




## Thermodynamic Analysis of GT-CO<sub>2</sub> Combined Cycles Utilizing Liquified Natural Gas Cold Energy

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### ABSTRACT

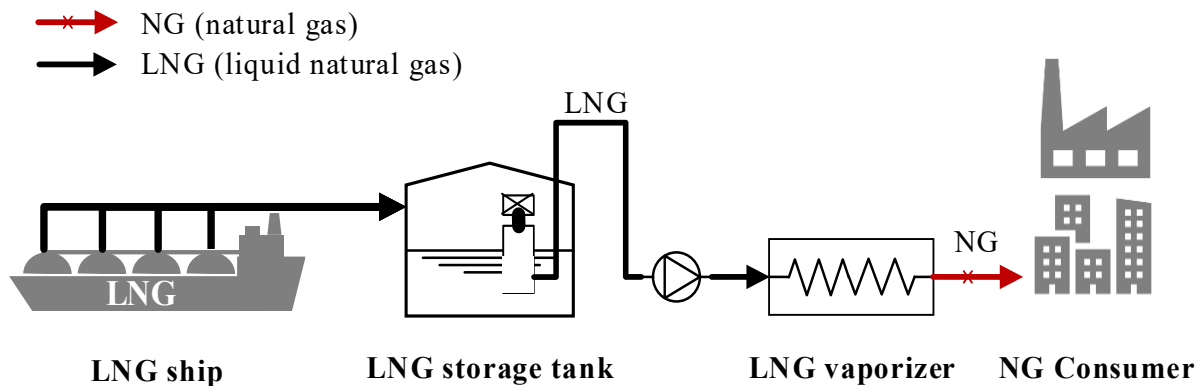
Research on the carbon dioxide (CO<sub>2</sub>) cycle has been conducted across various fields, including nuclear power plants, centralized solar power plants, natural gas combined cycle power plants, energy storage, and LNG cold energy recovery. In contrast to the conventional steam Rankine cycle, the CO<sub>2</sub> cycle enables higher performance by utilizing sub-zero temperature when LNG cold energy is available. This study proposes a novel configuration for a gas turbine–CO<sub>2</sub> combined cycle power plant (GT–CO<sub>2</sub> CCGT), integrating a turbine inlet air cooling (TIAC) and heat recovery (HR) system that leverages LNG cold energy. The TIAC and HR system cools the gas turbine inlet air using condensed CO<sub>2</sub>, thereby increasing power output. Simultaneously, the recovered air energy is utilized into the CO<sub>2</sub> bottoming cycle to produce additional power generation and increase overall thermal efficiency. The thermal performance

of the proposed configuration is analyzed based on a 62 MW SGT-800 gas turbine and compared to a conventional GT–steam CCPP. The results show that the proposed system enables an 18.7% (16.8 MWe) increase in power output and a 10.3% (6.0 percentage points) in efficiency compared to the conventional GT–steam CCPP. Moreover, the performance is favorable under higher ambient temperatures.

## INTRODUCTION

Research on CO<sub>2</sub> power cycles has researched across multiple application domains, including sodium-cooled fast reactor (SFR) nuclear power, concentrated solar power (CSP), combined cycle power plants (CCPP/GTCC), grid-scale energy storage, and liquefied natural gas (LNG) cold energy recovery. Among these, the CO<sub>2</sub> cycle can deliver higher specific power and thermal efficiency than the conventional steam Rankine cycle, especially when a sub-zero heat sink is available utilizing LNG cold energy [1]. It is expected that the research attention on CO<sub>2</sub> cycle to grow with increasing global LNG demand.

The CO<sub>2</sub> cycle has attracted sustained attention as a technology that can simultaneously enhance safety and efficiency in SFR-based nuclear power [2]. It has been investigated for solar thermal applications, where thermal efficiencies exceeding 50% [3], and for CCPPs where the compactness and high power density of CO<sub>2</sub> turbomachinery are advantageous [4]. Owing to its ability to operate effectively at sub-zero temperatures, CO<sub>2</sub> cycles have been widely studied for LNG cold energy recovery [5]. More recently, CO<sub>2</sub> cycles have also been integrated into carbon dioxide energy storage (CO<sub>2</sub>-ES) systems that store surplus renewable electricity and discharge during peak demand [6, 7].



