



Thermodynamic Analysis of GT-CO₂ Combined Cycles Utilizing Liquified Natural Gas Cold Energy

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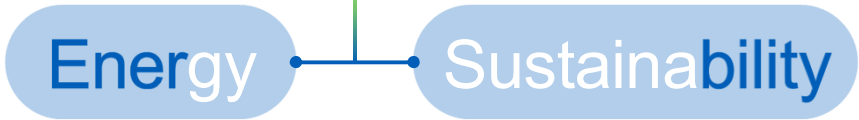
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New Start as Doosan Enerbility

Doosan Heavy Industries & Construction (DHI) renamed as **Doosan Enerbility** April 2022

DOOSAN Enerbility



Applying
new energy technologies



Creating a sustainable Earth



4.3 km² = 660 football field



Doosan Enerbility Business Portfolio

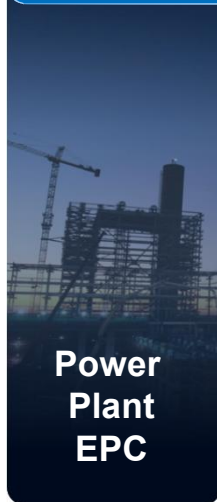
Doosan Enerbility has Three (4) business group to provide integrated solutions
(Plant EPC / Nuclear / Power Service / Wind / Strategy & Innovation)

130+
Years
Since Doosan

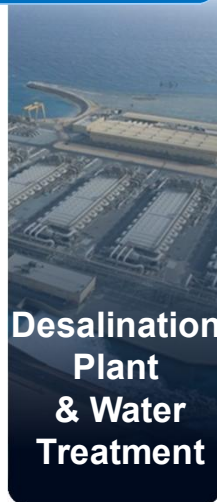
64+
Years
Since Doosan
Enerbility

330+
Global Projects
Over 100GW +

Plant EPC



Power
Plant
EPC

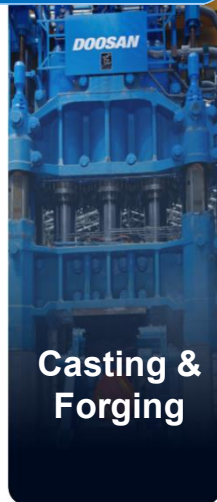


Desalination
Plant
& Water
Treatment

Nuclear

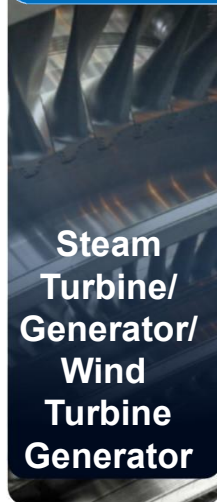


Nuclear
Component
& Services
/SMR

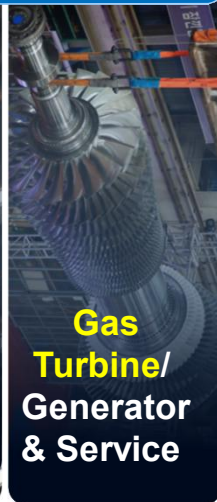


Casting &
Forging

Power Service



Steam
Turbine/
Generator/
Wind
Turbine
Generator



Gas
Turbine/
Generator
& Service

Strategy & Innovation



3D
Printing/
Digital AI



R&D



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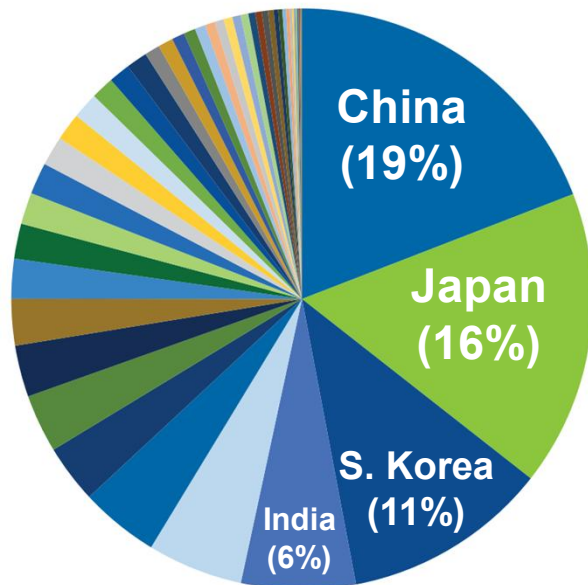
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Global LNG Import Market Share and Growth

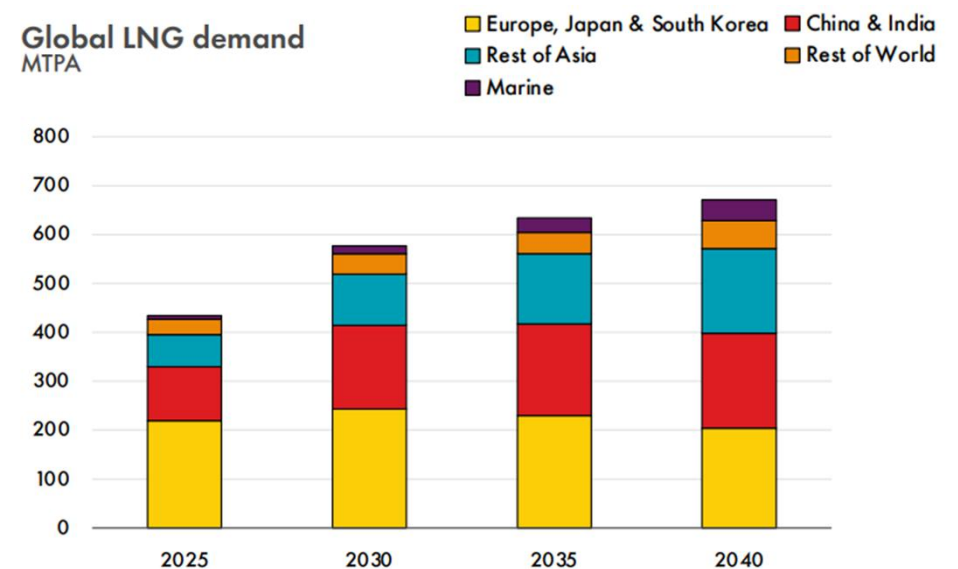
- The LNG import market is geologically concentrated in Asia, especially China, Japan, and S. Korea.
- LNG demand is projected to grow by ~ 50% by 2040, driven by decarbonization (coal to gas) and rising AI demand.
- As LNG demand grows, there would be opportunity for LNG **Cold energy** utilization.

LNG Import Market Share (2024)¹⁾



1) International gas union, IGU 2025 World LNG report, May. 2025.

LNG demand outlook (2020-2040)²⁾



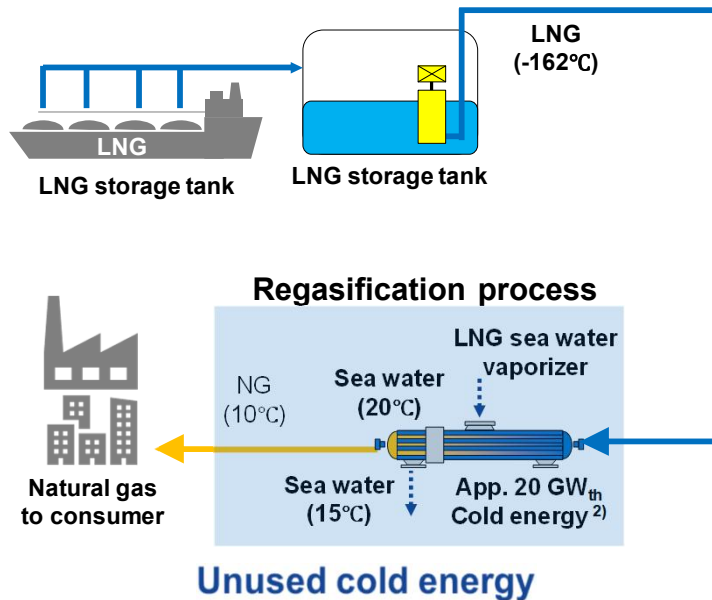
2) Shell LNG outlook 2025, Royal Dutch Shell, Feb. 2025.



