Natural Resources Canada   Ressources naturelles Canada

Canada

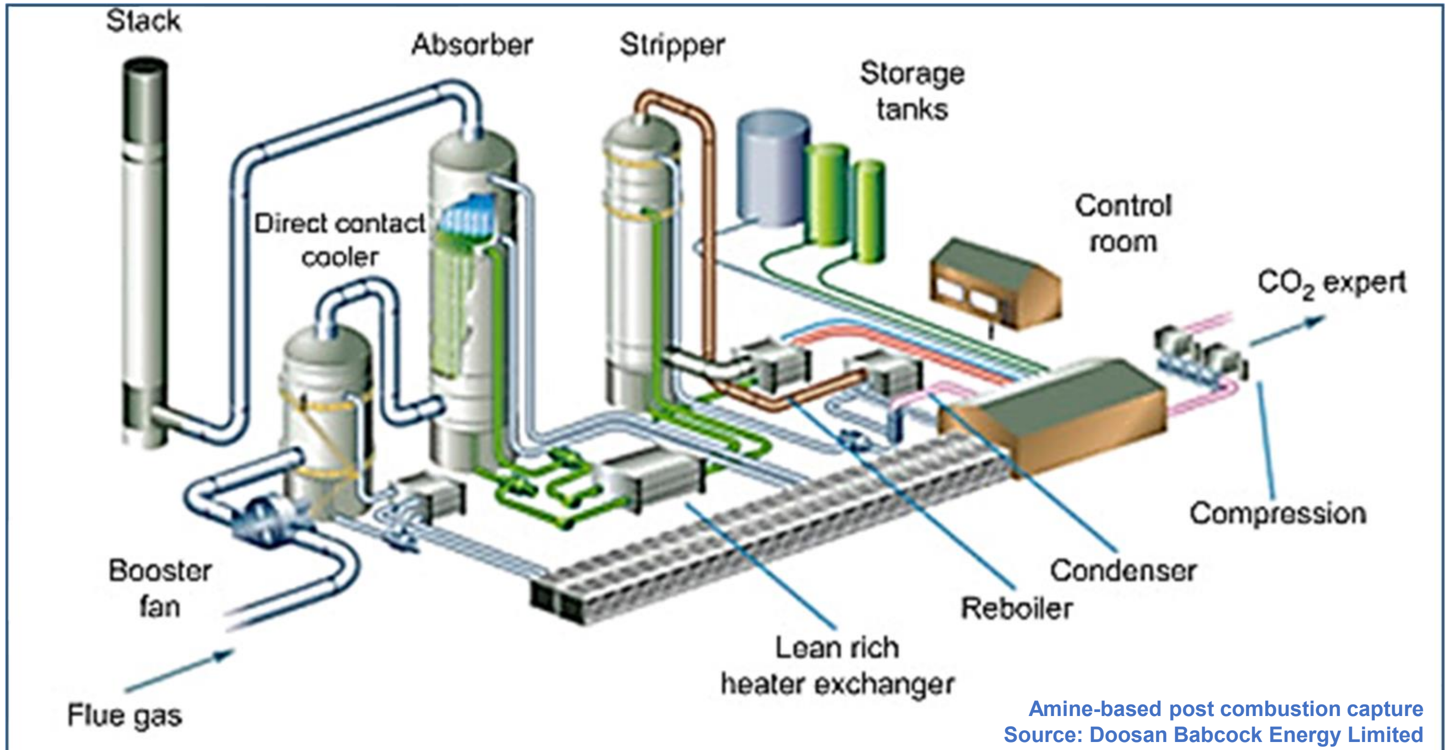
Integration of High-Temperature Heat Pumps for Steam Generation in Amine-Based CO_2 Capture: *A Techno-economic Study*

Post Combustion Capture Conference (PCCC-8), September 17th, 2025

Navid Teymouri, Marzieh Shokrollahi, Philippe Navarri
CCUS R&D Team | Industrial Systems Optimization group
CanmetENERGY
Natural Resources Canada

BACKGROUND AND MOTIVATION

- **Amine-based CO_2 capture** is widely considered the most robust technology for capturing carbon dioxide from industrial processes due to its **maturity**, **retrofit compatibility**, **high capture efficiency**, and **proven performance**. However, it's important to acknowledge its challenges.



Amine-based post combustion capture
Source: Doosan Babcock Energy Limited

CHALLENGE

- High energy demand
- 3 – 4 GJ steam/tonne CO_2 captured for MEA
- Secondary emissions of ~0.06 – 0.11 tonne CO_2/GJ steam

OPPORTUNITY

- Replace fossil steam with electrified heat via HTHPs + low carbon electricity
- State of the art HTHP (gas compression with or without MVR)

KEY QUESTIONS

- Feasibility of providing all the steam demand via HTHP from available waste heat?
- Best waste heat sources to consider?
- HTHP performance comparison against conventional steam production methods?

