Blue Front Solutions: Decarbonized Ammonia Production

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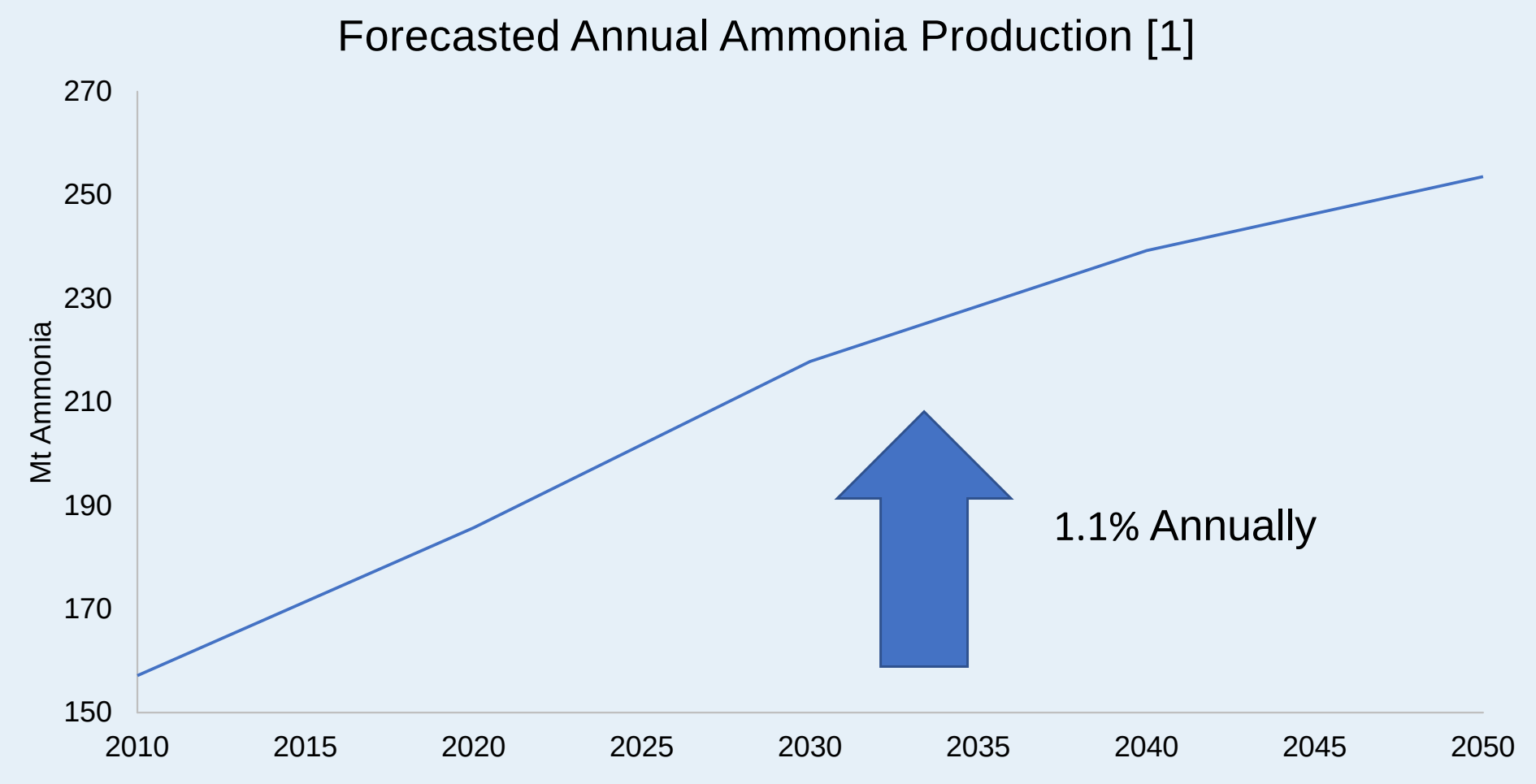
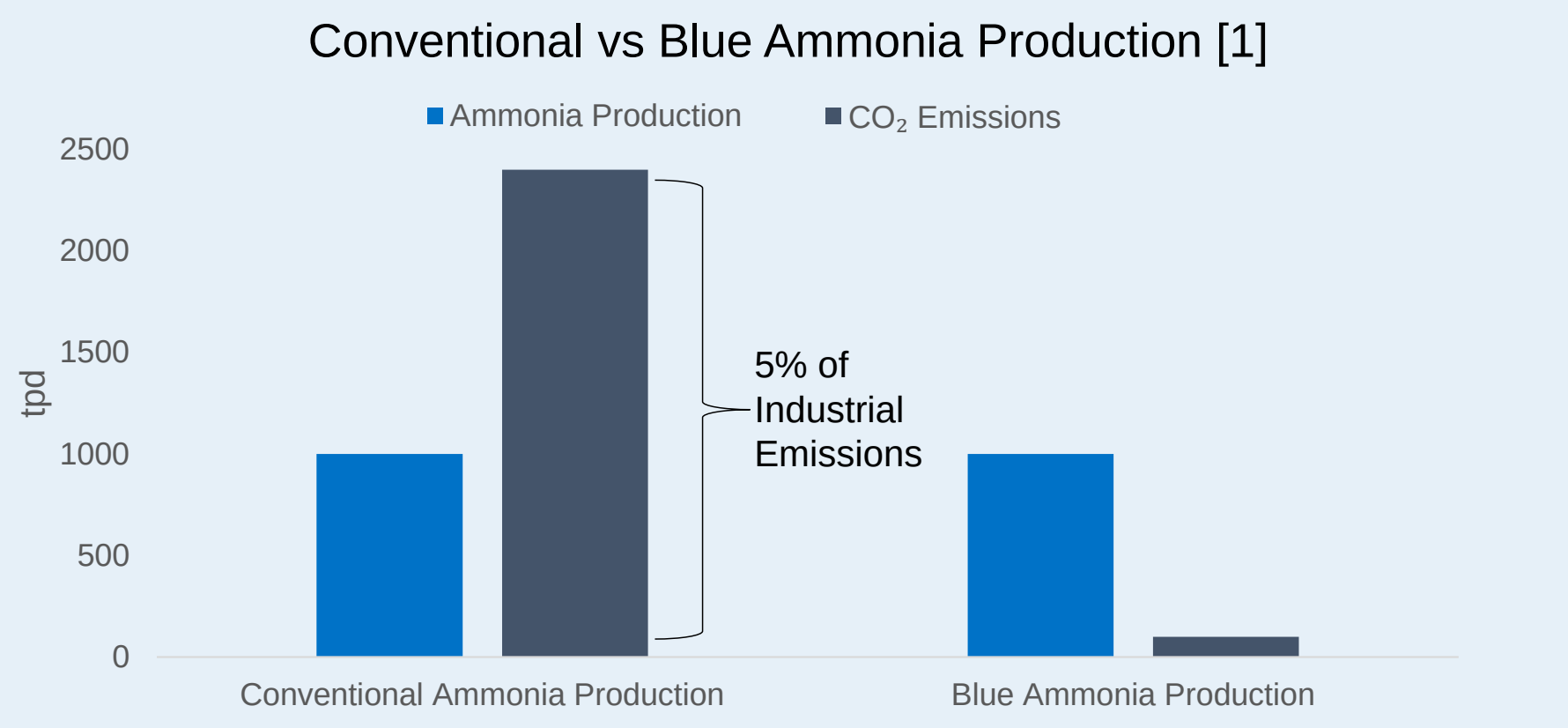
Project Drivers