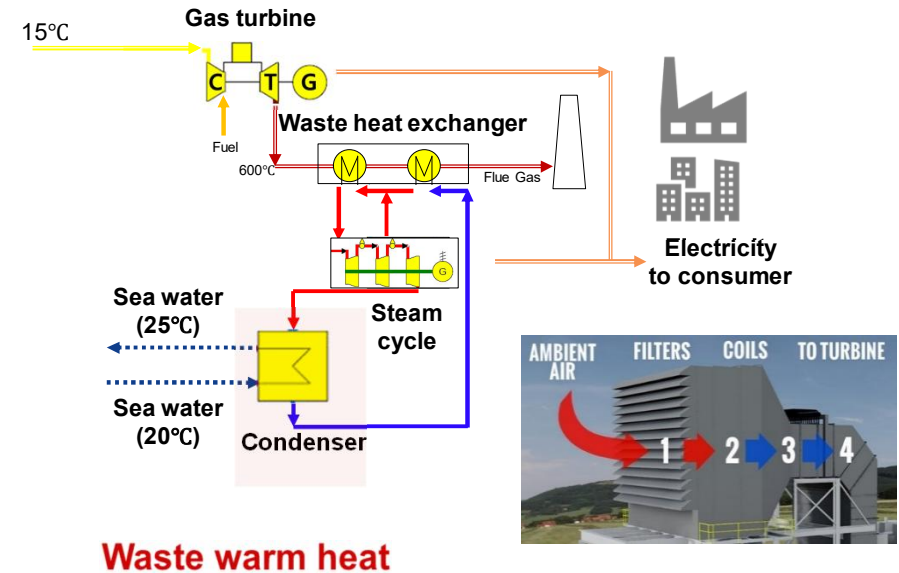
Sector Coupling LNG import terminals & power plants

- **Cold energy** is mostly unutilized in LNG terminals.
- Low-grade **Warm heat** is dissipated in power plants.
- Sector coupling between LNG terminal and Power Plant creates **Synergy**, mitigating inefficiency in both systems.

LNG terminal Regasification process



Combined Cycle Power Plants process



The International Supercritical CO₂ Energy Technologies Symposium • March 2 – 5, 2026 • Pittsburgh, PA, USA

1) TIAC & HR : Turbine Inlet Air Cooling and Heat Recovery system / 2) He T et al. LNG cold energy utilization: Prospects and challenges. Energy 2019

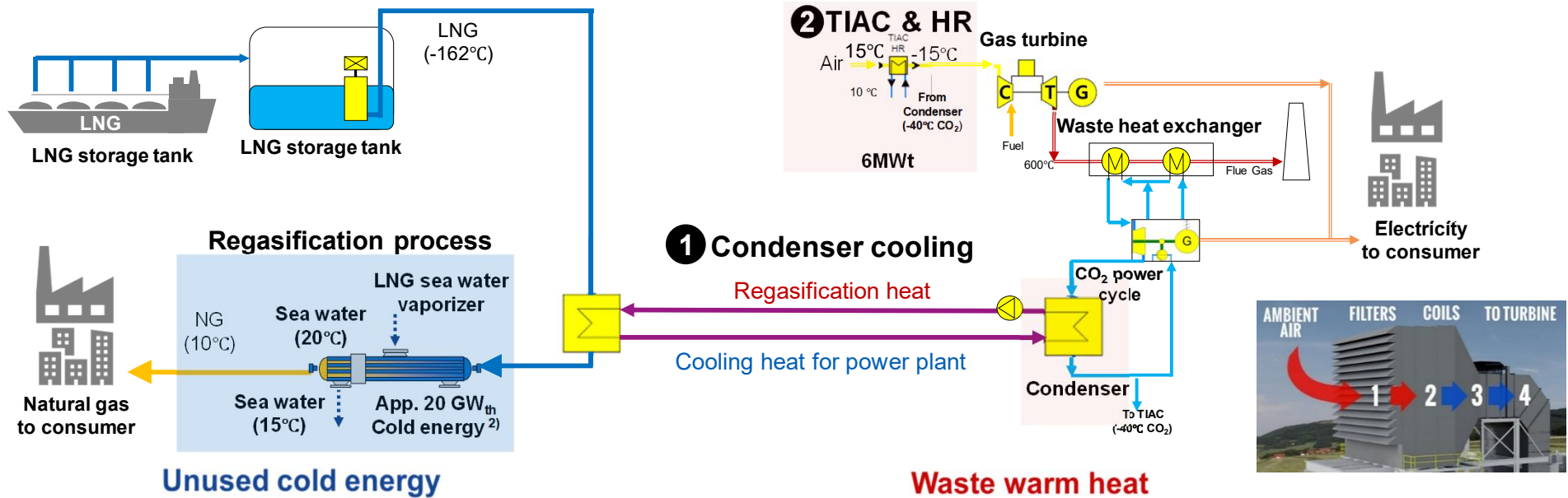


Sector Coupling LNG import terminals & power plants

- novel concept GT-CO₂ CCPP (Combined Cycle Power Plant) boosts sector coupling benefit further.
- Turbine Inlet Air Cooling (TIAC) enhance CCPP power output by 10 - 15%, and Air Heat Recovery (HR) into the CO₂ bottoming cycle improves overall CCPP efficiency by 1 - 2%.

LNG terminal Regasification process

Combined Cycle Power Plants process



The International Supercritical CO₂ Energy Technologies Symposium • March 2 – 5, 2026 • Pittsburgh, PA, USA

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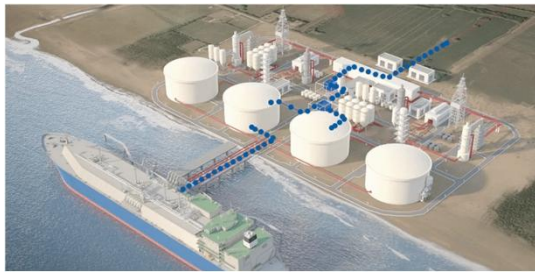
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LNG terminal capacity & Gas Turbine Model

- LNG terminals with capacity ≥ 6 MTPA account for $\sim 60\%$ of global, while those ≥ 3 MTPA account for $\sim 90\%$.
- **6 MTPA LNG terminal** is selected for simulation study, and its unused cold energy from 6 MTPA is $\sim 160 \text{ MW}_{\text{th}}$
- A Siemens **SGT-800** gas turbine (62.5 MW_e) is selected for simulation study.

