Carbon Neutral LNG: A Case Study for a New Baseload Export Facility Using Green Hydrogen and CO_2 from Direct Air Capture

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Agenda

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   - Green Hydrogen
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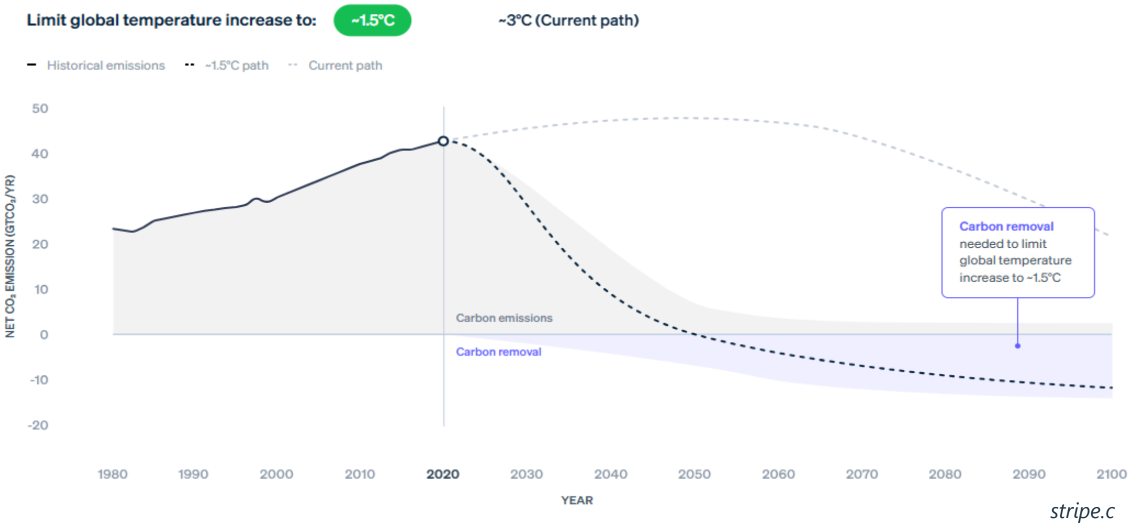
Introduction

Overview

- Carbon removal is essential to limit global temperature rise to 1.5°C
- Direct air capture will play a role in a truly circular carbon economy
- Carbon neutral LNG could be utilized in existing infrastructure
(shipping and gas pipeline systems)
- Case: One million ton per annum (1 MTPA) carbon neutral synthetic LNG:
  - CO_2 from Direct Air Capture
  - Green Hydrogen
(from electrolysis using renewable power)
  - Methanation (Sabatier reaction)



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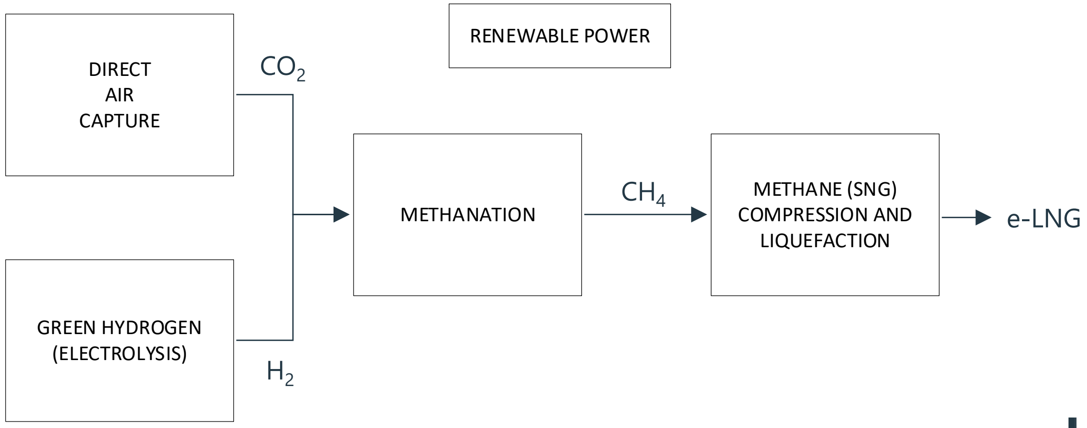

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Technology Overview

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Direct Air Capture (DAC)

Why capture CO_2 from the air (~420 ppm)?