- Canada Net-Zero by 2050 Goal
- $50 / tonne Alberta Carbon Tax

Goal

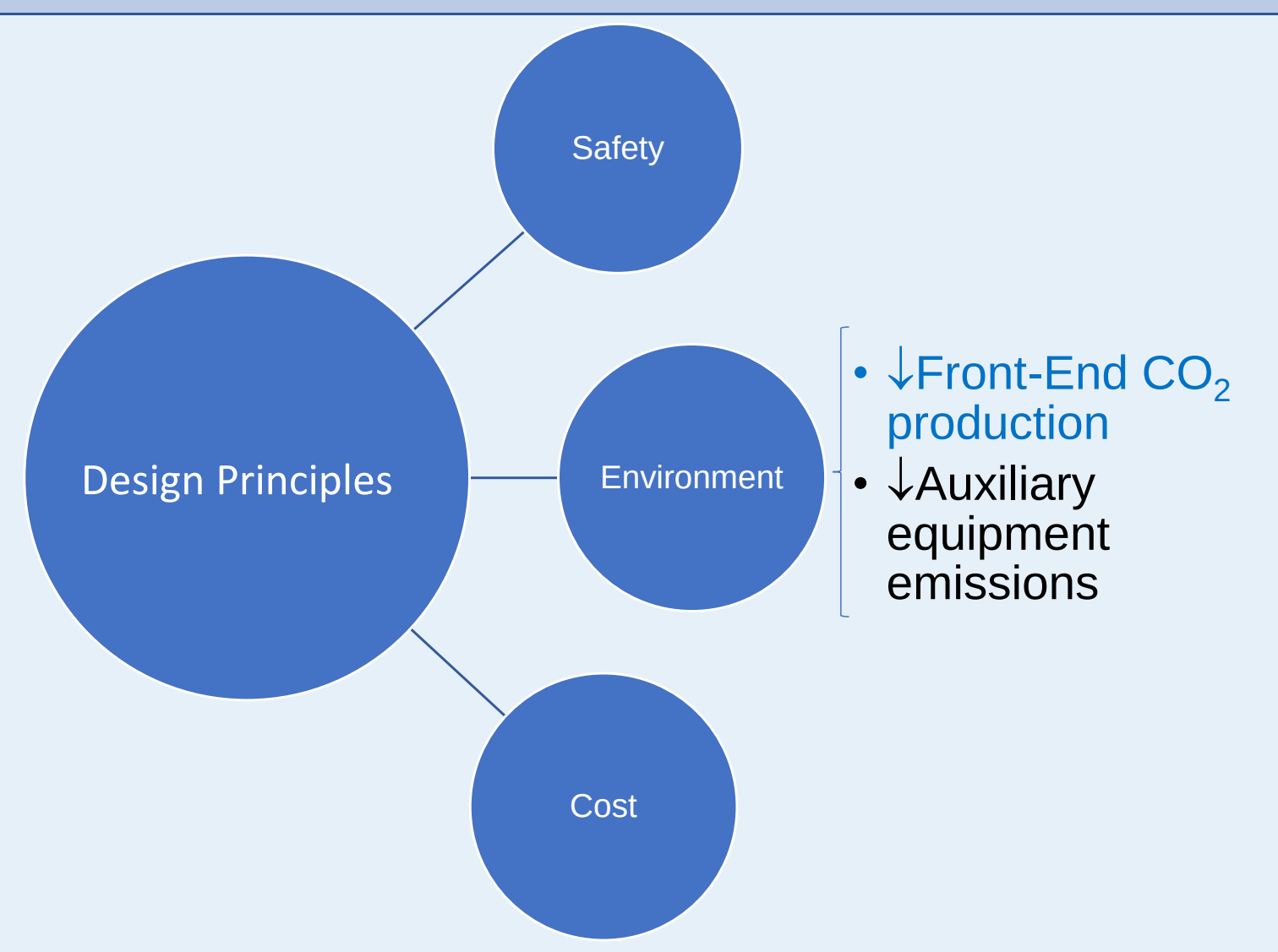
- Natural Gas →1,000 tpd NH_3
- 2.4 kg CO_2/kg NH_3 → 0.1 kg CO_2/kg of NH_3

KT Analysis

		Process					
Criteria	Weight	HTS (ASU/POx ATR)		KBR (SMR/ air fired ATR)		ASU/ATR with full Oxidation	
		Score	Justification	Score	Justification	Score	Justification
CO_2 Capture	10	3	• 91 % with single point • ↓ on-site emissions by 93% • ↑ electricity and upstream emissions 26%	2	• 85% with 2 capture points • ↓ on-site emissions by 78% • ↑electricity and upstream emissions by 115%	2	• Similar to KBR
Energy Usage	7	3	• Adiabatic • ASU ↑ electricity requirements by 62%	1	• 2nd CC unit ↑ electricity requirements by 70% • ATR ↓ heating requirements for SMR	2	• Adiabatic • ASU ↑ electricity requirements • 2nd CC unit ↑ electricity requirements
*Capex/ Opex	8	3	• $798.72MM (198 $M ASU) • ↓ S/C = ↓utility cost • CC ↑ H_2 cost by $0.43/kg H2.	2	• $889MM ($155MM 2nd CC) • ↑ S/C = ↑ utility cost (32%) • CC ↑ H_2 cost by $1.14/kg H_2.	1	• $953MM • Assumed higher than HTS and KBR