LNG receiving terminal capacity ¹⁾

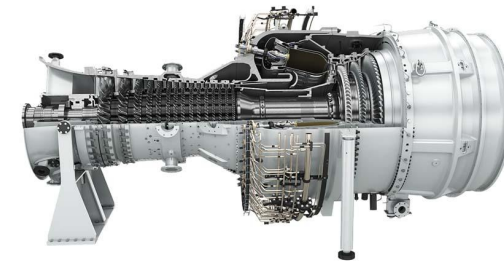


Capacity	Units (%)	Sum of capacity (%)
~ 3 MTPA	92 (35%)	118 MTPA (9%)
3 ~ 6 MTPA	96 (36%)	408 MTPA (30%)
6 ~ 9 MTPA	45 (17%)	312 MTPA (23%)
9 ~ 12 MTPA	15 (6%)	161 MTPA (12%)
12 ~ MTPA	15 (6%)	347 MTPA (26%)
Total	264(100%)	1346 MTPA (100%)

61%

1 MTPA (114 t/h) cold energy = $26.3 \text{ MW}_{\text{th}}$

Gas turbine selection ²⁾ (SGT-800)



	SGT-800	GE 6F.01	MHI H-25
SCPP output	62.5 MW	57.0 MW	41 MW
SCPP efficiency	41.1%	38.4%	36.2%
CCPP output	88 MW	85 MW	60.1 MW
CCPP efficiency	59.0%	57.9%	54.5%

Siemens SGT-800 88 MW / 59.0%

1) International gas union, IGU 2024 World LNG report, 2024. / MTPA : Million ton per annum

2) Pequot Publication Inc. Gas turbine world 2024 Volume 39th Ed. Fairfield, CT: 2024



Combined cycle modeling parameters

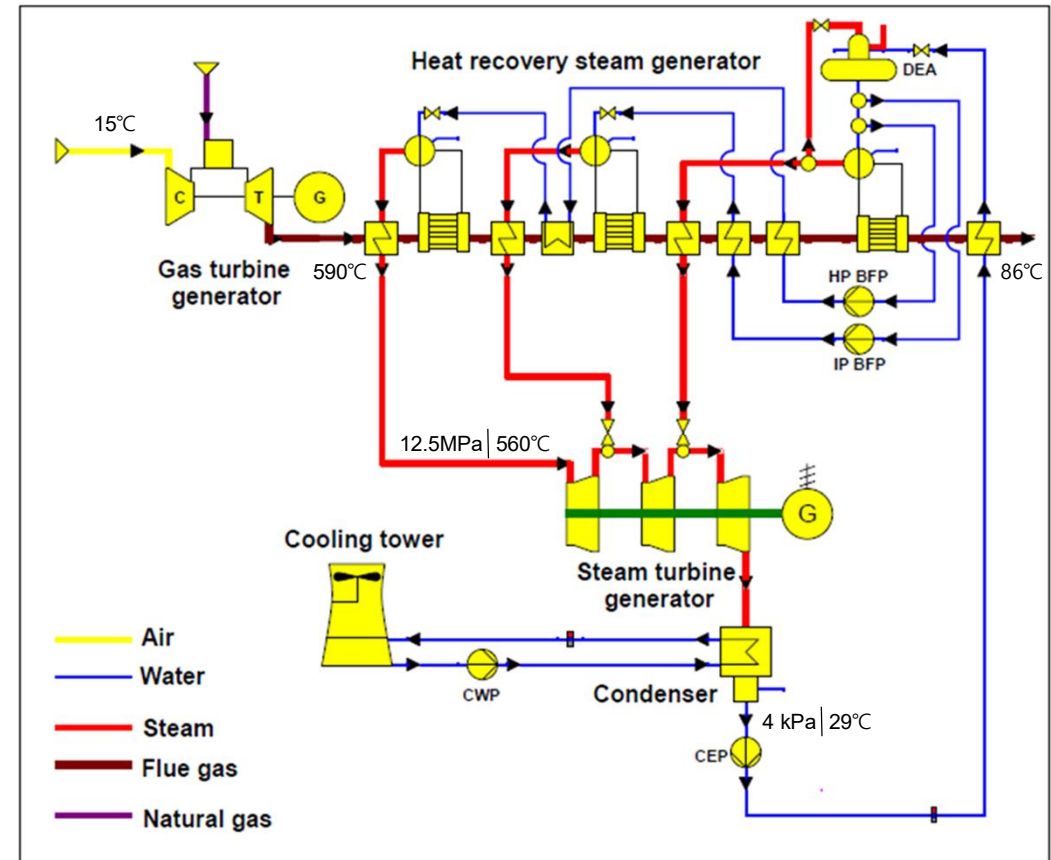
	Case No.	Case #1	Case #2	Case #3	Case #4
Gas Turbine	Model	SGT-800			
	Ambient T / P / RH	15°C / 1.013 bar / 60%			
	TIAC applied	N/A	N/A	Applied	Applied
	Comp. inlet T.	15°C	15°C	- 5°C (SGT-800 curve)	-15°C (Ideal GT curve)
	Power output	61.2 MW	61.2 MW	66.5 MW	71.4 MW
	LHV efficiency	40.3%	40.3%	40.6%	41.7%
	EGT / EGM	590°C / 139kg/s	590°C / 139kg/s	582°C / 146kg/s	575°C / 150kg/s
Bottoming cycle	Configuration	3PNRH Steam cycle	Partial heating CO ₂ trans-critical cycle	Partial heating CO ₂ trans-critical cycle with TIAC & HR system	
	Turbine Isentropic efficiency	88%			
	Turbine inlet press.	12.5 MPa	18.5 MPa		
	Condenser inlet press.	4 kPa (1.2 inHg)	0.7 MPa		
	Piping press. loss	4% / 3% / 10%	4% / 3%		
	Piping heat loss	3°C			
	HRSG or WHE pinch	8°C			
	Pump isentropic eff.	80%			
	Generator efficiency	98.5%			
	Recuperator dP	N/A	1 bar		
Recuperator pinch	N/A	3°C			
Cooling	Source	Cooling Tower	LNG cold energy		



Case studies - Cycle Configuration and Parameters

	Case No.	Case #1
Gas Turbine	Model	SGT-800
	Ambient T / P / RH	15°C / 1.013 bar / 60%
	TIAC applied	N/A
	Comp. inlet T.	15°C
	Power output	61.2 MW
	LHV efficiency	40.3%
	EGT / EGM	590°C / 139kg/s
	Configuration	3PNRH Steam cycle
Bottoming cycle	Turbine Isentropic efficiency	88%
	Turbine inlet press.	12.5 MPa
	CND inlet press.	4 kPa (1.2 inHg)
	Piping press. loss	4% / 3% / 10%
	Piping heat loss	3°C
	HRSG or WHE pinch	8°C
	Pump isentropic eff.	80%
	Generator efficiency	98.5%
	Recuperator dP	N/A
	Recuperator pinch	N/A
Cooling	Source	Cooling Tower