OBJECTIVE AND METHODOLOGY

SCOPE

- Model HTHP cycles using various refrigerants with different configurations to produce LP steam
- Assess performance based on COP, compressor power requirements, refrigerants limits, etc.
- Define multiple scenarios to identify optimal configuration for integration based on their performance

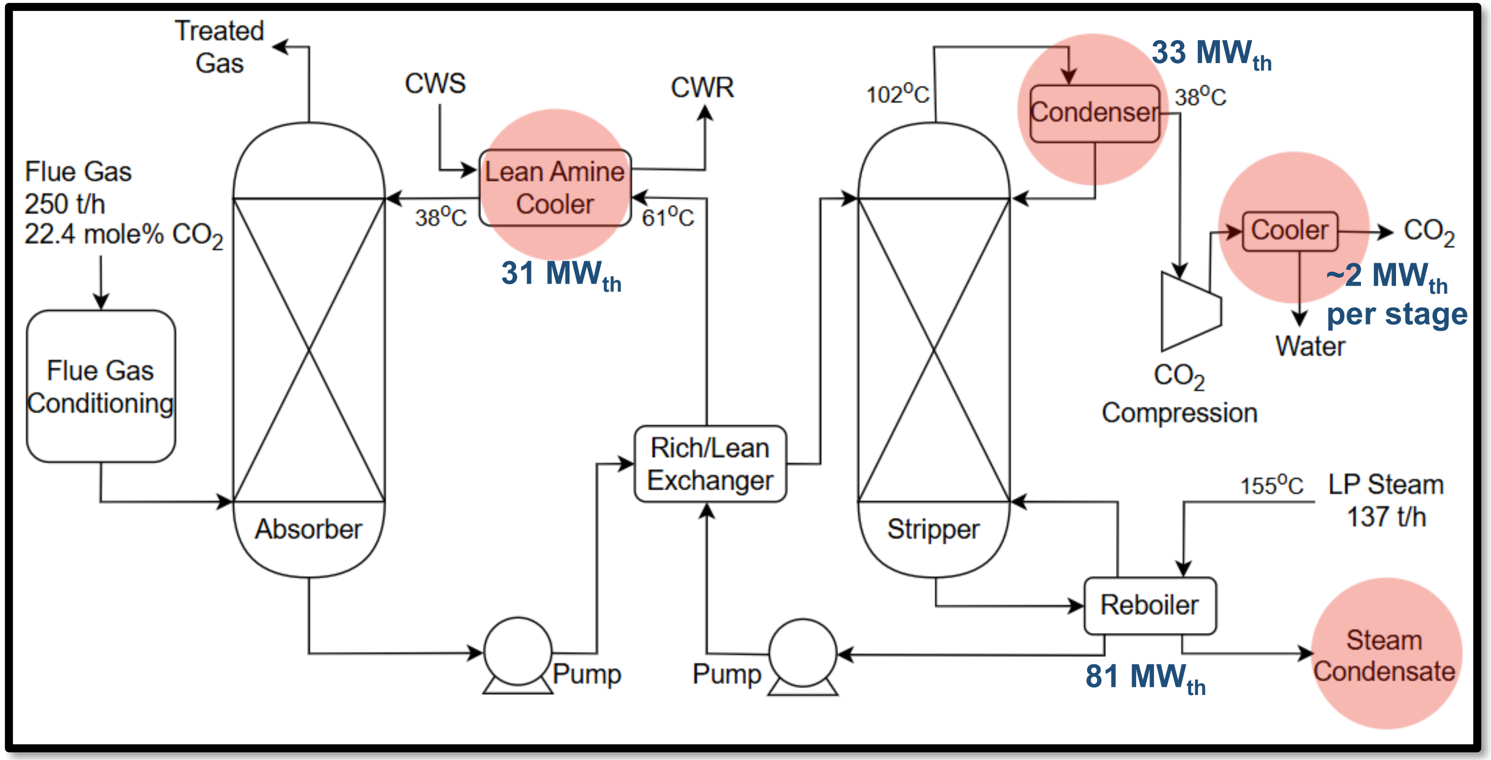
METHODOLOGY & PROCESS CONDITIONS

- Simulation platform: **Aspen HYSYS V14**(1)
- Flue gas source from a representative cement plant
- CO_2 capture reboiler temperature: 117ºC
- **Target steam: 137 t/h at 5.2 bara and 155ºC**(2)
- **Available heat sources**
  - Stripper overhead stream
  - Lean amine stream to amine cooler
  - CO_2 compression section (if included)
  - Steam condensate exiting the reboiler

