastructure and sold as renewable natural gas.
- Blending hydrogen with natural gas in pipelines is likely safe below 10% however, due to lower density will reduce pipeline energy delivery capability.
    - Therefore, blue hydrogen may be complementary to natural gas demand at lower carbon emissions – wide scale replacement would cause sizable price inflation to natural gas consumers.
- Exporting blue hydrogen large distances in commercial quantities will be difficult to compete with LNG in the near term.

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ASSUMPTIONS

Average Heating Value for Natural gas and Hydrogen and conversions for $/kg to $/MMBtu rely on the simple average calculated from Hydrogen Tools DOE website (https://h2tools.org/hyarc/hydrogen-data/lower-and-higher-heating-values-hydrogen-and-other-fuels).

	Average Heating Value			
	Btu/ft3	Btu/lb	MJ/kg	Btu/kg
Natural gas	1,036	21,360	50	46,992
Hydrogen	317	56,405	131	124,090

Exchange Rate has been assumed to be US$1.00 per Cdn$1.30

Rail Cost Based on CN Rail instantaneous price tool: https://www.cn.ca/en/customer-centre/tools/carload-shipping-tools/

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