Case #1 : Reference GT-ST CCGP

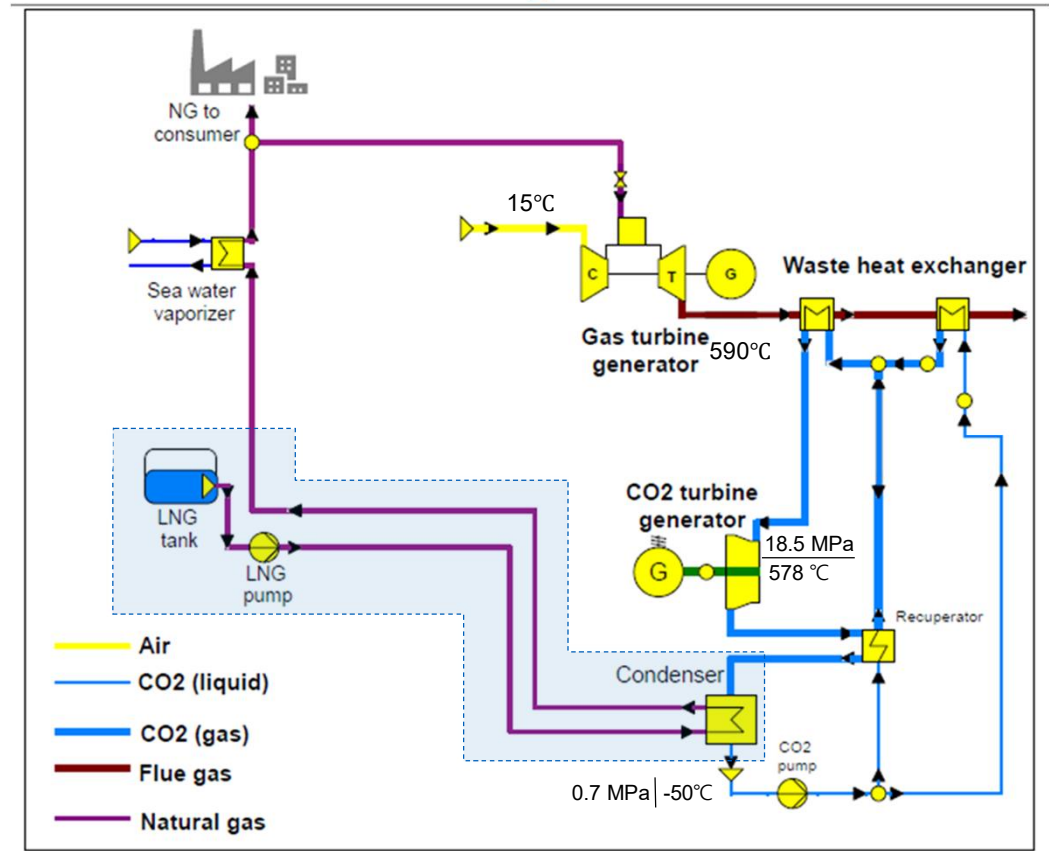




Case studies - Cycle Configuration and Parameters

	Case No.	Case #2
Gas Turbine	Model	SGT-800
	Ambient T / P / RH	15°C / 1.013 bar / 60%
	TIAC applied	N/A
	Comp. inlet T.	15°C
	Power output	61.2 MW
	LHV efficiency	40.3%
	EGT / EGM	590°C / 139kg/s
	Configuration	Partial heating CO ₂ trans-critical cycle
Bottoming cycle	Turbine Isentropic efficiency	88%
	Turbine inlet press.	18.5 MPa
	CND inlet press.	0.7 MPa
	Piping press. loss	4% / 3%
	Piping heat loss	3°C
	HRSG or WHE pinch	8°C
	Pump isentropic eff.	80%
	Generator efficiency	98.5%
	Recuperator dP	1 bar
	Recuperator pinch	3°C
	Cooling	Source

Case #2 : GT-CO₂ CCPP W/O TIAC

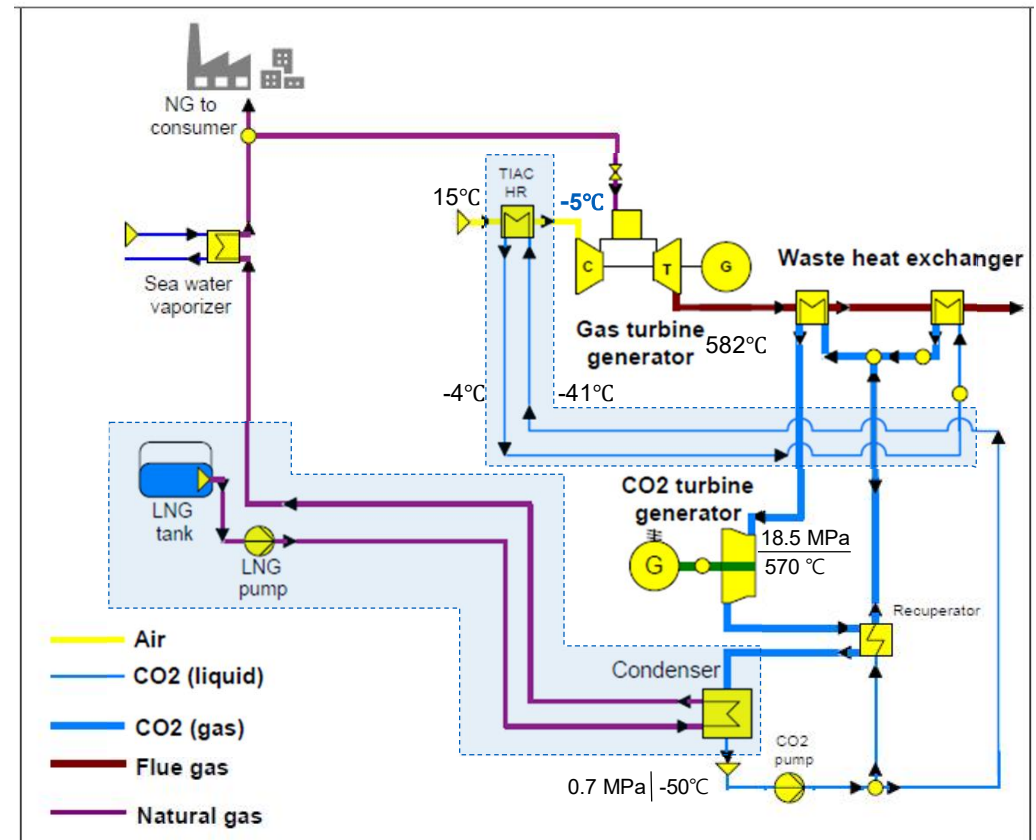




Case studies - Cycle Configuration and Parameters

Case No.		Case #3
Gas Turbine	Model	SGT-800
	Ambient T / P / RH	15°C / 1.013 bar / 60%
	TIAC applied	Applied
	Comp. inlet T.	-5°C (SGT-800 curve)
	Power output	66.5 MW
	LHV efficiency	40.6%
	EGT / EGM	582°C / 146kg/s
	Configuration	Partial heating with TIAC & HR
Bottoming cycle	Turbine Isentropic efficiency	88%
	Turbine inlet press.	18.5 MPa
	CND inlet press.	0.7 MPa
	Piping press. loss	4% / 3%
	Piping heat loss	3°C
	HRSG or WHE pinch	8°C
	Pump isentropic eff.	80%
	Generator efficiency	98.5%
	Recuperator dP	1 bar
	Recuperator pinch	3°C
Cooling	Source	LNG cold energy