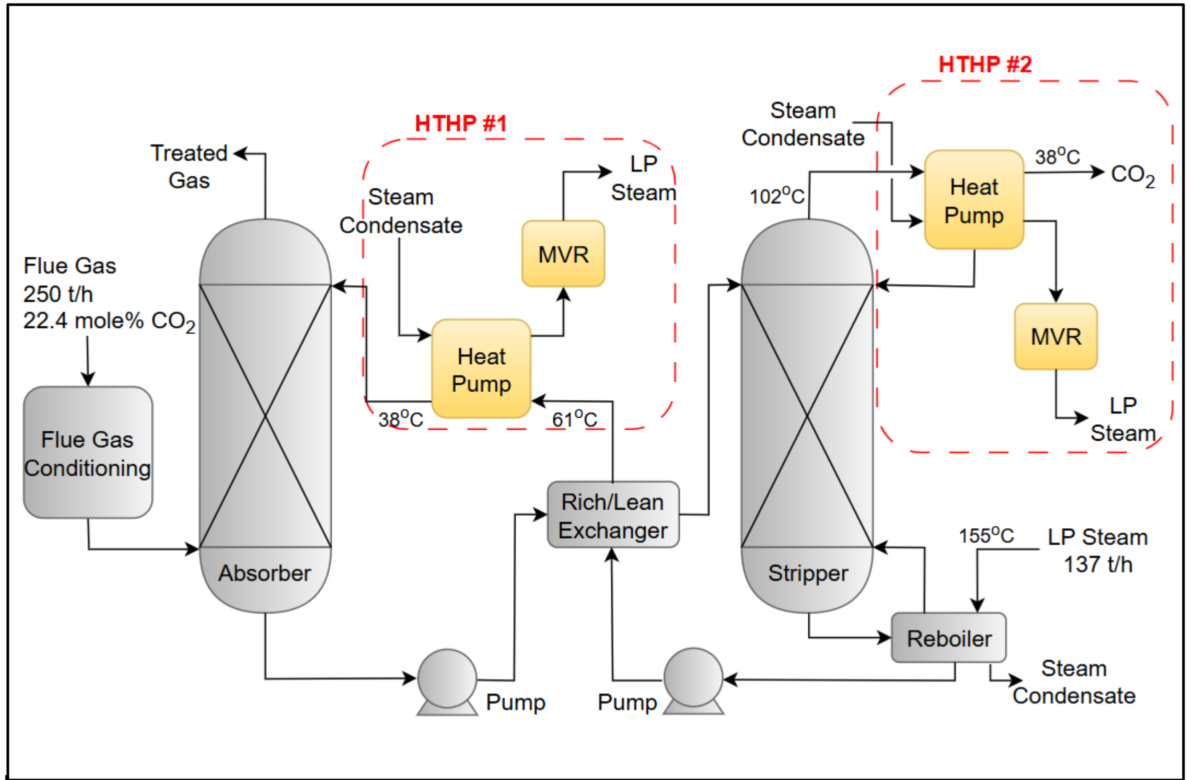
(1) Property packages: Peng-Robinson for refrigeration section and IAPWS-95 for steam production section

(2) Heating duty: 290 GJ/h; 3.76 GJ/t CO_2 for capture rate of 97%

Available Heat Sources within a Typical Amine-Based CO_2 Capture and Compression Unit



SINGLE STAGE HIGH TEMPERATURE HEAT PUMPS ON LEAN AMINE AND STRIPPER OVERHEAD STREAMS



Design Basis

- Refrigerant condensation temperature: 130ºC
- Refrigerant evaporation temperature: 33ºC
- **Compressors efficiency: 75%**
- Heat exchangers minimum **approach temperature: 5°C**
- **No pressure drop across heat exchangers**
- **No internal heat loss** in the system

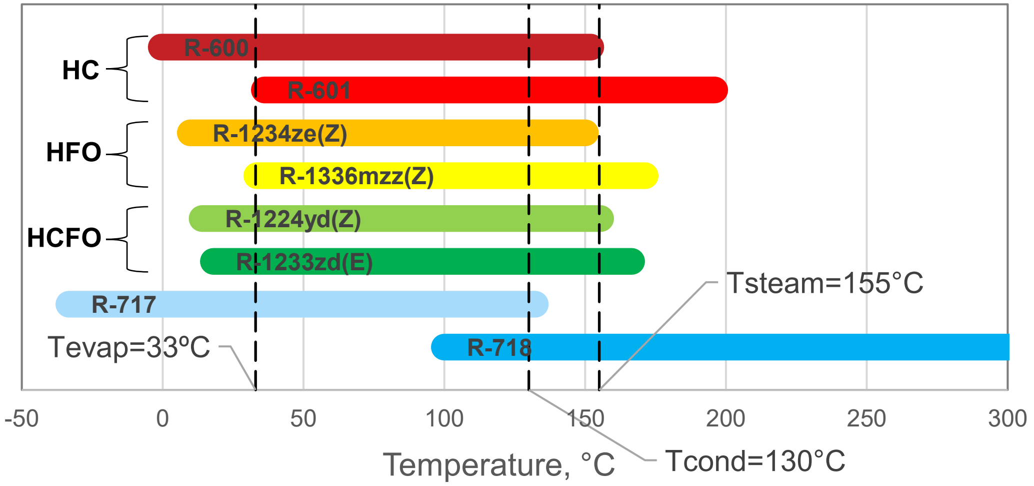
Performance Results of a R-600 Single Stage Cycle + MVR on Lean Amine vs. Stripper Overhead Stream