**Figure 1. Overview of the LNG terminal regasification process**

When natural gas is liquefied, its volume condenses to roughly 1/600 of the gaseous state, facilitating marine transport as LNG [8, 9]. Figure 1 illustrates the regasification process at consumer-country terminals. LNG is imported at approximately  $-162\text{ }^{\circ}\text{C}$ , passes through LNG vaporizers for regasification, and is delivered as natural gas at around  $10\text{ }^{\circ}\text{C}$  to end-users such as households and natural gas-fired power plants. The literature estimates that approximately 20 GW of LNG cold energy remains unutilized globally [8, 9]. For reference LNG terminals with a capacity  $\geq 3$  MTPA (Million Ton per annum) constitute  $\sim 90\%$  of global capacity based on worldwide survey, while those  $\geq 6$  MTPA account for  $\sim 60\%$  as shown in Table 1. For this study, a 6 MTPA regasification terminal is selected as a baseline, which can provide about  $160\text{ MW}_{\text{th}}$  of cold energy [8], where there is a potential opportunity to cover about 60% of worldwide LNG receiving terminal application.

Table 1 LNG receiving terminal capacity [10]

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%)

While Organic Rankine Cycle (ORC) and steam Rankine cycles are viable options for cold energy power generation, the CO<sub>2</sub> cycle also has substantial potential to recover this LNG cold energy. The working fluid in a steam Rankine cycle is H<sub>2</sub>O with a triple point at 273.16 K (0.01 °C), whereas a closed CO<sub>2</sub> cycle uses CO<sub>2</sub> with a triple point at 216.55 K (-56.60 °C). Consequently, CO<sub>2</sub> cycles can operate stably under sub-zero temperature range, allowing lower heat-rejection temperatures and improved thermodynamic second-law efficiency, with performance benefits [5]. Prior studies have reported > 50% cycle efficiency when operating with a -50 °C heat sink.

Meanwhile, previous research has shown that turbine inlet air cooling (TIAC) using LNG cold energy can increase gas turbine (GT) net power [11]. Additional studies have applied transcritical CO<sub>2</sub> (tCO<sub>2</sub>) refrigeration or ORC-based cooling to the inlet air of GT-steam CCPPs, yielding gains in both output and efficiency [12, 13].

Although previous literature is focused on turbine inlet temperature in CO<sub>2</sub> cycles, few studies have targeted efficiency improvement via bottoming CO<sub>2</sub> cycle which is deeply coupled between a gas turbine topping cycle and a CO<sub>2</sub> bottoming cycle. This study proposes a GT-CO<sub>2</sub> combined cycle power plant configuration that leverages LNG cold energy to enhance overall plant efficiency, while using the CO<sub>2</sub> working fluid to deliver TIAC, thereby increasing inlet air density and GT output. Moreover, absorbed cooling duty in the TIAC/HR heat exchanger, from ambient air, is recovered within the CO<sub>2</sub> bottoming cycle to further improve cycle efficiency. This study presents a comprehensive thermal performance analysis of this configuration benchmarked a conventional GT-steam CCPP [14]. The results shows that the GT-CO<sub>2</sub> configuration achieves higher performance.

## SYSTEM DESCRIPTION

### Case 1 - Reference Gas turbine – Steam Turbine Combined Cycle Power Plant (GT-ST CCPP)

The reference GT–ST CCPP is based on a 62.5 MWe SGT-800 gas turbine, delivering approximately 88 MW net power output and 59% Lower Heating Value (LHV) efficiency in a combined cycle configuration [14]. This gas turbine (SGT-800) is suitable for 3 MTPA design capacity, which corresponds to about 80 MW<sub>th</sub> of cold energy, but is targeted for 6 MTPA, which corresponds to 160 MW<sub>th</sub> of cold energy per LNG terminal, that cover 60% of global LNG terminal capacity when considering annual LNG demand fluctuations [8].

Under ISO conditions, the SGT-800 has performance with a power rating of 61.2 MWe and LHV efficiency of 40.3%, with an exhaust temperature of 590 °C and mass flow rate of 138.5 kg/s in the combined cycle. When the inlet air temperature is reduced to –5 °C from 15 °C, the output increases to 66.9 MWe, efficiency improves to 40.7%, exhaust temperature drops to 582 °C, and mass flow increases to 146.2 kg/s.

Because the gas turbine exhaust is still high enough to recovery to bottoming cycle, the system equipped a heat recovery steam generator (HRSG) to produce steam for the bottoming cycle, thereby generate additional power. The bottoming cycle configuration is Triple Pressure Non-Reheat (3PNRH) referenced for SGT-800 systems [14]. The steam turbine inlet conditions are designed at 12.5 MPa and 566 °C [1], with an exhaust pressure of 4 kPa, assuming a cooling tower for heat rejection [14]. Steam turbine isentropic efficiency is assumed at 88% for HP/IP/LP stages, and generator efficiency at 98.5%. Additional modeling details and stream tables are available in prior studies [1], and summarized in Table 2.