Case #3 : GT-CO₂ CCPP W TIAC

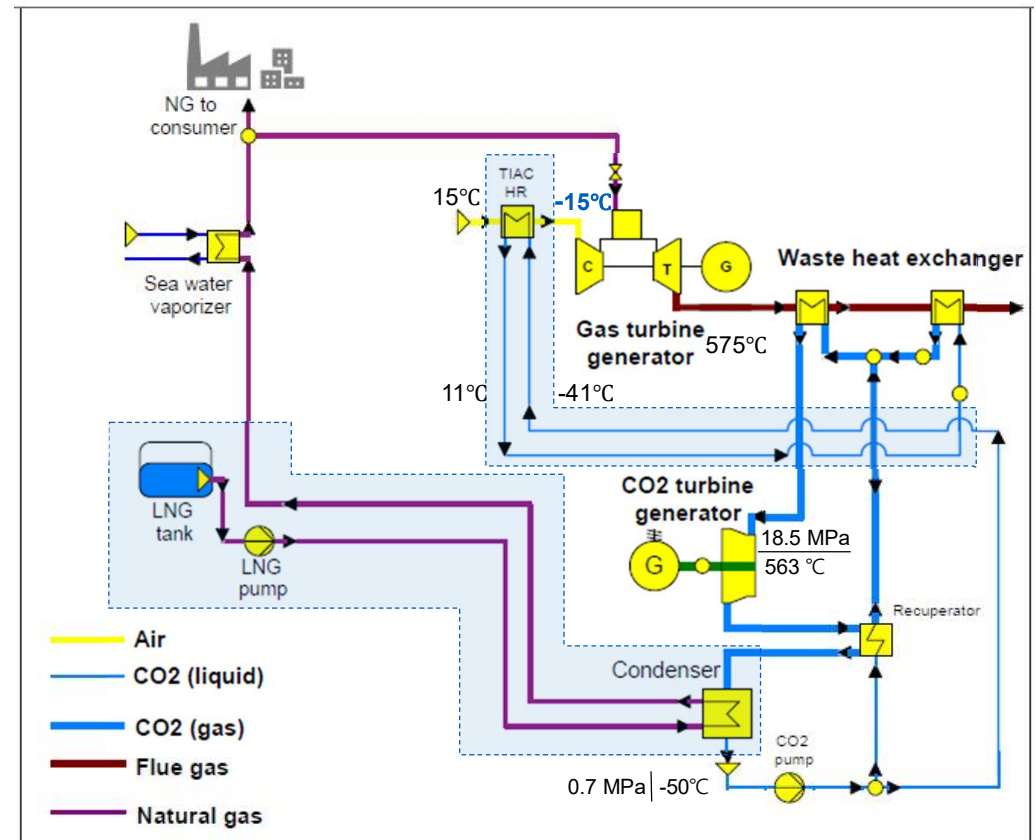




Case studies - Cycle Configuration and Parameters

	Case No.	Case #4
Gas Turbine	Model	SGT-800
	Ambient T / P / RH	15°C / 1.013 bar / 60%
	TIAC applied	Applied
	Comp. inlet T.	-15°C (Ideal GT curve)
	Power output	71.4 MW
	LHV efficiency	41.7%
	EGT / EGM	575°C / 150kg/s
	Bottoming cycle	Configuration
Turbine Isentropic efficiency		88%
Turbine inlet press.		18.5 MPa
CND inlet press.		0.7 MPa
Piping press. loss		4% / 3%
Piping heat loss		3°C
HRSG or WHE pinch		8°C
Pump isentropic eff.		80%
Generator efficiency		98.5%
Recuperator dP		1 bar
Recuperator pinch		3°C
Cooling	Source	LNG cold energy

Case #4 : GT-CO₂ CCPP W TIAC

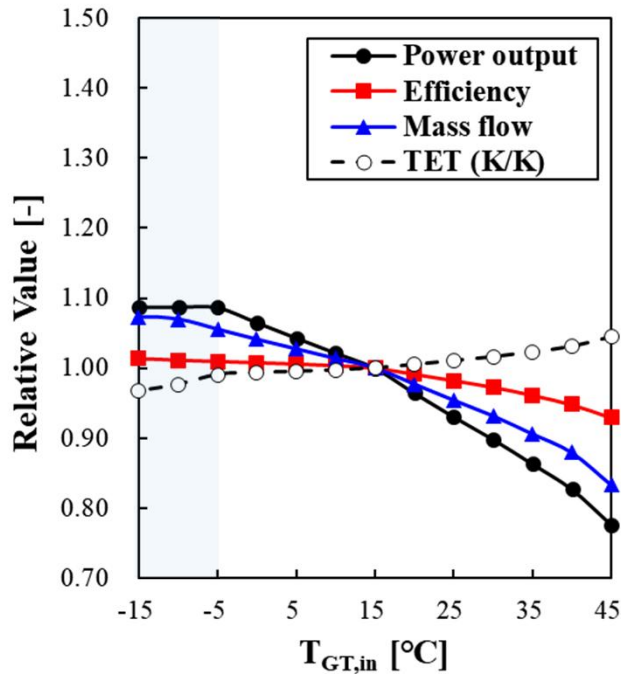




Gas turbine performance curve

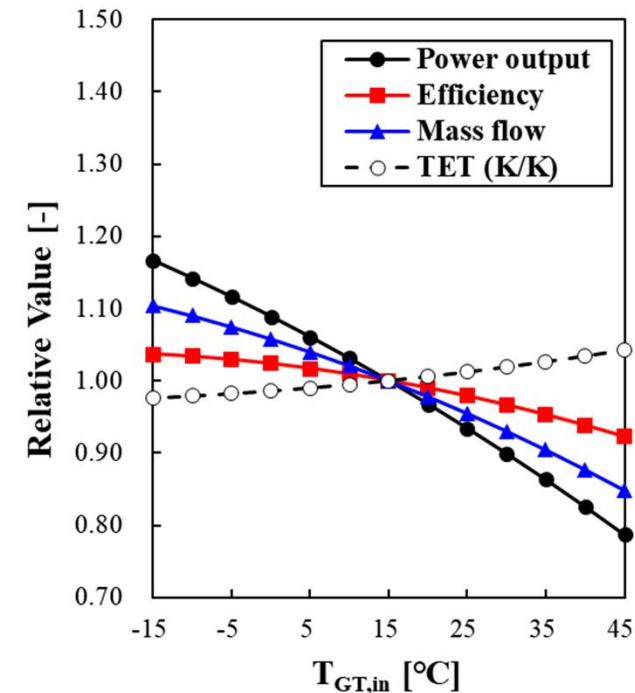
SGT-800 62.5MW GT perf. curve ¹⁾

GT output is remaining constant below -5 °C because of its constraint.



1) ENEXSA Gas Turbine Library for EBSILON (Release 7.2), 2022 [Software].

Ideal Gas Turbine correction curve ²⁾



2) Siemens AG. Siemens gas turbine SGT6-5000F application overview. Orlando, FL: Siemens Power Generation; 2006.



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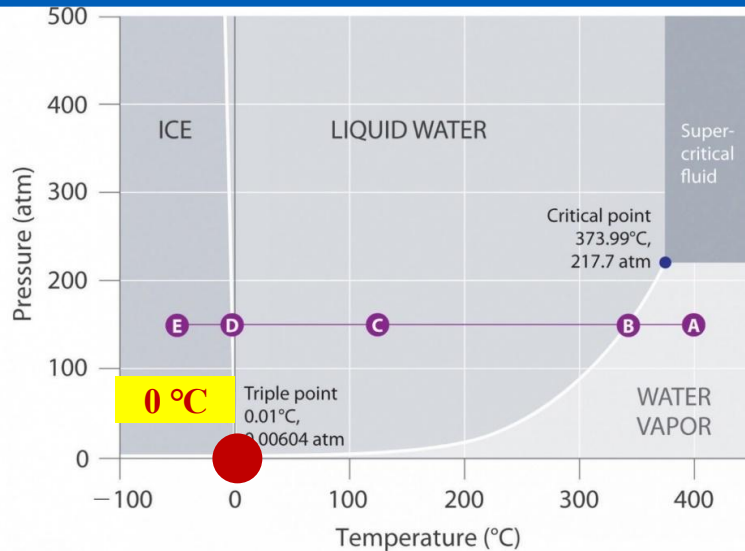
4. Conclusion



H₂O vs CO₂ : Lower Triple-Point Advantage

- Triple point of **H₂O is 0.01 °C at 0.611 kPa**, while **CO₂ is -56.6 °C at 0.518 MPa**.
- Therefore, the much lower triple point of CO₂ make it a more suitable working fluid for LNG cold energy utilization.
- **CO₂ has good properties enables sub-zero operation without freezing.**