Parameter	HTHP #1	HTHP #2
Heat source	**Lean amine**	**Stripper overhead**
Configuration	**Single stage cycle + MVR**	**Single stage cycle + MVR**
Heat Pump Section		
Refrigerant	R-600 (n-butane)	R-600 (n-butane)
Available heat, GJ/h	**111.5**	**117.1**
Evaporation T/P, ºC/bar	33 / 3.1	33 / 3.1
Condensation T/P, ºC/bar	130 / 26.5	130 / 26.5
Temperature lift	97	97
Pressure ratio	8.6	8.6
HP compressor power, MW	36.1	38.0
HP condenser duty, GJ/h	241.6	253.8
Heat pump COP	**1.86**	**1.86**
Refrigerant VHC(1), kJ/m³	1,586	1,586
MVR Section		
MVR compressor power, MW	7.8	10.7
MVR COP	4.55	4.55
Steam production rate, t/h	**119.8 (87%)(2)**	**125.9 (92%)(2)**

(1) Volumetric heat capacity
(2) Percent of total steam demand

PERFORMANCE OF DIFFERENT REFRIGERANTS ON HEAT AVAILABLE FROM LEAN AMINE STREAM

Work Range of Different Refrigerants



Refrigerant selection criteria:

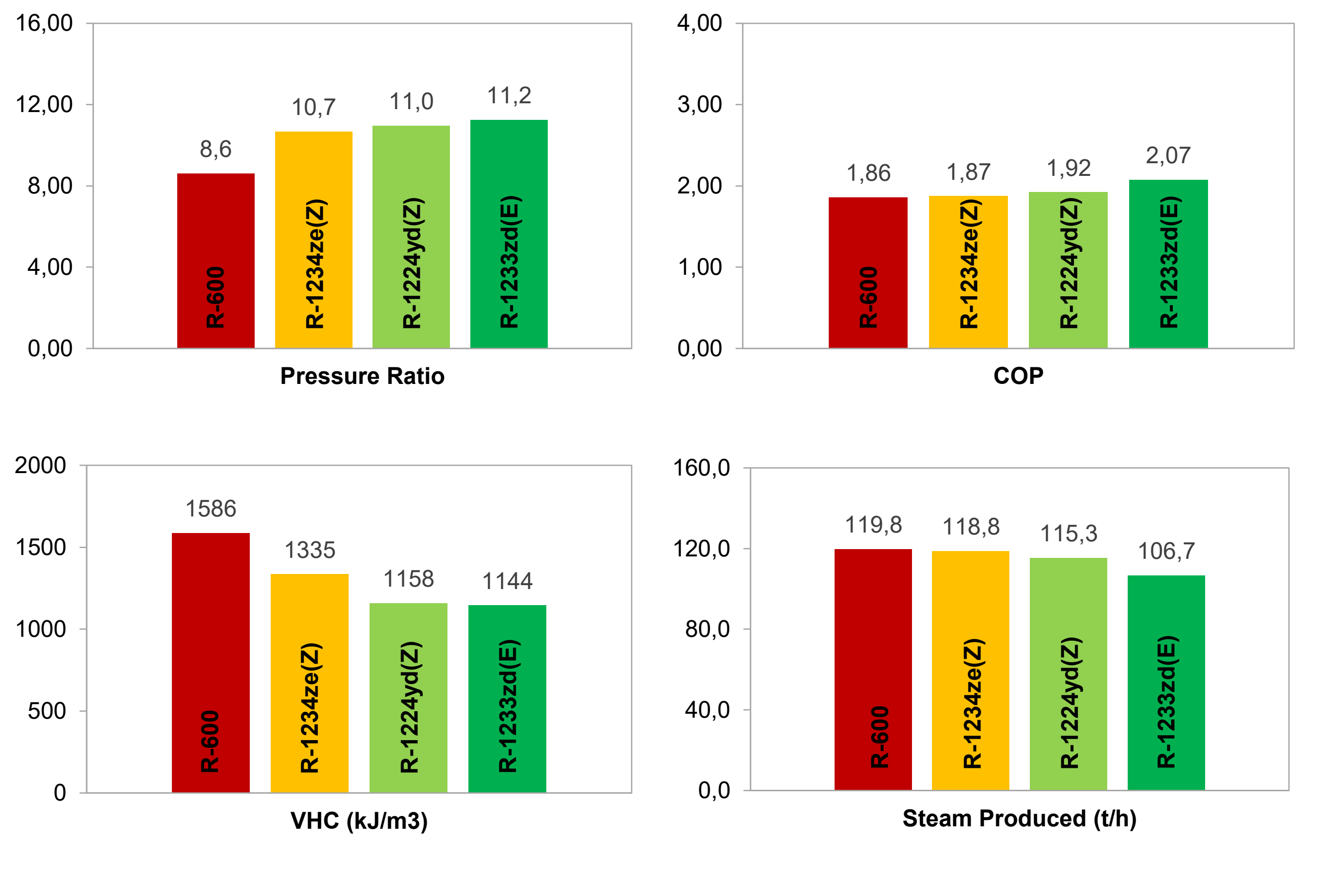
- Evaporation and condensation temperatures are within the refrigerant's work range