*Based on a capacity of 607 tpd, $1.96/GJ natural gas price, electricity assumed to be from Alberta's grid, 10% IRR [2]

Key Design Principles



- ↓Front-End CO_2 production
- ↓Auxiliary equipment emissions

Design and Performance

Pre-reforming Reactor

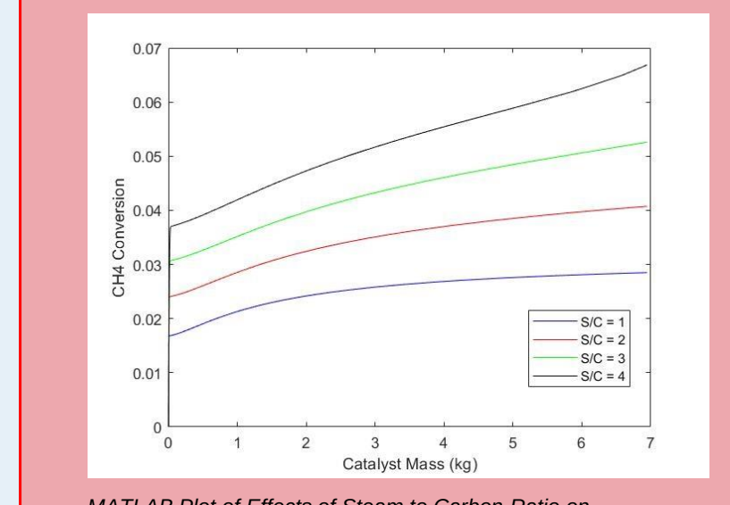
Adiabatic Packed Bed Reactor

Purpose:

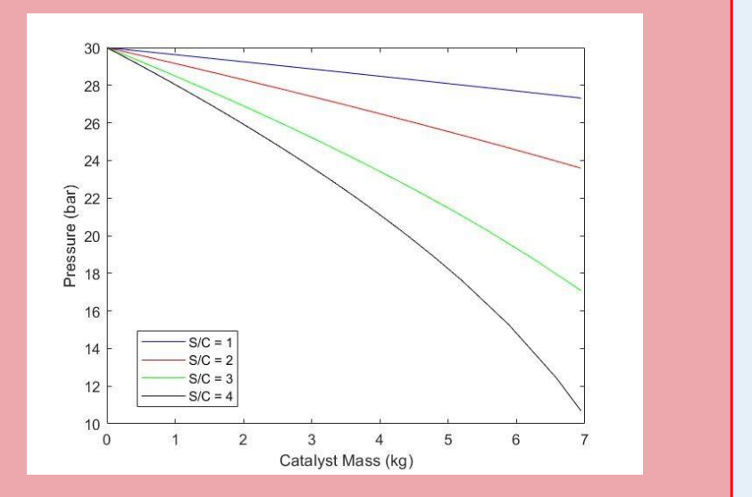
- Conversion of C2+ Alkanes in Natural Gas to CH_4
  - Prevents coke formation in catalyst
  - Normalizes Temperature and Pressure dependencies downstream

Reactions:

$$C_nH_m + mH_2O \rightarrow nCO + (n + \frac{m}{2})H_{2,}\ \Delta H > 0$$
$$CH_4 + H_2O \rightleftharpoons CO + 3H_2, \Delta H > 0$$
$$CO + H_2O \rightleftharpoons CO_2 + H_2, \Delta H < 0$$



MATLAB Plot of Effects of Steam to Carbon Ratio on Methane Conversion



MATLAB Plot of Effects of Steam to Carbon Ratio on Pressure Drop

Properties:

Inlet Temperature (°C)	480
Inlet Pressure (bar)	30 (based on Natural Gas specification)
Nominal Tube Diameter (m)	0.0508 (2”)
Tube Length	3 m
Number of Tubes	5,400
S/C	2
Ni/MgO Catalyst Mass/ tube (kg)	12

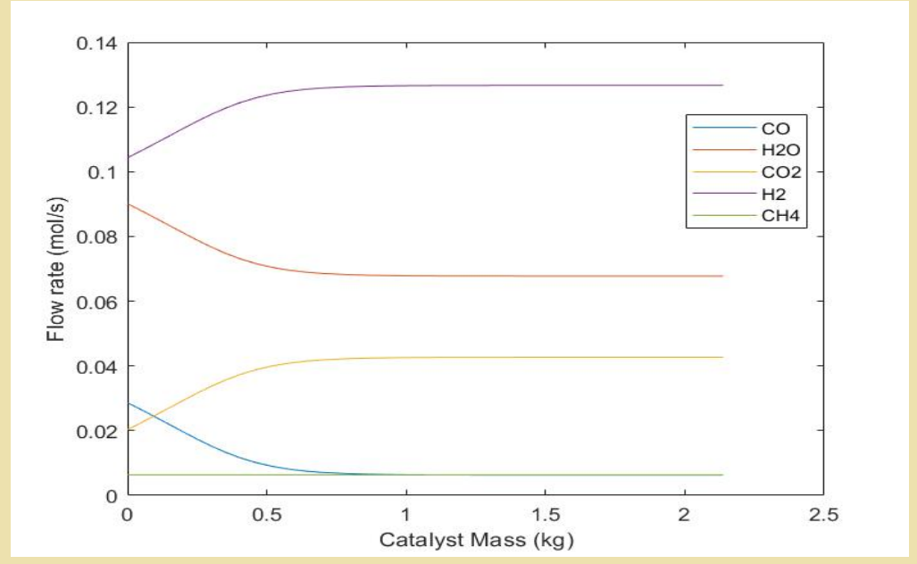
Water Gas Shift Reactors

2X Adiabatic Packed Bed Reactors (High Temperature & Low Temperature)