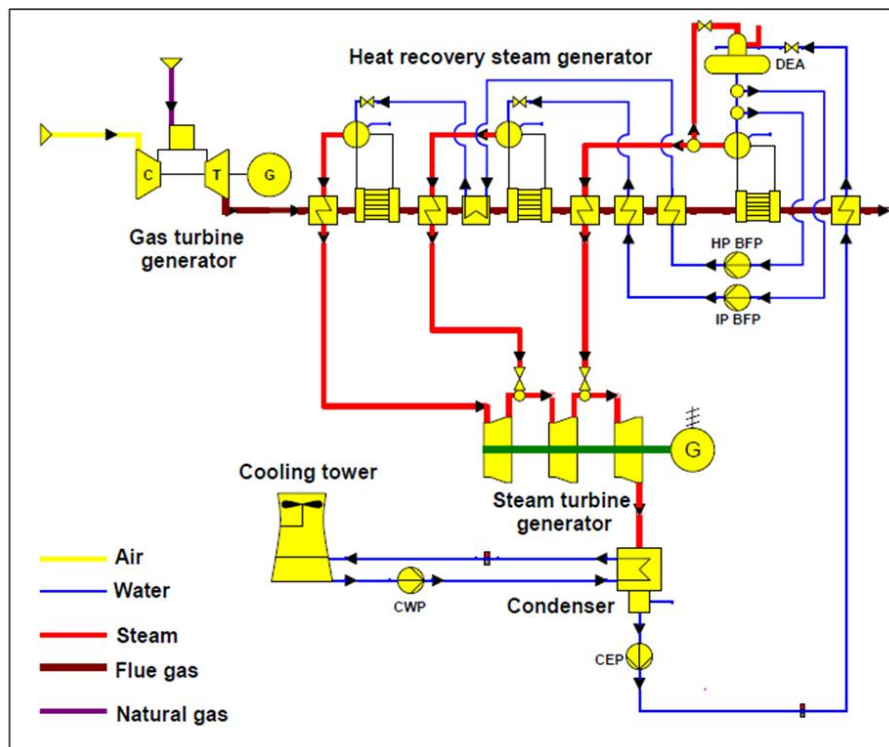


Figure 2. Reference Natural gas fired GT-ST CCPP

**Table 2. Combined cycle modeling parameters [1]**

		Case 1 (reference case)	Case 2 (GT-CO <sub>2</sub> CCPP)	Case 3 / Case 4 (Proposed CCPP)
Gas turbine	Model	SGT-800	SGT-800	SGT-800
	Ambient Temp. / Pressure / RH	15 °C / 1.013 bar /60%	15 °C / 1.013 bar /60%	15 °C / 1.013 bar /60%
	Power output	61.2 MW	61.2 MW	66.5 MW
	LHV Efficiency	40.3%	40.3%	40.6%
	Exhaust mass flow	138.5 kg/s	138.5 kg/s	146.2 kg/s
	Exhaust temp.	590.1 °C	590.1 °C	582.3 °C
	compressor inlet air temperature	15 °C	15 °C	- 5 °C (SGT-800) / -15 °C (Ideal GT curve)
Bottoming cycle configuration		3PNRH cycle (Steam Cycle)	Partial heating (CO <sub>2</sub> Cycle)	Partial heating w TIAC & HR (CO <sub>2</sub> Cycle)
Cooling source		Cooling Tower	LNG cold energy	LNG cold energy
Steam or CO <sub>2</sub> Turbine	Isentropic Efficiency	88%	88%	88%
	Inlet Pressure	12.5 MPa	18.5 MPa	18.5 MPa
	Outlet pressure	4 kPa	0.7 MPa	0.7 MPa
HRSG or WHE Pinch		8 °C	8 °C	8 °C
Piping pressure loss		4% / 3% / 10%	4% / 3%	4% / 3%
Piping heat loss		3 °C	3 °C	3 °C
Recuperator pinch		N/A	3 °C	3 °C
Recuperator press. difference		N/A	1 bar	1 bar
Pump Isentropic efficiency		80%	80%	80%
Generator efficiency		98.5%	98.5%	98.5%