Suitable Refrigerants

- R-600
- R1234ze(Z)
- R-1224yd(Z)
- R-1233zd(E)

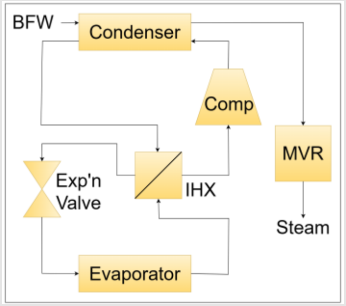
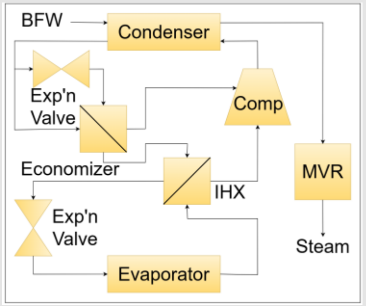
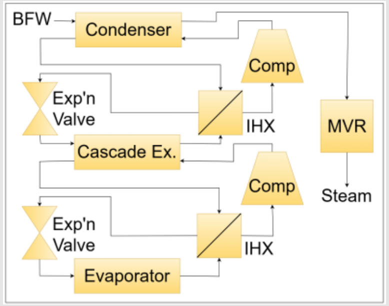
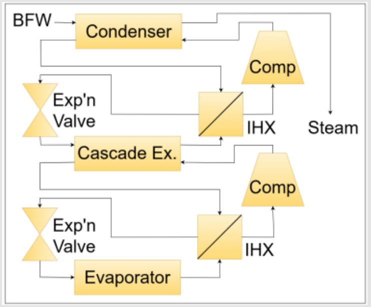
Single Stage Heat Pump + MVR on Lean Amine Stream(Available Heat: 111.5 GJ/h)

Result Highlights for Various Refrigerants
Single Stage HP Cycle + MVR on Lean Amine Stream



PERFORMANCE OF DIFFERENT HEAT PUMP CYCLES AND ARRANGEMENTS ON LEAN AMINE STREAM HEAT SOURCE

Performance Summary of Different HTHP Configurations on <u>Lean Amine Stream</u> (Heat available: 111.5 GJ/h)

Parameter	Config. #1	Config. #2	Config. #3		Config. #4	
Description	**Single stage HP + MVR**	**Single stage HP with economizer + MVR**	**Cascade HP + MVR**		**Cascade HP**	
			LT cycle	**HT cycle**	**LT cycle**	**HT cycle**
Refrigerant	R-600	R-600	R-600	R-601	R-600	R-601
Sketch digram						
Evaporation/Condensation, ºC	33 / 130	33 / 130	33 / 90	80 / 130	33 / 100	90 / 163
Pressure ratio	8.6	8.6	4.1	3.0	5.0	4.3
Temperature lift	**97**	**97**	**97**		**130**	
Heat pump COP	**1.86**	**2.48**	**2.50**		**1.89**	
MVR COP	4.55	4.55	4.55		-	
Steam production rate, t/h	**119.8**	**92.5**	**91.8**		**112.2**	
Percentage of total steam demand	**87%**	**68%**	**67%**		**82%**	

HTHP SYSTEMS TO PROVIDE THE TOTAL AMOUNT OF STEAM REQUIRED BY CO_2 CAPTURE PROCESS

Scenario #1

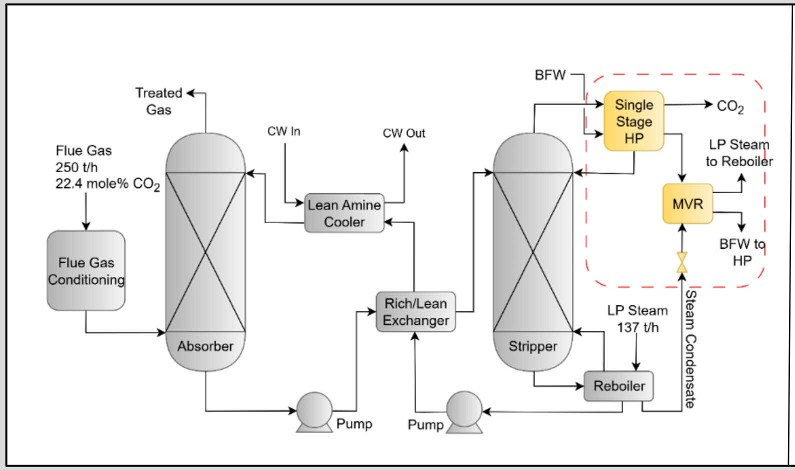
- Multiple heat sources: one single stage HP cycle on stripper overhead stream + MVR fed from the HP and steam condensate from the reboiler outlet