Purpose:

- Increasing the ratio of H_2 to CO

Reaction: $CO + H_2O \rightleftharpoons CO_2 + H_2, \Delta H < 0$



MATLAB Plot of Flow Profile in Water Gas Shift Reactor

Properties:

	HT - WGS	LT - WGS
Inlet Temperature (°C)	300	225
Inlet Pressure (bar)	25.84	22.95
Nominal Tube Diameter (m)	0.0254 (1”)	0.0508 (2”)
Tube Length	3 m	6 m
Number of Tubes	6000	6000
H_2O/CO	3	10.75
Catalyst Mass/ tube (kg)	3.8 (Fe_2O_3/Cr_2O_3)	27.3 (Cu/ZnO/Al_2O_3)

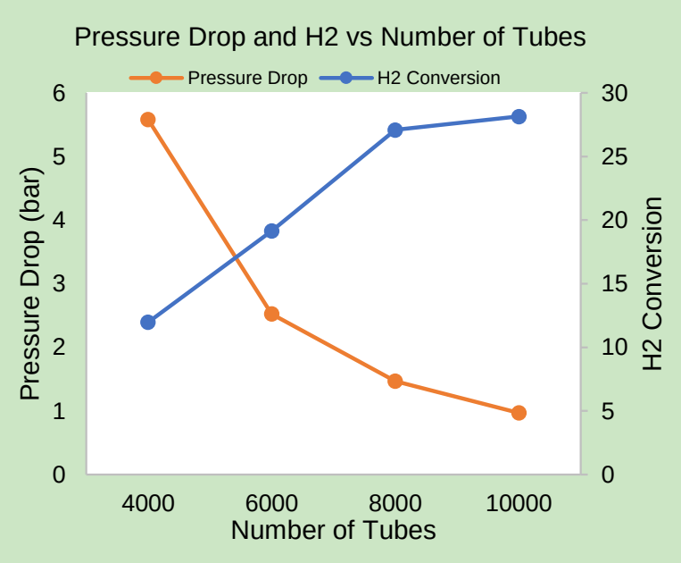
Ammonia Synthesis Reactor & Joule Thomson Valves

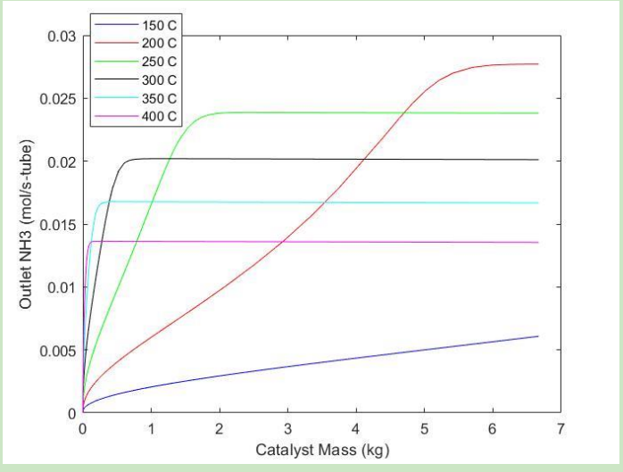
Adiabatic Packed Bed Reactor

Purpose:

- Combine H_2 from the front-end reactors and N_2 from the ASU to produce ammonia via the Haber-Bosch reaction

Reaction: $3H_2 + N_2 \rightleftharpoons 2NH_{3,}\ \Delta H < 0$





MATLAB Plot of Effects of Inlet Temperature for Ammonia Synthesis Reactor

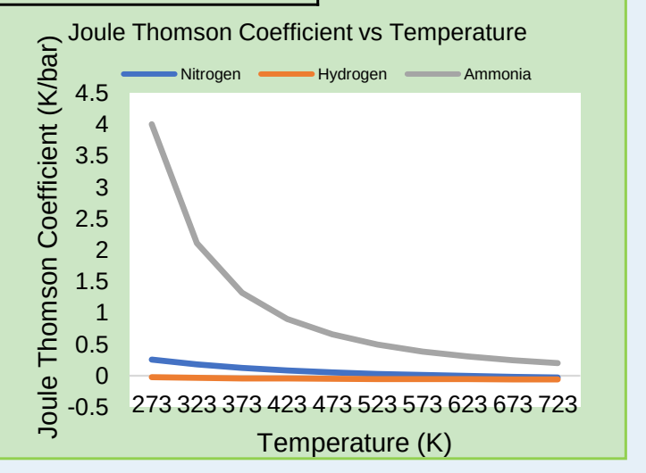
Properties:

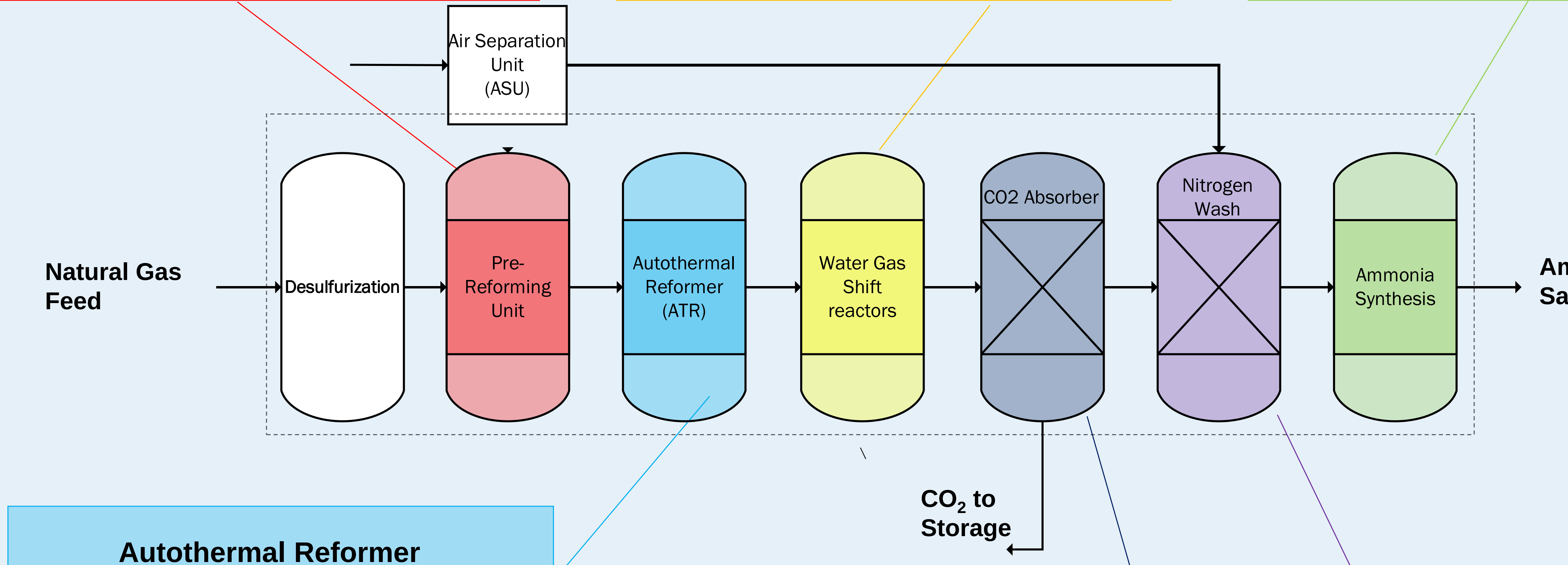
Inlet Temperature (°C)	200
Inlet Pressure (bar)	80
Nominal Tube Diameter (m)	0.01905 (3/4”)
Tube Length	12 m
Number of Tubes	10000
FeO/Al_2O_3 Catalyst Mass/ tube (kg)	6.8