- Solution for legacy emissions
- Balance hard to avoid emissions

Current deployment state:

- >30 plants around the world, total ~60 kta
- Capacity of plants increasing:
  - Climeworks Mammoth (2024): 36 kta
  - Carbon Engineering Stratos (under construction): 500 kta

Wide range of reported cost estimates:

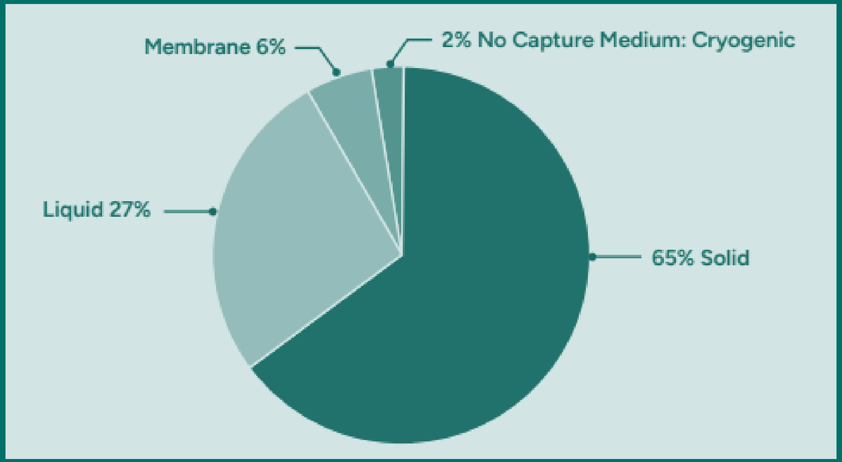
- Current estimates: $300 – $1,000/tonne
- Future projections: $90 – $230/tonne

Current IRA Credits:

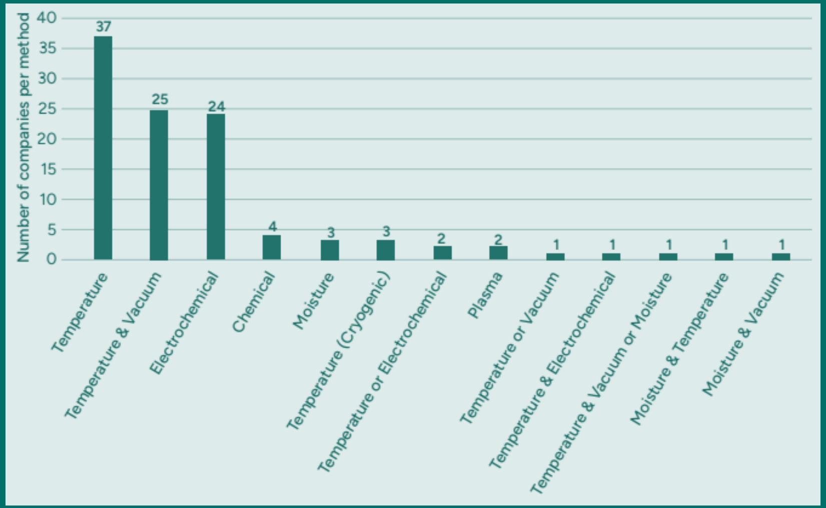
- DAC + Sequestration: $180/tonne
- DAC + Utilization: $135/tonne

DAC Approaches

Capture Media



Regeneration Approach



energy.gov

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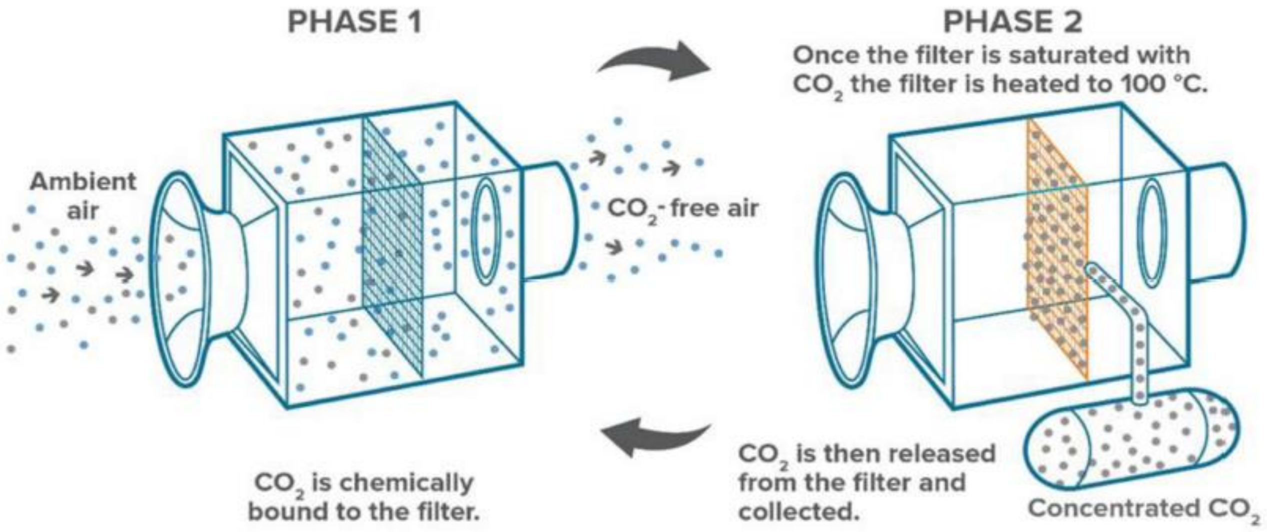
DAC Approach: Solid Adsorbents