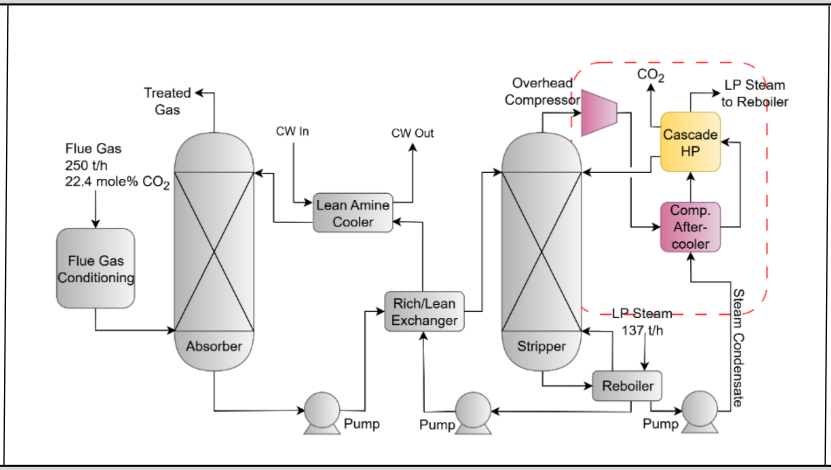
Scenario #2

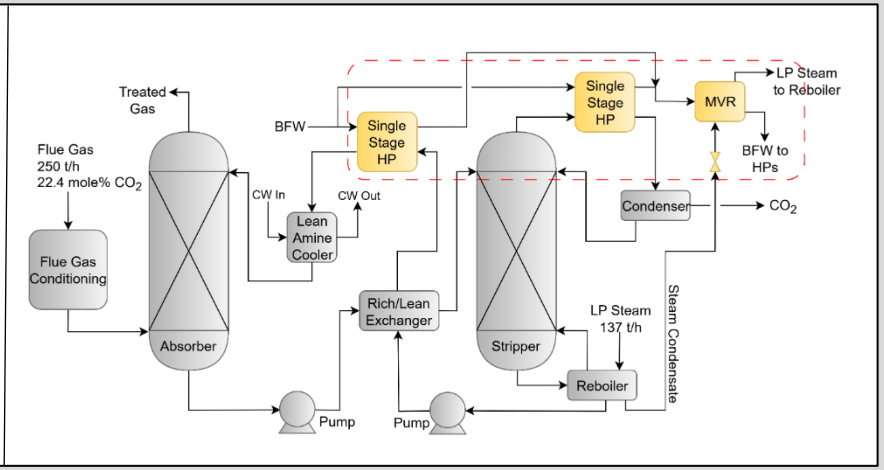
- Single heat source: one cascade HP cycle on compressed stripper overhead stream (to boost heat duty) that directly produces steam at target temperature.

Scenario #3

- Multiple heat sources: single stage/economizer HP cycles on both stripper overhead and lean amine streams + MVR fed from the two HPs and steam condensate from the reboiler outlet.







HTHP SYSTEMS TO PROVIDE THE TOTAL AMOUNT OF STEAM REQUIRED BY CO_2 CAPTURE PROCESS

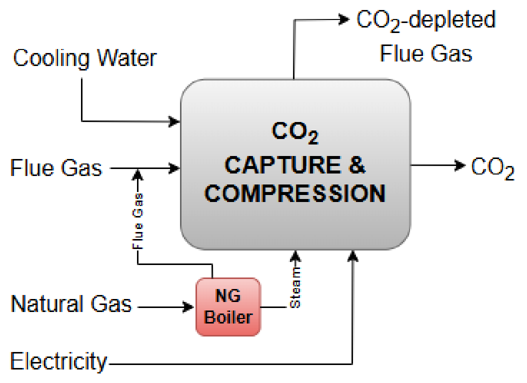
Parameter	Scenario #1	Scenario #2		Scenario #3	
	Heat Pump Section	**Heat Pump Section**		**Heat Pump Section**	
Cycle configuration	Single stage cycle	Cascade cycle		Single stage/economizer	Single stage/economizer
Source Heat	Stripper overhead stream	Compressed stripper overhead stream		Lean amine stream	Stripper overhead stream
Refrigerant	R-600	R-600	R-601	R-600	R-600
Evaporation/condensation temperature ºC	33 / 130	33 / 100	90 / 164	43 / 130	53 / 130
Temperature lift	97	131		87	77
Pressure ratio	8.6	5.0	4.3	6.5	5.0
Compressor power, MW	38.0	15.7	24.9	10.1	13.7
Condenser duty, GJ/h	254.1	274.7		99.5	155.9
Heat pump COP	1.86	1.88		2.73	3.15
	MVR Section	**Overhead Compression Section**		**MVR Section**	
Compressor power, MW	9.8	6.5		9.5	
MVR COP	4.54	-		4.55	
Direct heating duty, GJ/h	-	15.1		-	
Steam production rate, t/h	**137.2**	**137.4**		**137.3**	
Power demand per tonne of steam, kWh/t steam	**348**	**296 (344)**(1)		**243**	