Joule Thomson Valves

Purpose:

- Throttling valves to condense gaseous ammonia
- Eliminates the need for cryogenic cooling





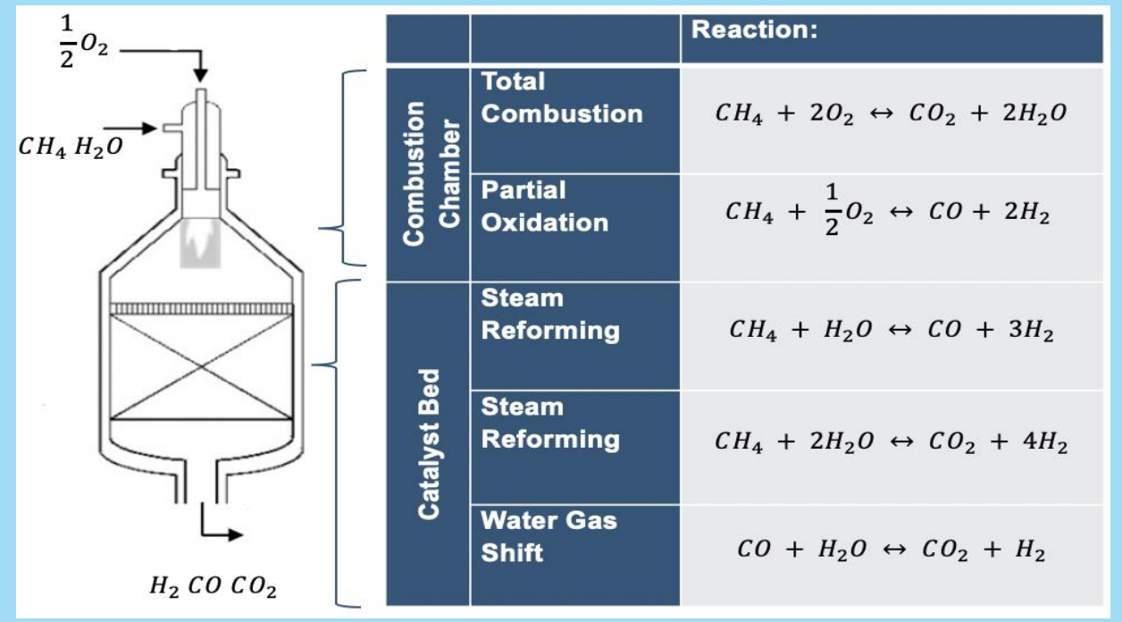
Autothermal Reformer

Adiabatic Packed Bed Reactor with upper combustion chamber

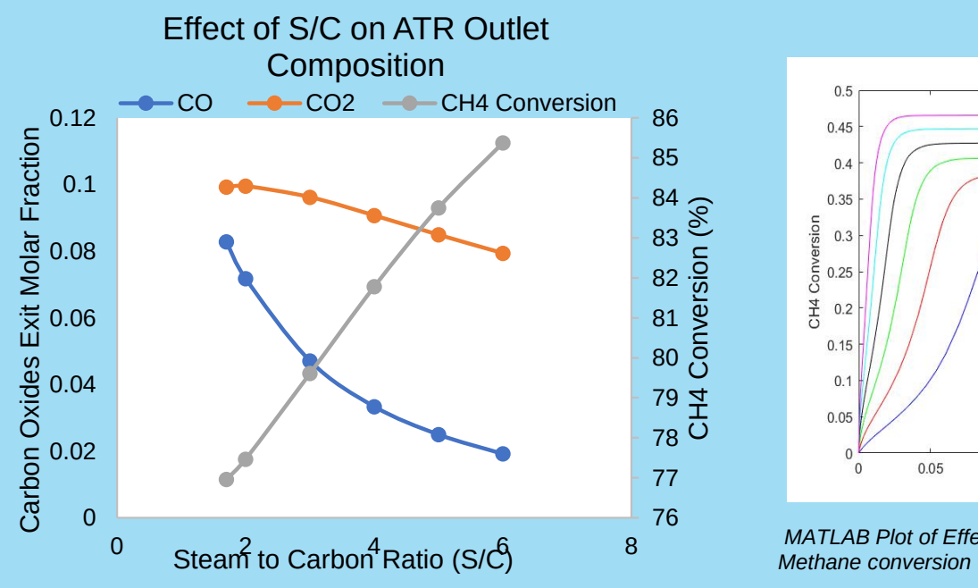
Purpose:

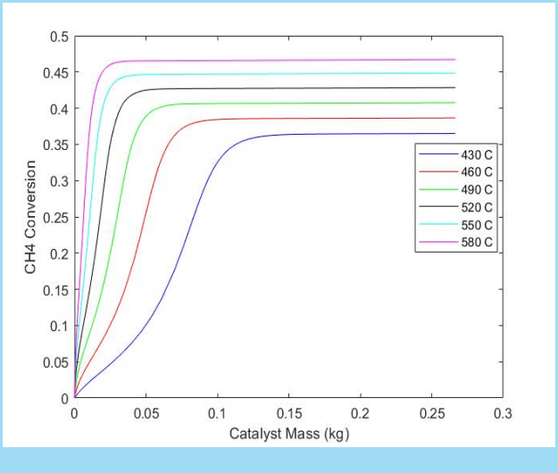
- Production of Synthesis gas (H_2/CO) from CH_4 using steam and oxygen
  - Partial Oxidation with sub-stoichiometric O_2 favors CO production over CO_2
  - Exothermic oxidation provides heat for endothermic reforming

Reactions:



		Reaction:
Combustion Chamber	Total Combustion	$CH_4 + 2O_2 \leftrightarrow CO_2 + 2H_2O$
	Partial Oxidation	$CH_4 + \frac{1}{2}O_2 \leftrightarrow CO + 2H_2$
Catalyst Bed	Steam Reforming	$CH_4 + H_2O \leftrightarrow CO + 3H_2$
	Steam Reforming	$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2$
	Water Gas Shift	$CO + H_2O \leftrightarrow CO_2 + H_2$





MATLAB Plot of Effects of varying inlet Temperature on Methane conversion

Properties:

Inlet Temperature (°C)	580
Inlet Pressure (bar)	29.66
Nominal Tube Diameter (m)	0.01905 (3/4”)
Tube Length	1 m
Number of Tubes	6000
S/C	1.7
O/C	1.1
Ni/Al_2/O_3 Catalyst Mass/tube (kg)	0.25

CO_2 Absorber & Stripper

Purpose:

- *Absorption Column:*
  - Remove CO_2 from process stream
- *Stripping Column:*
  - Regenerate MDEA solvent for re-use in absorption process
  - Captured CO_2 is sent to storage

Properties:

Absorption Column

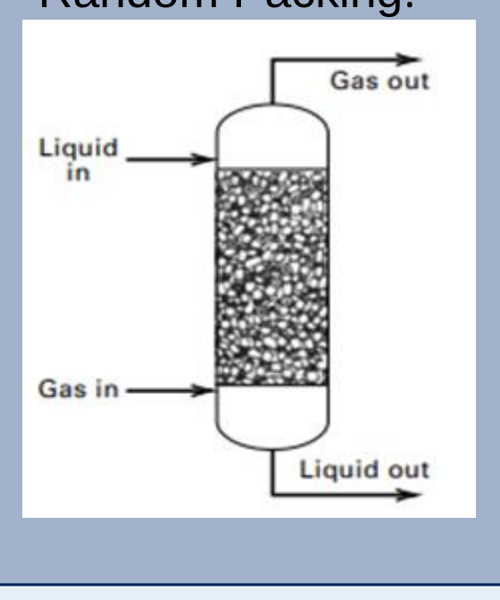
Column Diameter	3.3m
Column Height	5.3m
Packing Type	2” Plastic Pall Rings
Packing Structure	Random Packing

Stripping Column

Column Diameter	3.9m
Column Height	19.8m
Packing Type	2” Plastic Pall Rings
Packing Structure	Random Packing
Solvent Circulation Rate	1100 m^3/hr
Heating Requirement	3.5×10^8 Btu/hr

2” Plastic Pall Rings:

Random Packing:



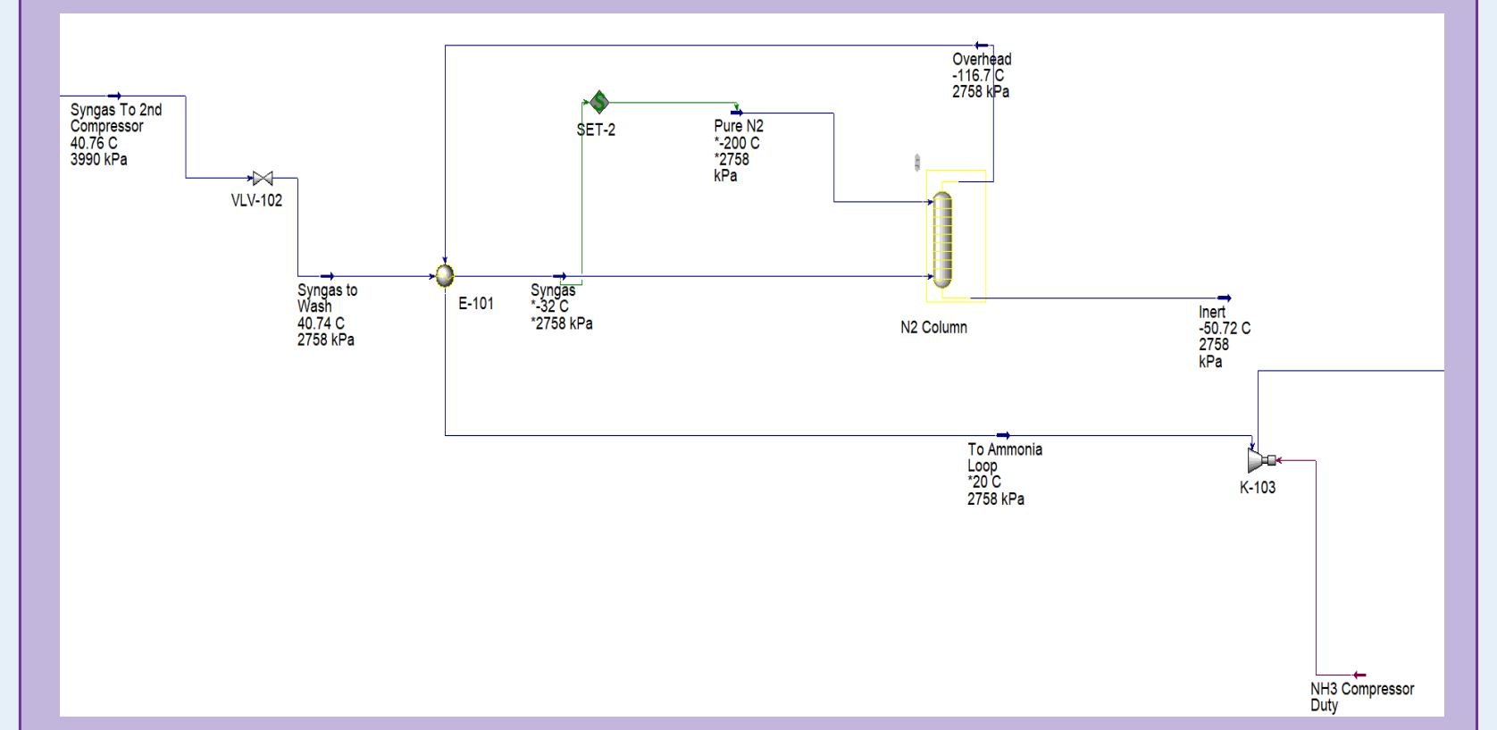
Nitrogen Wash Column

Purpose:

- Removes remaining inerts from Synthesis Gas (CO, CO_2, CH_4) to protect ammonia synthesis catalyst
- Ensures the correct stoichiometric ratio of H_2:N_2

Properties:

Average Operating Temperature (°C)	-95
Operating Pressure (bar)	27.6
Column Diameter (m)	8.83
Height of packing in Column (m)	1.44
Height of Column (m)	3.44



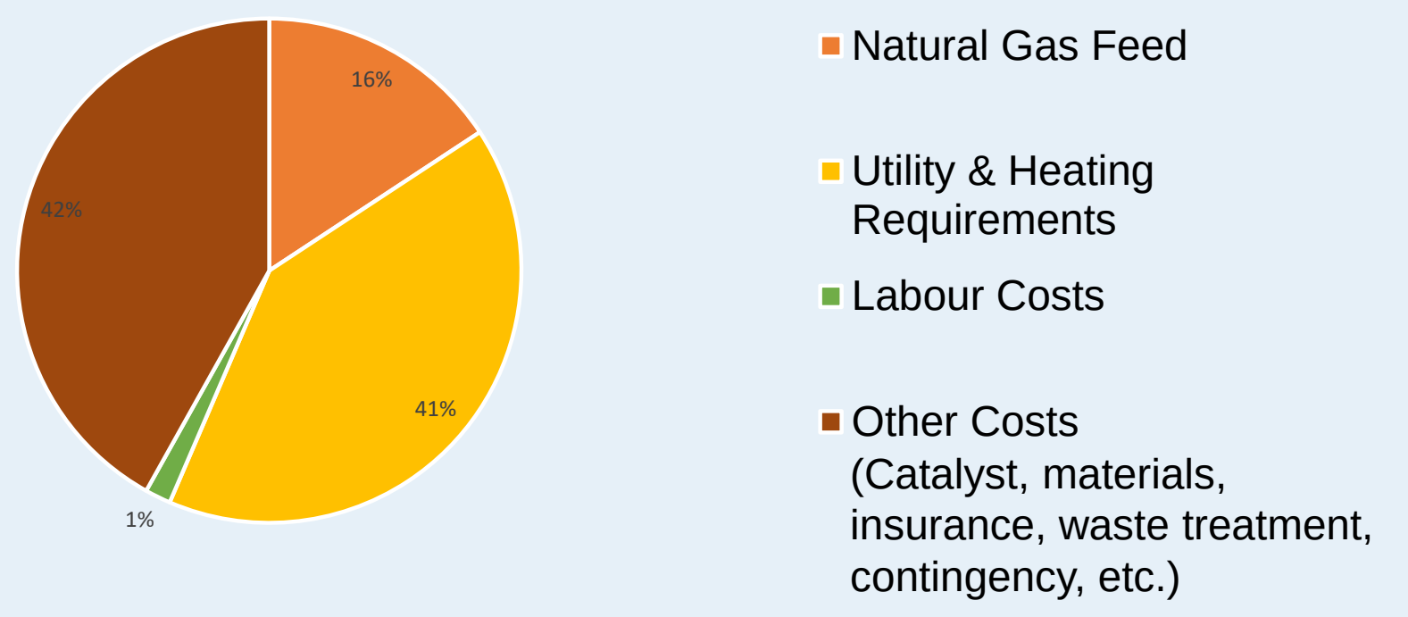
Feasibility

Cost Metrics

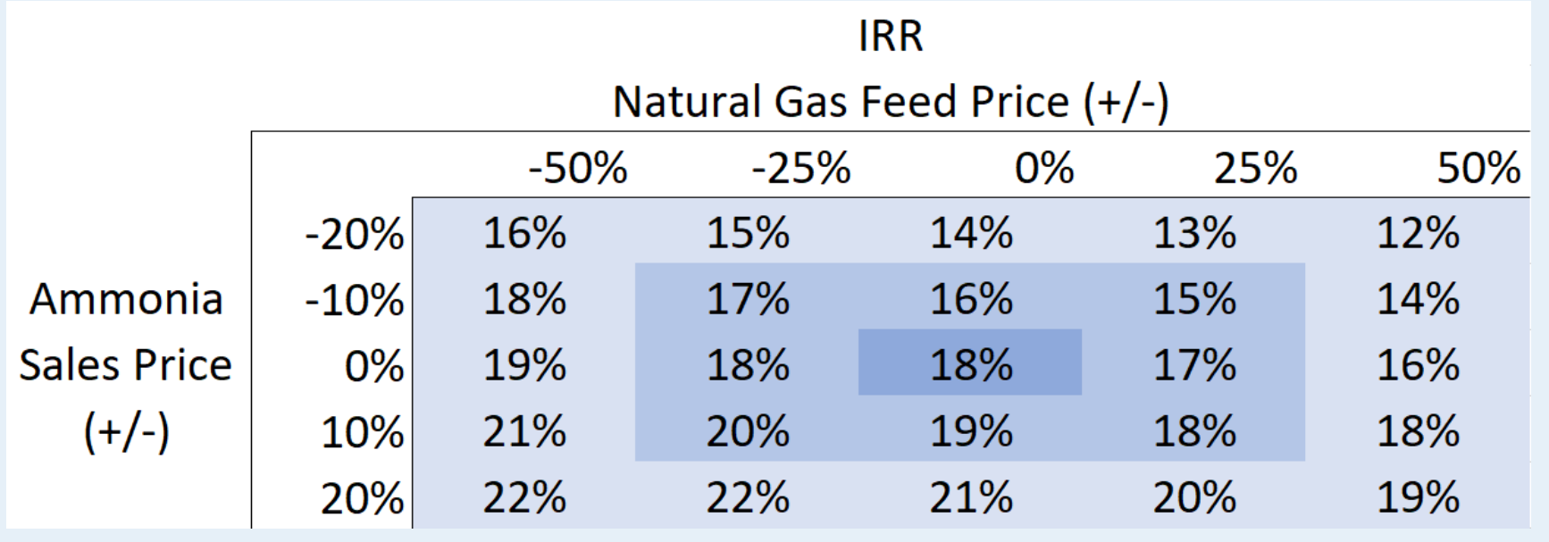
Total Capital Investment	$515MM
Total Equipment Cost	$331MM
Annual Operating Costs	$295MM + 3.8% growth
Profitability Metrics	
NPV	$2.02B
IRR	18%
Payback Period	10 years