## Case 2 - Gas turbine – Carbon Dioxide Combined Cycle Power Plant (GT-CO<sub>2</sub> CCPP) utilizing LNG Cold energy

Figure 3 illustrates the natural gas-fired GT–CO<sub>2</sub> CCPP configuration that recovers LNG cold energy to lower the CO<sub>2</sub> condensation temperature to sub-zero levels. The gas turbine performance is identical to that of the reference GT–ST CCPP. However, the steam bottoming cycle is replaced with a CO<sub>2</sub> partial heating cycle, and LNG cold energy is utilized for CO<sub>2</sub> working fluid condensation, lowering the CO<sub>2</sub> pump inlet temperature to –50 °C from ambient conditions. The CO<sub>2</sub> flow splits into two paths. One stream passes through the recuperator for preheating. The other stream flows to partial heating in a low-temperature waste heat exchanger (LT-WHE). The two streams then merge and are further heated via a high-temperature waste heat exchanger (HT-WHE) before entering the CO<sub>2</sub> turbine. The CO<sub>2</sub> turbine inlet pressure is set at 18.5 MPa, comparable to state-of-the-art steam Rankine cycles, while the outlet pressure is 0.8 MPa, resulting in a pressure ratio of 23—significantly higher than the typical CO<sub>2</sub> cycle range of 2–5. This improvement is enabled by LNG cold energy utilization. The turbine isentropic efficiency is assumed at 88%, consistent with Case 1, and pump efficiency at 80%. A recuperator pinch point of 3 °C, and pressure drop of 1 bar are considered. Other design parameters aligned literature standards [1].

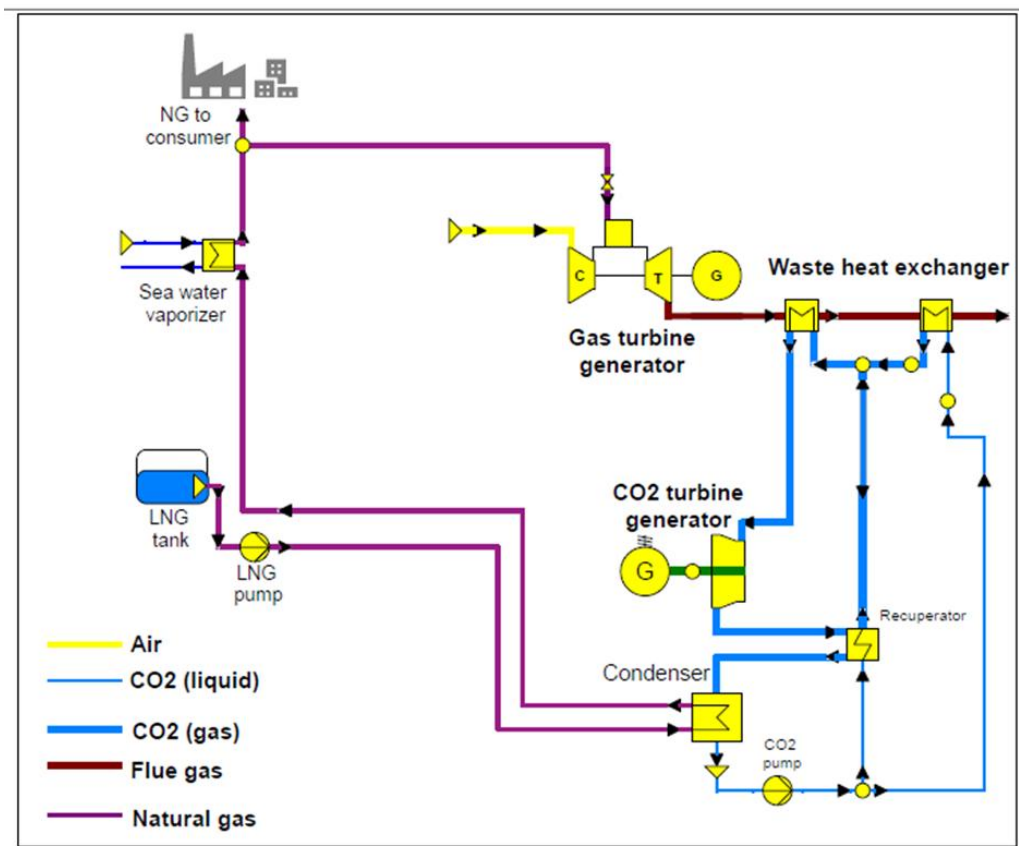


Figure 3. Natural gas fired GT-CO<sub>2</sub> CCPP

### Case 3 - Gas turbine – Carbon Dioxide Combined Cycle Power Plant (GT-CO<sub>2</sub> CCPP) with TIAC & HR utilizing Cold energy

Figure 4 shows the proposed cycle configuration. The design conditions are identical to Case 2, except that a portion of the CO<sub>2</sub> flow route directed to the LT-WHE is changed to a Turbine Inlet Air Cooling (TIAC) and Heat Recovery (HR) system. This system cools the gas turbine inlet air from 15 °C to -5 °C, achieving a 20 °C temperature drop under ISO conditions. The TIAC & HR system increases air density, thereby boosting gas turbine output, while simultaneously absorbing thermal energy from air that is recuperatively recovered in the CO<sub>2</sub> bottoming cycle. This integrated approach enhances both power output and overall cycle efficiency.