(1) Power demand including overhead compressor power

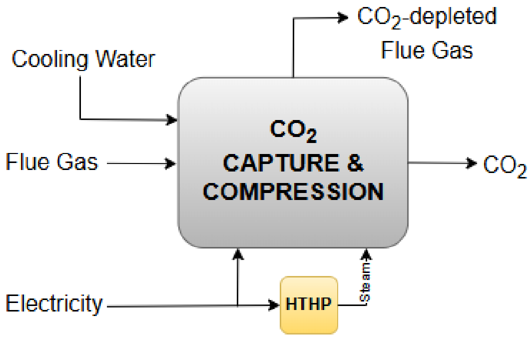
NG BOILER VS. HTHP FOR STEAM PRODUCTION PERFORMANCE SUMMARY

Performance Summary and Utility Demand of CO_2 Capture and Compression for NG Boiler vs. HTHP Steam Production Cases

Natural Gas Boiler Case



High Temp. Heat Pump Case

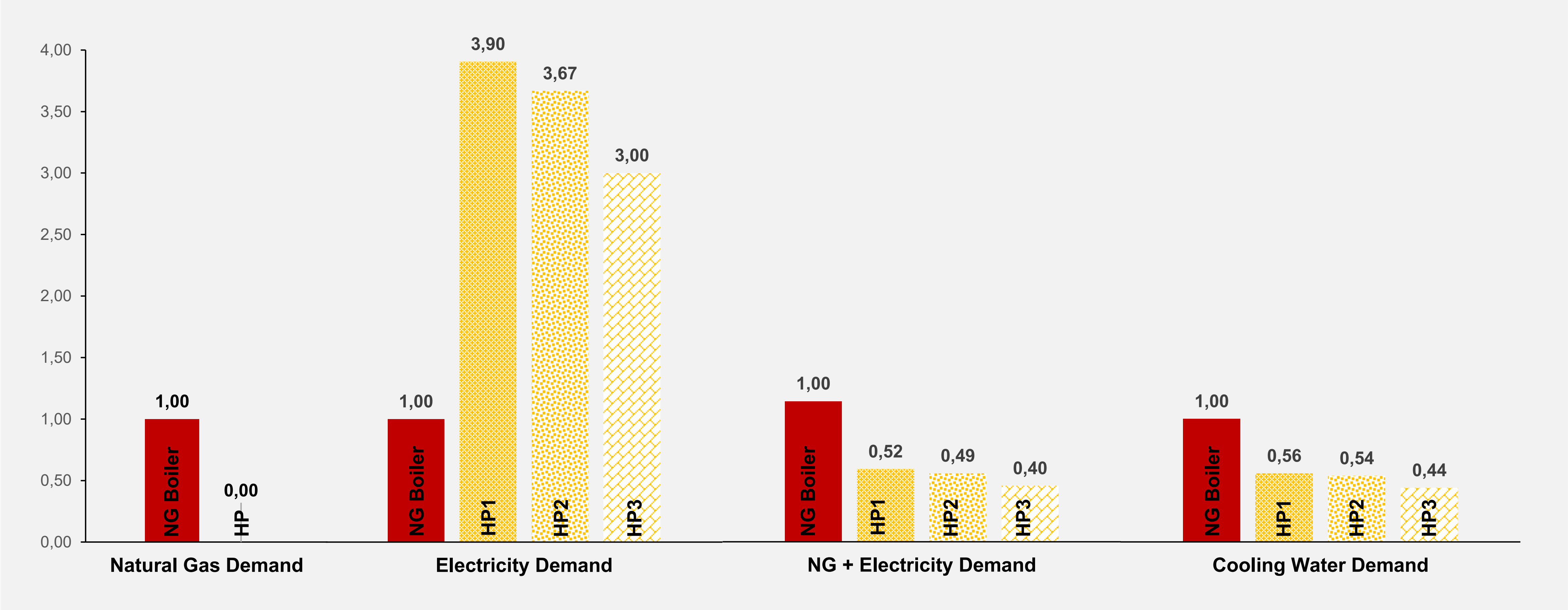


Parameter	Unit	NG Boiler Case(1)	HP Scenario #1	HP Scenario #2	HP Scenario #3
Flue gas flow rate	**t/h**	**437.6**	**250.0**		
CO_2 in flue gas	**mole%**	**16.0**	**22.4**		
CO_2 capture rate	%	97.0	97.0		
Captured CO_2	**t/h**	**101.5**	**77.0**		
Non-captured CO2	t/h	3.1	2.4		
CO_2 product pressure	bara	150	150		
CO_2 capture steam demand	t/h	186	137		
Utility Demand					
Electricity	MW	21.4	63.2	59.2	48.7
	MWh/t-CO_2	0.21	0.82	0.77	0.63
Cooling water	t/h	13,245	5,589	5,389	4,409
	t/t-CO_2	130.5	72.6	70.0	57.3
Natural gas	GJ/h	502.9	0.0		
	GJ/t-CO_2	4.96	0.0		
NG + Electricity	**GJ/t-CO_2**	**5.71**	**2.95**	**2.78**	**2.27**