- Adsorbents: zeolites, silica-based, activated carbon, MOFs, etc.
- Adsorption at ambient conditions
- Regeneration at higher temperature, > 80 °C (use steam, residual heat, electricity)
- Many companies: different adsorbents and approaches for regeneration
- Modular deployment
- Main utilities, representative values:
  - Power: 150 – 300 kWh/ton CO_2
  - Heat: 1000 – 2000 kWh/ton CO_2
  - Cooling (air/water)

Solid adsorbents chosen as representative of DAC due to its current and expected deployment



Climeworks.com

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Green Hydrogen

H_2 produced from water electrolysis using Renewable Power (from Solar, Wind, Hydroelectric):

Water is split into hydrogen and oxygen using an electric current.

- Water undergoes a reaction at the electrodes
- Hydrogen is collected at the Cathode
- Oxygen is released from the Anode

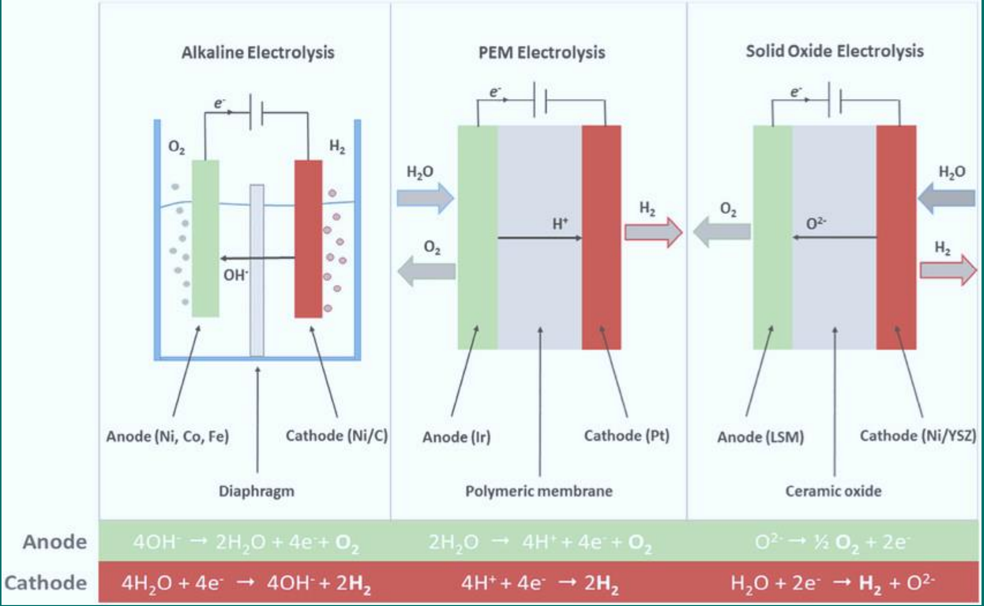
Water Electrolysis Reaction

$$2H_2O \rightarrow 2H_2 + O_2$$

Range of reported cost estimates:

- Current estimates: \$4-7/kg H_2
- Future projections: \$1-3/kg H_2

Current IRA Credits: up to \$3 /kg H_2



Types of Electrolyzers:

- **Alkaline Electrolyzers**
- **Proton Exchange Membrane (PEM) Electrolyzers**
- **Solid Oxide Electrolyzers**