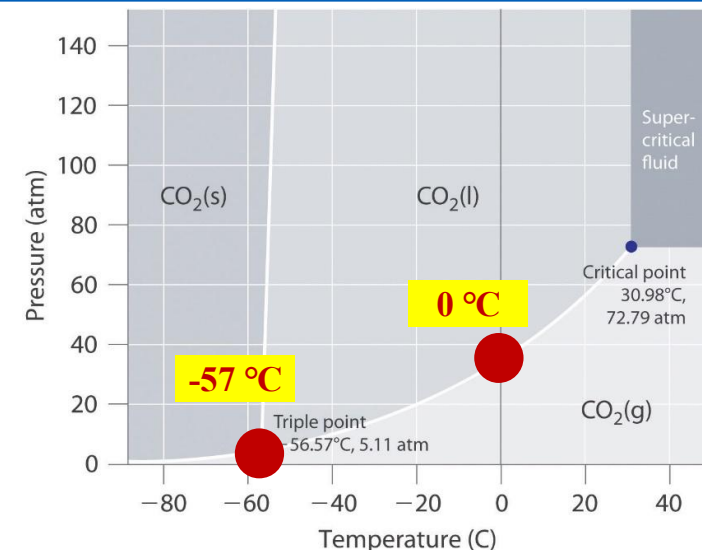
Conventional steam GT-ST CCPP



Critical Point of H₂O : 22.1 MPa / 374 °C

Triple point of H₂O : 0.611 kPa / 0.01 °C

Proposed cold energy GT-CO₂ CCPP



Critical Point of CO₂ : 7.4 MPa / 31 °C

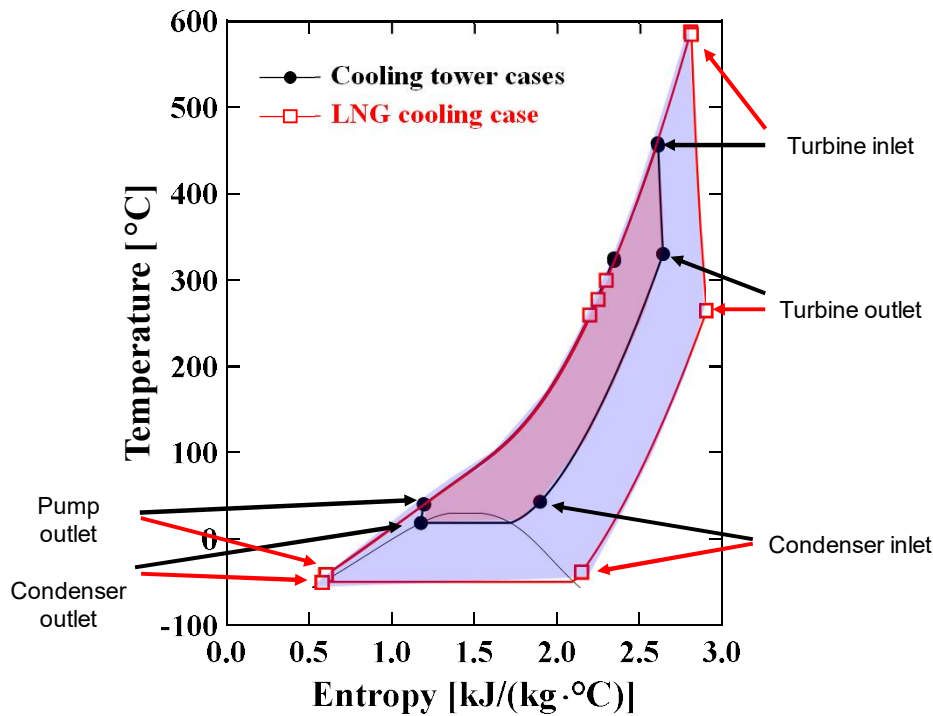
Triple point of CO₂ : 0.5 MPa / -57 °C



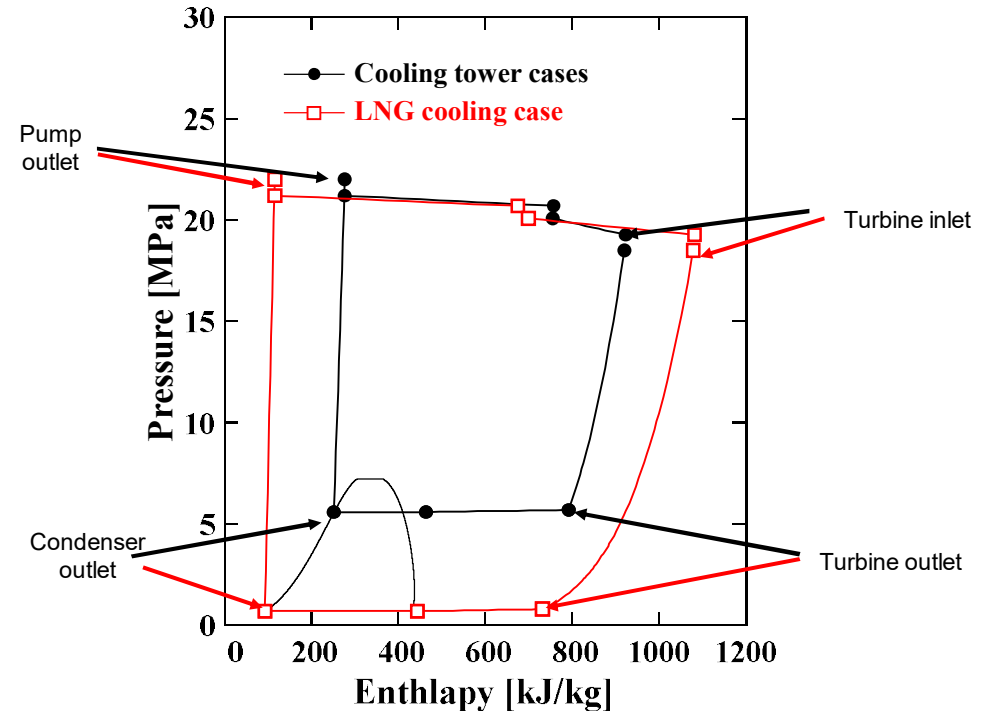
CO₂ cycle enhancement with LNG cold energy

- LNG cold energy enables deep sub-ambient heat rejection (44°C → -38°C), increasing the CO₂ turbine pressure ratio (4 → 23), lowering CO₂ pump inlet temp. (19°C → -50°C) and boosting specific work (120 → 307 kJ/kg)

T-s diagram of CO₂ Cycle



P-h diagram of CO₂ Cycle



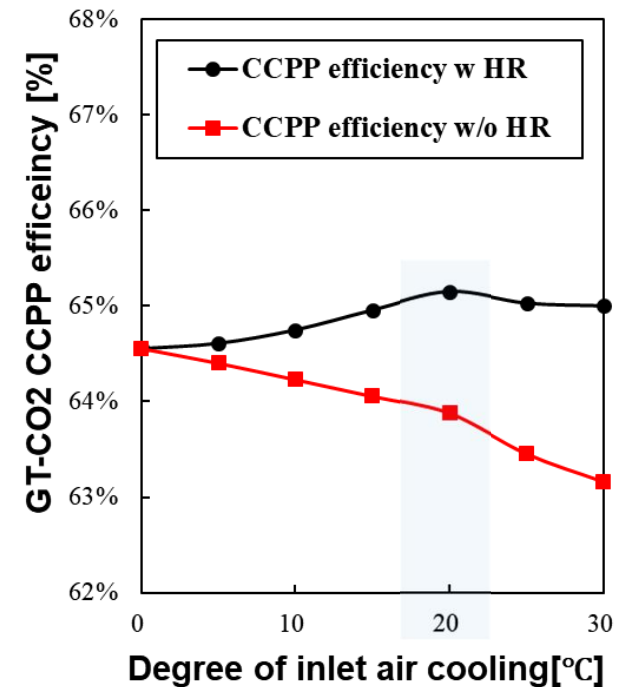
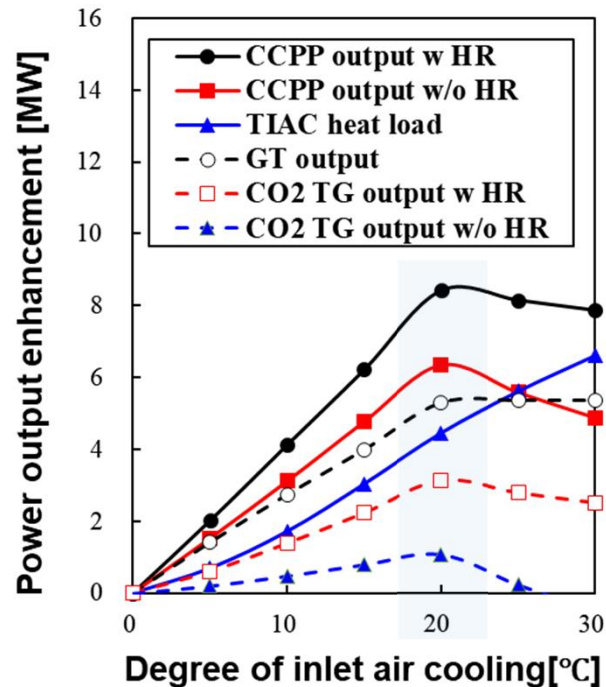


Effect of TIAC & HR Cooling degree on performance

- Turbine Inlet Air Cooling (TIAC) boosts CCPP power output by ~ 10%, while air side air Heat Recovery (HR) into the CO₂ bottoming cycle improves overall CCPP efficiency by ~ 2%.