(1) NG boiler efficiency = 80%

NG BOILER VS. HTHP FOR STEAM PRODUCTION
HTHP UTILITY DEMAND COMPARED TO NG BOILER

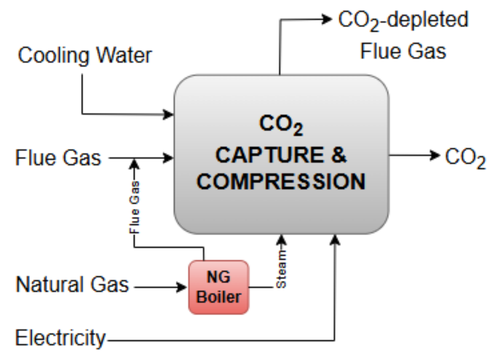
Heat Pump Scenarios Specific Utility Demand – Normalized Results Based on NG Boiler Case



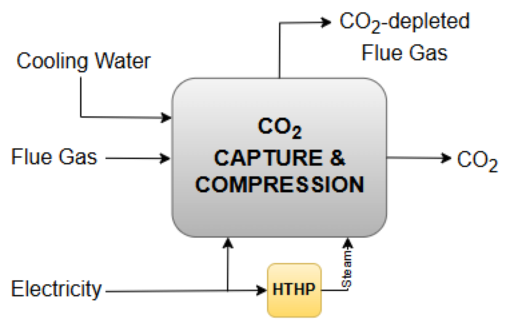
NG BOILER VS. HTHP FOR STEAM PRODUCTION ECONOMIC ANALYSIS – PRELIMINARY RESULTS

Economics Summary of CO_2 Capture and Compression for NG Boiler vs. HTHP Steam Production Cases

Natural Gas Boiler Case



High Temp. Heat Pump Case



Cost Parameter[1]	Unit	NG Boiler Case	HP Scenario #1	HP Scenario #2	HP Scenario #3
Captured CO_2	t/yr	808,912	613,671		
Equipment Cost Breakdown					
FG conditioning & CO_2 capture	MM USD	32.3	21.8	21.8	21.5
CO_2 compression	MM USD	9.8	8.0	6.4	8.0
Steam production via NG boiler	MM USD	4.2	0.0		
Steam production via HTHP	MM USD	-	25.0	27.1	23.1
Stripper overhead compression	MM USD	-	-	4.2	-
Total equipment cost	**MM USD**	**46.4**	**54.8**	**59.6**	**52.6**
Total capital investment	**MM USD**	**307.2**	**362.0**	**393.2**	**347.5**
Annualized capital investment	**MM USD/yr**	**28.8**	**33.9**	**36.8**	**32.6**
Operating costs[2]	**MM USD/yr**	**62.1**	**70.2**	**71.7**	**61.0**
Total cost per tonne of CO_2 captured	**USD/t CO_2**	**112.4**	**169.6**	**176.9**	**152.5**

(1) Cost estimation has been conducted for 2024 with CEPCI of 798.8 and Interest rate 8.0%. Plant lifetime is 25 years with plant availability of 0.91.
(2) Based on **natural gas, electricity, and cooling water prices of $4.0/GJ, $0.067/kWh, and $0.016/t**, respectively. Labor wage is $105k/year-person.

CONCLUSION AND NEXT STEPS

Conclusion:

- Heat pumps can eliminate fossil fuel use, reduce cooling demand, and cut total energy consumption, but at higher CAPEX and OPEX due to significant increase in electricity demand.
- In this case study, using a natural boiler for steam generation in carbon capture is more cost-effective per tonne of CO_2 captured, but it results in higher levels of uncaptured emissions.

Next steps:

- Assess whether HTHP scenarios could be more economical in certain regions of Canada considering upstream emissions (from both natural gas and electricity production), as well as regional variations in energy prices (sensitivity and uncertainty analysis).
- Consider the cost of avoided CO_2 in addition to captured CO_2.
- Investigate non-hydrocarbon or natural refrigerants such as NH_3.

THANK YOU!

CONTACT

Navid Teymouri, M.Sc.
Process Engineer
navid.teymouri@nrcan-rncan.gc.ca

Marzieh Shokrollahi, Ph.D.
Senior Process Engineer
marzie.shokrollahi@nrcan-rncan.gc.ca

Philippe Navarri, Ph.D.
Manager, CCUS R&D Team
philippe.navarri@nrcan-rncan.gc.ca

CanmetENERGY
Energy Efficiency and Technology Sector
Natural Resources Canada