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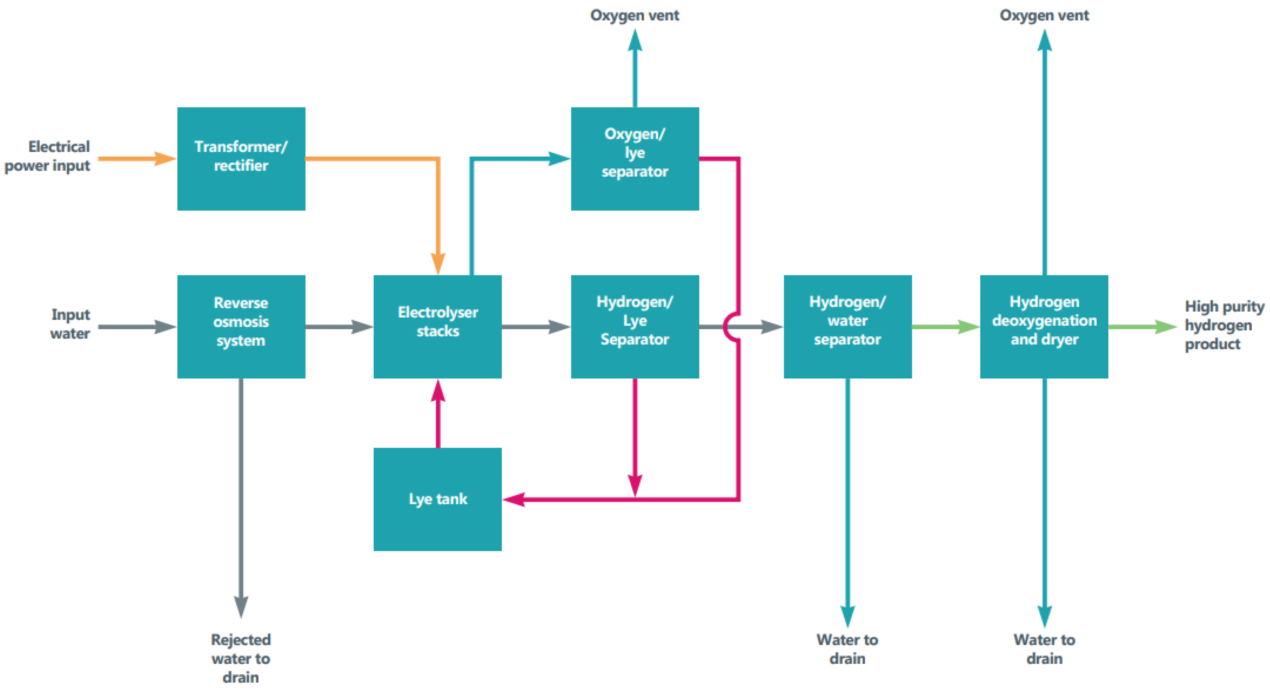
Green Hydrogen: Alkaline Water Electrolizers (AWE)

AWE chosen due to technology maturity and lower cost

- Efficiency: ~50 -55 kWh/kg H_2
- Modular deployment
- Main utilities, representative values:
  - Power: 50 -55 kWh/kg H_2
  - Water: ~11 kg water/kg H_2 (9 lts is the stoichiometric ratio)
  - Cooling: ~20% of power consumed needs to be removed as heat



Simplified AWE Block Flow Diagram

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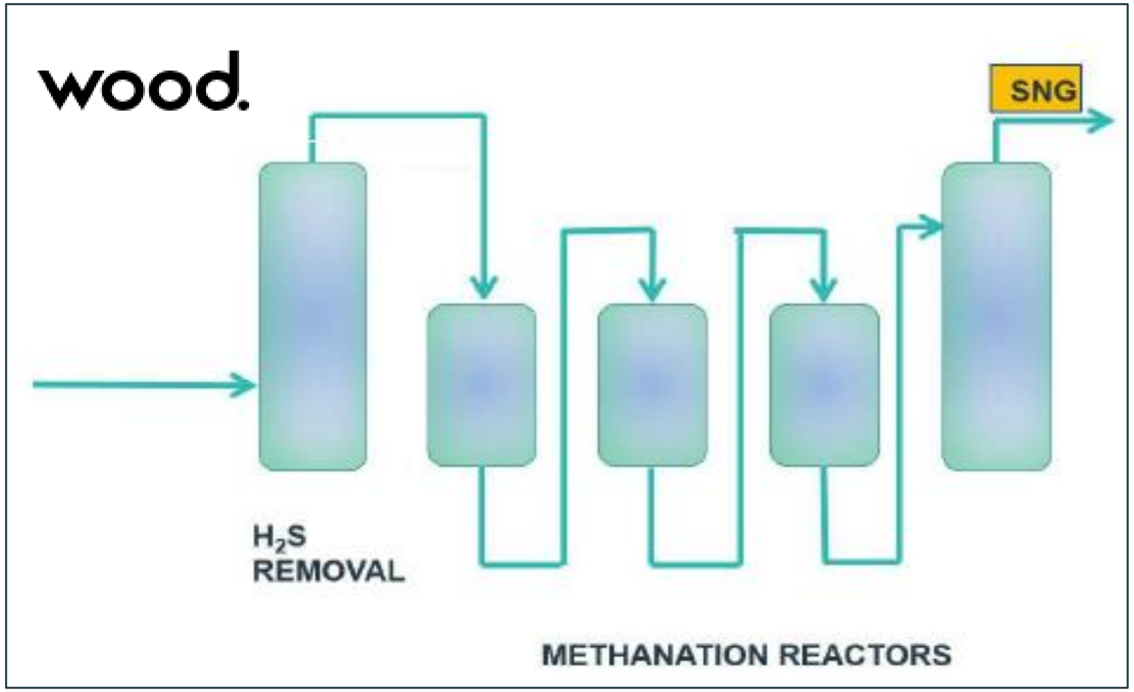
Methanation

$$CO_2 + 4H_2 \rightleftharpoons CH_4 + 2H_2O$$

- Methanation from CO_2 is based on process used for biomass or coal, but it is simpler (no gasification, cleaner gas, less steps)
- Highly exothermic
- Heat removal is critical in design
- Multiple stages (catalyst beds) typically used to reach high conversions (>99% possible)
- Multiple licensors