Power enhancement by TIAC & HR

Efficiency improvement by TIAC & HR



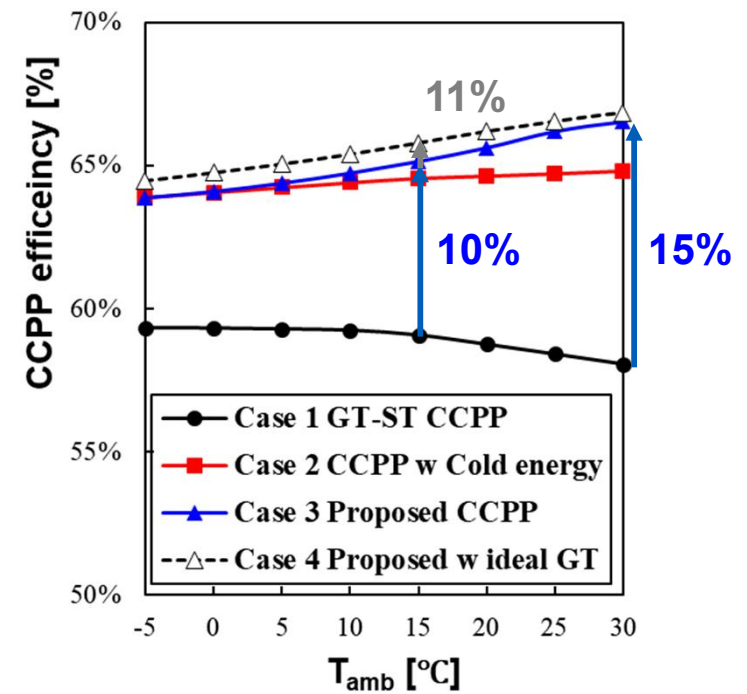
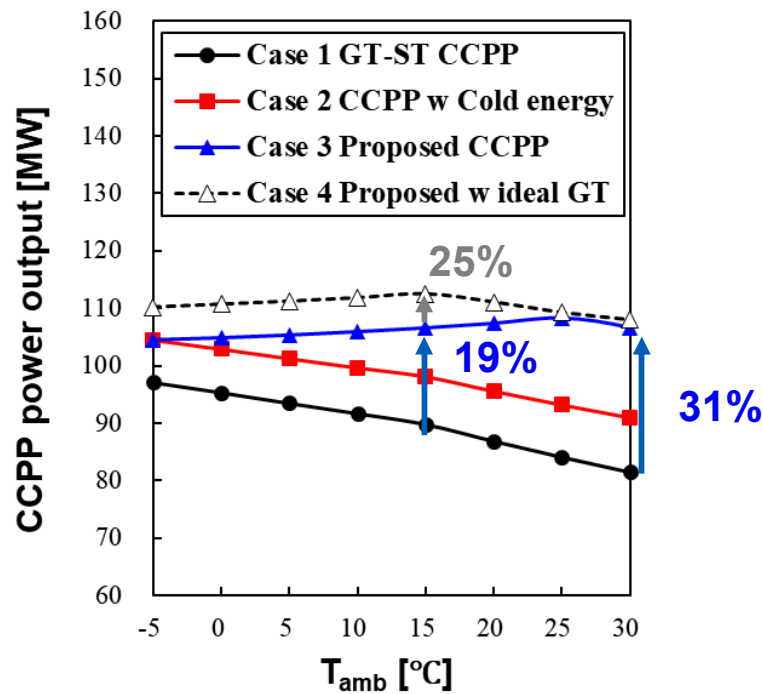


Effect of Ambient Temperature on performance

- Novel GT-CO₂ Concept boosts power output by ~19% (89.8 MW → 106.6 MW) and improves efficiency by 10% (+6%.pts, 59.1% → 65.1%) at 15°C (vs. Case1). Further gain are possible with ideal GT performance curve (Case 4)
- Hot weather is favorable, output by 31% (81.5 → 106.6 MW) and efficiency by 15% (8.8%.pts, 58.1 → 66.9%) at 30°C

Power output according to ambient air

Efficiency according to ambient air





Performance Summary

- The Suggested Novel Concept improved thermal performance significantly
- TIAC (+15 - 30% power output) + air Heat Recovery (1-2% efficiency gain) + LNG Cold Recovery (~9% eff. gain)

Parameter	Case 1	Case 2	Case 3	Case 4
Cooling Source	Cooling Tower	LNG Cold energy	LNG Cold energy	LNG Cold energy
TIAC & HR application	N/A	N/A	Applied	Applied
Bottoming Configuration	3PNRH Steam Cycle	Partial Heating CO ₂ Cycle	Partial Heating CO ₂ Cycle	Partial Heating CO ₂ Cycle
Gas turbine output [MW]	61.2	61.2	66.5	71.4
Gas turbine efficiency [%]	40.3	40.3	40.6	41.7
Btm cycle shaft power [MW]	29.5	40.2	43.6	44.8
Bottoming pump power [MW]	0.5	2.7	2.9	3.1
Bottoming net output [MW]	28.6	36.9	40.1	41.1
Regasification LNG Flow [t/h]	N/A	284.2 (2.5 MTPA)	311.9 (2.7 MTPA)	323.4 (2.8 MTPA)
Combined Cycle output [MW]	89.8 (Base)	98.1 (109.3%)	106.6 (118.7%)	112.5 (125.2%)
Combined cycle Efficiency [%]	59.1 (Base)	64.6 (109.3%)	65.1 (110.3%)	65.8 (111.4%)
Remark	Reference case		SGT-800 GT per. curve	Ideal GT per. Curve w modi.



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Conclusion

- **Enhanced Sector Coupling (Industrial Integration)**
 - A **Novel sector–coupling concept** that integrate **LNG terminals** with **Combined–Cycle Power Plants** enables effective utilization of LNG cold energy, delivering **significant system–level efficiency gains**.
 - This concept covers ~ 60% of LNG terminals and has potential for ~ 90% of LNG terminals
- **Thermodynamic Performance Improvements**
 - At 15 °C (ISO), novel concept (GT-CO₂ CCPP, Case 3) achieves **~19% higher power output** and **~10% higher overall efficiency** vs. the reference (GT-ST CCPP, Case 1), enabled by TIAC & HR integration
 - With idealized GT performance curve (Case 4), the GT-CO₂ CCPP can improve further (**~25% higher power output** and **~11% higher efficiency**)
 - At 30°C, benefits increase to **~ 31% higher** power output and **~ 15% higher** efficiency (vs. reference), showing that **hot weather is favorable** for the Novel Concept.
- **Future Potential**
 - By leveraging **CO₂ properties advantages** (e.g., effective sub-zero operation and compact turbomachinery), this work **proposes CO₂-cycle applications space (LNG cold energy utilization)** beyond traditional focus domains (i.e., Nuclear/CSP/NGCC/energy storage and Oxy-Combustion) and strengthening LNG terminal–Power Plant integration.