IRR (18%) > Cost of Capital (7.7%) → Project is Economically Feasible

Operating Cost Breakdown



Sensitivity Analysis



		IRR				
		Natural Gas Feed Price (+/-)				
		-50%	-25%	0%	25%	50%
	-20%	16%	15%	14%	13%	12%
Ammonia Sales Price (+/-)	-10%	18%	17%	16%	15%	14%
	0%	19%	18%	18%	17%	16%
	10%	21%	20%	19%	18%	18%
	20%	22%	22%	21%	20%	19%

Carbon Intensity

CI= 0.0027 kg CO_2/ kg NH_3 + 0.133 kg CO_2e/kg NH_3 = 0.136 kg CO_2**e**/ kg NH_3

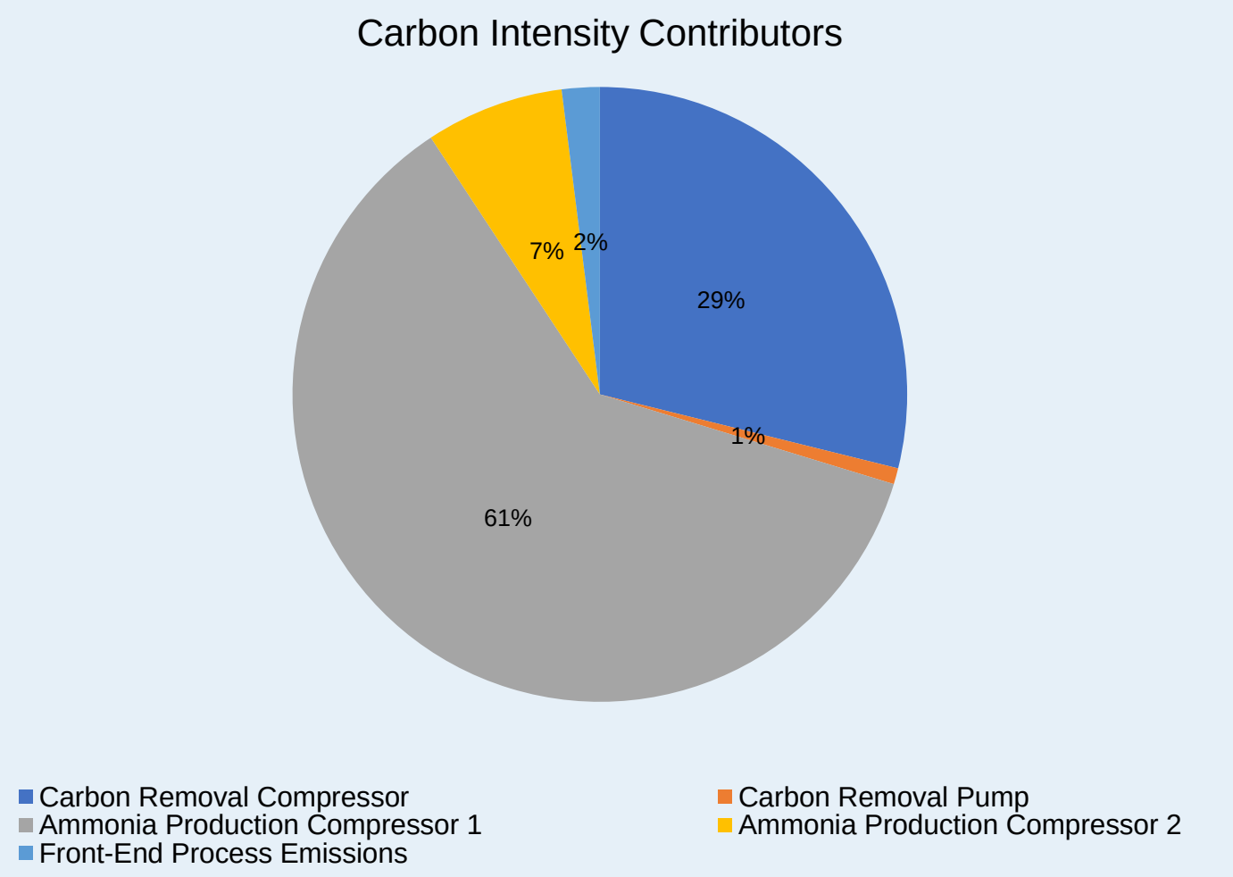
Process CO_2 from Synthesis Gas Production

CO_2 from Electricity Use in Auxiliary Equipment (Pumps, Compressors etc.)

Based on Government Canada Emission Factor of 0.64 kg CO_2e/kWh [3]

Equivalent includes all GHG Emissions (CH_4, N_2O etc.)

∴ kg CO_2**e** > kg CO_2



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[2] Oni, A., Anaya, K., Giwa, T., Di Lullo, G., & Kumar, A. (2022). Comparative assessment of blue hydrogen from steam methane reforming, autothermal reforming, and natural gas decomposition technologies for natural gas-producing regions. *Energy Conversion and Management, 254*, 115245. doi:10.1016/j.enconman.2022.115245

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