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Wood Vesta Methanation Diagram

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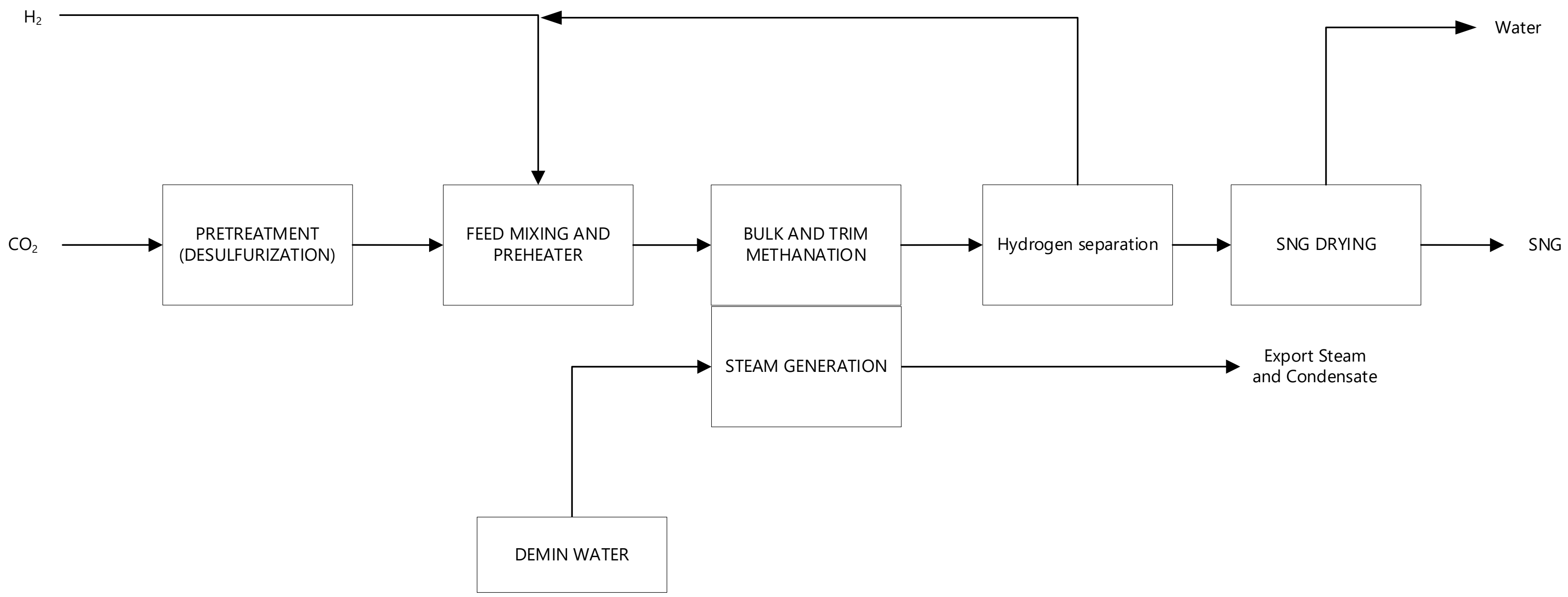
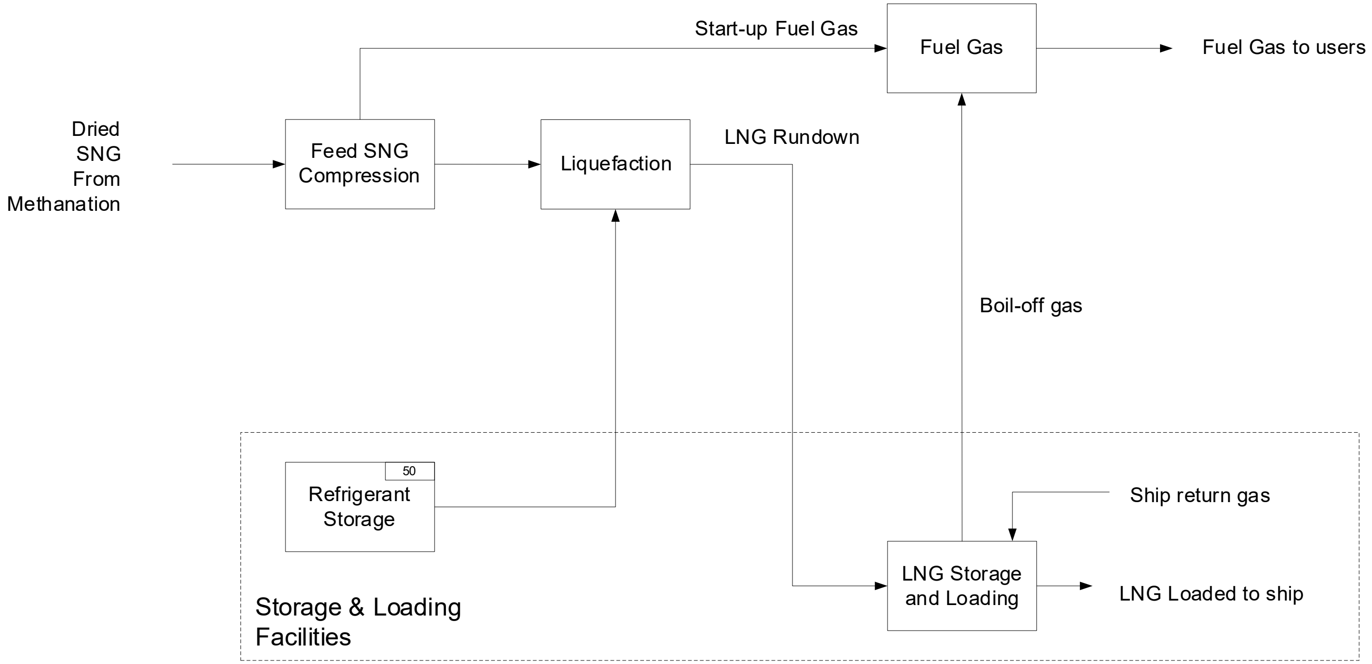
Methanation: Process