THANK YOU

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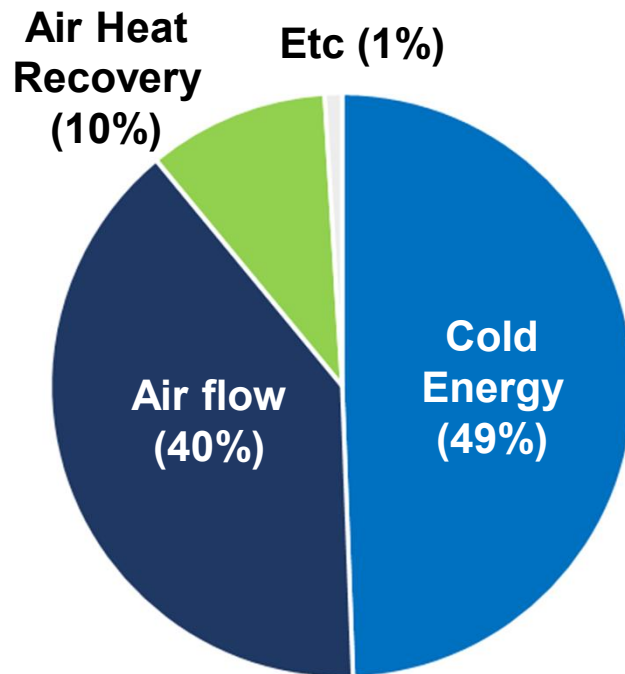
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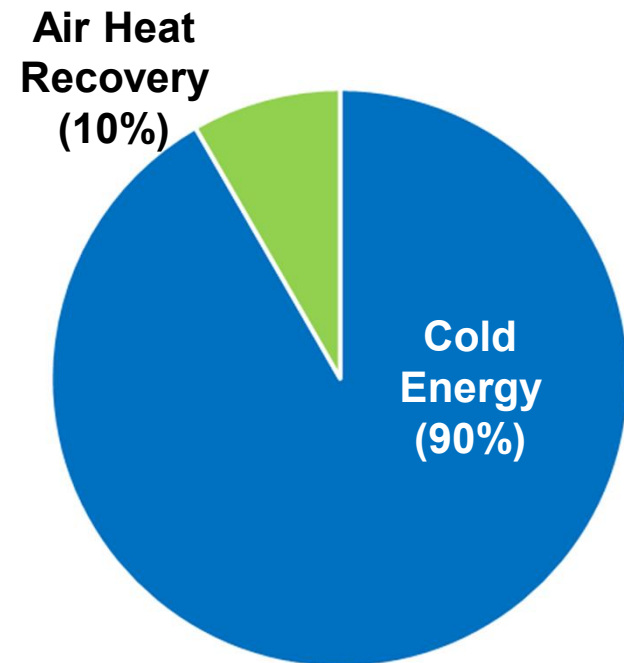
Appendix : Back-up for Q&A

- Expected Question : It seems that the power and efficiency gains are driven by a combination of TIAC, HR, and LNG cold-energy utilization. Can we isolate and quantify the individual contribution of each factor?

Power output improvement portion



Efficiency improvement portion





Appendix : Back-up for Q&A

- Expected Question : As the pressure ratio increases, could the CO₂ cycle's key benefits—compact turbomachinery and high power density—be diminished or offset?

Parameters	Steam turbine	CO ₂ Turbine	CO ₂ Turbine	CO ₂ Turbine
Condensate Temp. [°C]	29.0	30.0	18.8	-50.0
Cooling Source	Cooling Tower	Cooling Tower	Cooling Tower	LNG cold energy
Turbine inlet pressure [bar.a]	125	185	185	185
Turbine exhaust pressure [bar.a]	0.04	73.3	56.9	8
Pressure ratio [-]	3125	2.5	3.3	23.1
Turbine exhaust temperature [°C]	29.0	331	330	249
Specific volume [m ³ /kg]	29.3	0.015	0.020	0.123
Turbine exhaust volume flow [m ³ /s]	690	4.64	4.83	16.4
Ratio of volume flow [-]	base	1 / 149	1 / 143	1 / 42.0



Appendix : Back-up for Q&A

- Expected Question : How did you define the cycle efficiency, power output, turbine efficiency, and pump efficiency? Also, were the cases at different ambient conditions simulated as off-design points, or were they treated as separate design-point simulations?

$$\eta_{GT} = \frac{\dot{W}_{GT}}{\dot{m}_{fuel} \times LHV_{fuel}}$$

$$\eta_{CCPP} = \frac{\dot{W}_{GT} + \dot{W}_{ST \text{ or } CO_2T}}{\dot{m}_{fuel} \times LHV_{fuel}}$$

$$\eta_{turbine,CO_2} = \frac{(h_{turbine,in} - h_{turbine,out})}{(h_{turbine,in} - h_{turbine,out,Isentropic})}$$

$$\eta_{pump,CO_2} = \frac{(h_{pump,out,Isentropic} - h_{pump,in})}{(h_{pump,out} - h_{pump,in})}$$

$$\dot{W}_{GT} = \dot{W}_{turbineGT} - \dot{W}_{compressor} - \dot{W}_{mechanical\ loss} - \dot{W}_{generator\ loss}$$

$$\dot{W}_{ST} = \dot{W}_{turbine,HP} + \dot{W}_{turbine,IP} + \dot{W}_{turbine,LP}$$

$$\dot{W}_{CO_2T} = \dot{W}_{turbine,CO_2} - \dot{W}_{pump,CO_2} - \dot{W}_{mechanical\ loss}$$

$$\dot{W}_{turbine,CO_2} = \dot{m}_{CO_2} (h_{turbine,in} - h_{turbine,out})$$

$$\dot{W}_{pump,CO_2} = \dot{m}_{CO_2} (h_{pump,out} - h_{pump,in})$$

→ Answer : In this study, the different operating conditions were simulated as design mode. However, off-design analysis can be referenced as following.

	Off-design modeling & Boundary condition data
Gas Turbine data	• OEM GT curve
Steam Turbine & CO₂ Turbine	• Inlet Flow and Inlet pressure correction → Stodola Equation • Efficiency correction by Volumetric flow
Pump	• Variable Speed • Head – Flow Curve set • Efficiency – Flow curve set
Heat exchanger	• Heat transfer coefficient correction by (Mass flow) ^{0.78} or ^{0.61} • Pressure difference correction by (volume) ¹ and (mass) ²
Ambient air Temperature	• 10 years data from Korea Meteorological Administration • (Monthly Ambient Temperature: – 2 ~ 26 °C)
LNG demand	• LNG demand fluctuation data (64 ~ 151% of 342 t/h)



Appendix : Back-up for Q&A

- Expected Question : In the other cases, efficiency decreases (or stays roughly constant) as ambient temperature increases. Why does efficiency increase with ambient temperature in this concept?
→ Answer : **Ambient-temperature effect on efficiency (air-side heat recovery)**
As ambient temperature increases, the amount of air-side heat recovery increases. In particular, with relative humidity fixed at 60%, the latent heat associated with water condensation rises significantly, which increases the recoverable heat and contributes to higher efficiency.
- Expected Question : Did you assess alternative cycle configurations for utilizing LNG cold energy (beyond the selected configuration)
→ Answer : **CO₂ cycle configurations**
I have evaluated both a partial-heating CO₂ cycle and a cascade CO₂ cycle. The partial-heating configuration showed better overall performance under our boundary conditions, so we retained it as the baseline configuration.
- Expected Question : What was the rationale for choosing a 6 MTPA regasification terminal rather than 3 MTPA as the reference case?
→ Answer : **Why a 6 MTPA LNG terminal (not 3 MTPA)**
LNG demand shows strong seasonal variation. Because winter and summer demand can differ by nearly a factor of two, I have assumed that at least about half of a 6 MTPA terminal's throughput can be maintained, supporting more stable baseload operation for GT-CO₂ CCPP. Therefore, although a 6 MTPA terminal represents roughly 60% of global terminal capacity, we selected 6 MTPA as the baseline for stable operation.