- Product > 98% CH_4
- Balance is mostly CO_2 and H_2 (will also have impurities from H_2 or CO_2 feed)
- Reaction water produced
- Excess hydrogen recovered and recycled
- Utilities:
  - Power
  - Demin water for steam generation
  - Cooling water



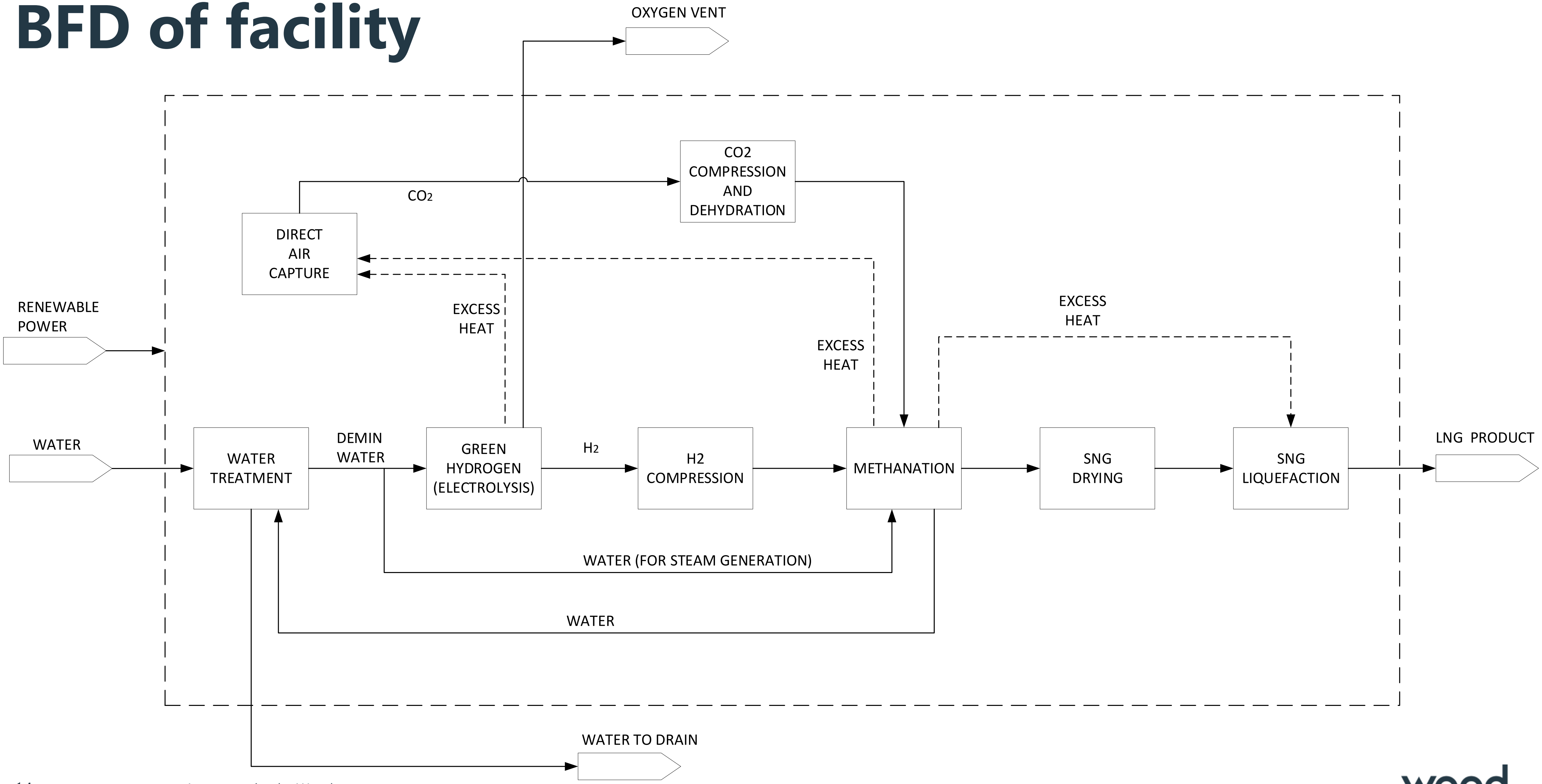
LNG Plant Overview

- Single Mixed Refrigerant (SMR)
- Simplification: feed is SNG, already pre-treated
- <50ppm mol CO_2 assumed in SNG feed
- <1 ppm mol H_2O assumed (already dried)
- No requirement for gas pre-treatment units or heavy hydrocarbon removal
- Assumes refrigerant is imported
- SNG boosted in pressure >70 barg for liquefaction efficiency
- LNG flashed in storage
- 1x LNG storage tank 150,000 m^3
- Electric drive refrigerant compressors with minimal fuel usage
- Terminal and storage included



Facility Design

BFD of facility



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Unit Capacities

	Ton/yr	kmol/yr
CH_4 (from methanation)	1,000,000	62,344,140
H_2 (from electrolyzers)	517,825	256,857,855
CO_2 (from DAC)	2,826,079	64,214,464

Note: 3% excess in H_2 and CO_2 to cover inefficiencies/losses

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Utilities Requirements

	DAC	Green H_2 (electrolysis)	Methanation	LNG	Total (Net)
Capacity (MTPA)	2.83	0.52	1.00	1.00	------
Power (MWh)	636,000	28,435,000	409,000	367,000	29,847,000
Heat Requirement (MWh)	4,381,000	------	------	92,000	4,473,000
Excess Heat (MWh)	------	6,325,000	4,303,000	------	10,628,000
Process water (tons)	------	5,780,000	(2,247,000) (produced)	------	3,533,000

Integration Opportunities

Heat

- Excess heat, conditions:
  - Electrolyzers: 6,325 GWh at 60-80 °C
  - Methanation: 4,303 GWh can be recovered as a mix of HP and LP steam
- Heat users, requirements:
  - DAC: 4,381 GWh at ~80–100 °C
  - LNG: 92 GWh ~half at 160 °C and half at 300 °C
- Summary:
  - Heat requirements from DAC and LNG can be fully satisfied by heat integration
  - Assumed: ~45% of electrolyzers' excess heat can be used in DAC together with ~35% of (higher grade) excess heat from methanation to supplement DAC requirements.
  - LNG heat requirements can be satisfied with excess heat from methanation

Water:

- Water produced in the methanation reaction can be recovered and used to feed the electrolyzers, thus lowering the net water demand

Power – Commentary

- Renewable power production can be on or off site
- It was assumed that renewable electrical power is available 24 h (via PPA)
  - Accounting for renewable variability by adding batteries and/or large storage of H_2 would have a large impact on project cost
- For the cost estimate, power was accounted as an Opex

- If the renewable power assets were to be included in the project:
  - Expected Capacity required: 12,000 - 14,000 MW

  (This assumes a 25% capacity factor)
- Land area required, if all solar: Aprox 350 km^2

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Cost Overview

High level Cost: CAPEX and OPEX

	DAC	Green H_2 (electrolysis)	Methanation	LNG	Total Capex ($MM)
Capex (TIC) ($MM)	2,000	6,860	500	950	**10,310**

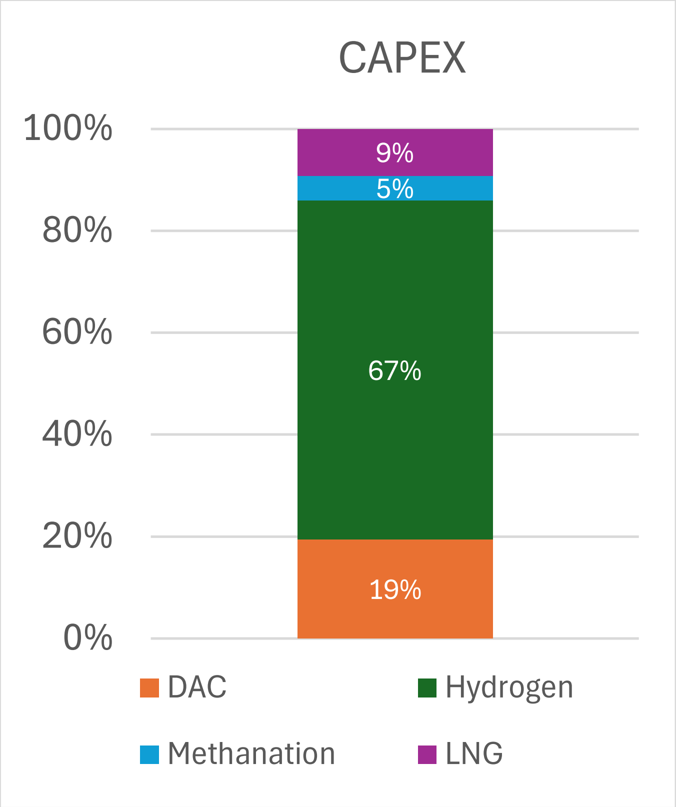
Opex	DAC	Green H_2 (electrolysis)	Methanation	LNG	Total (net)	Cost per Unit	Yearly Opex ($MM/pa)
Power (MWh)	636,000	28,435,000	409,000	367,000	29,847,000	35	1,045
Heat Requirement (MWh)	4,381,000	------	------	92,000	4,473,000	------	------
Excess Heat (MWh)	------	6,325,000	4,303,000	------	10,628,000	------	------
Process water (tons)	------	5,780,000	(2,247,000)	------	3,533,000	30	106
Maintenance and other fixed Opex ($MM)	70	340	20	30	460	------	460
Total							**1,611**

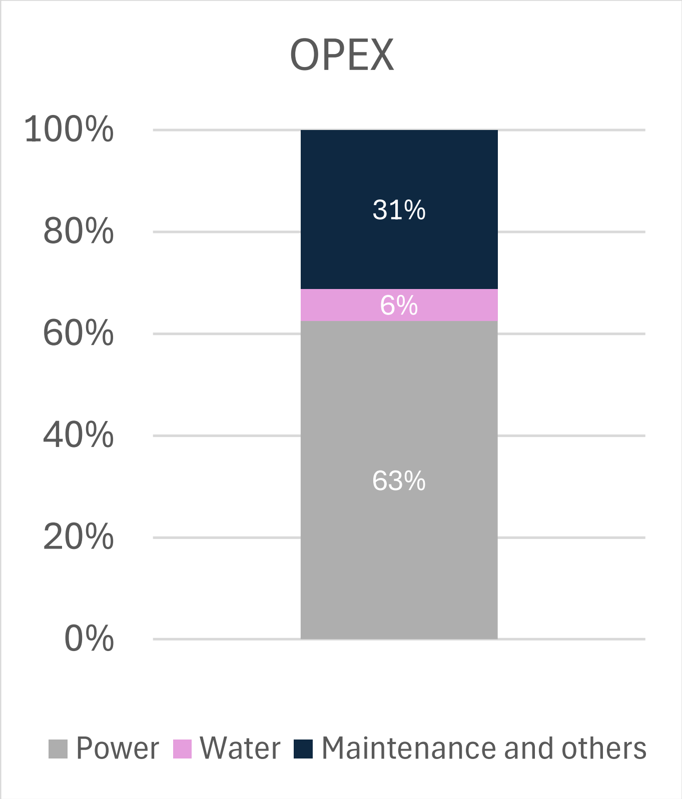
Cost estimated from public data from multiple sources

Cost Summary

	$/ton SNG	$/ MMBTU SNG
Levelized cost (*), without tax credits	2,882	54.7
Levelized cost (*) with tax credits (**) for Green H2 and DAC	947	18.0

(*) 20 years plant life. 10% Capital recovery rate.
(**) Assumed tax credits for life of plant: 3$ /kg H_2 and 135 $/ton DAC CO_2





- Cost, without tax credits, considerably higher than LNG (fossil fuel based) market price (~$12-14/MMBtu to East Asia)
- Largest contributors (higher sensitivity):
  - Capex: Hydrogen production
  - Opex: Power
- Feasible with tax credits attracting a premium price for LNG being truly carbon-neutral

Wrap-Up

Conclusions

- 1 MTPA LNG plant design using DAC, green hydrogen and renewable power would have near-zero on-site emissions and be able to provide LNG for existing infrastructure
- Levelized cost calculated at ~55 $/MMBTU
- Significant impact on cost from tax credits, possibly lowering the levelized cost to ~18 $/MMBTU
- Power generation and hydrogen production were identified as the largest cost contributors
- Great potential in the future as the cost of production of green hydrogen reduces
- A viable solution to a true circular carbon economy

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Q&A and discussion