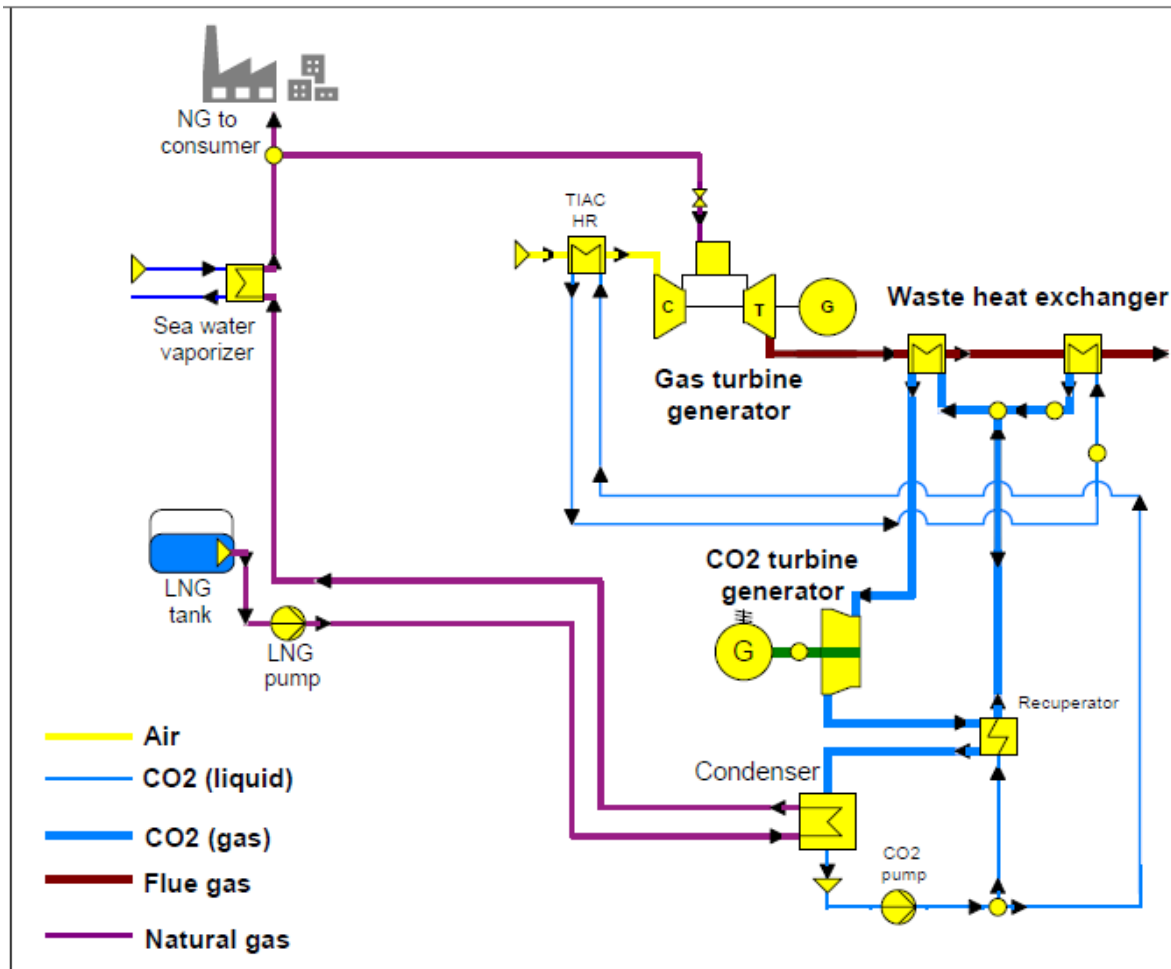


Figure 4. Natural gas fired GT-CO<sub>2</sub> CCPP with TIAC & HR

## MODELING DESCRIPTION

This study is conducted modeling and performance calculations using STEAG EBSILON® Professional v15 [15], a commercial process simulation software widely utilized for power plant thermodynamic analysis. The program performs iterative compute heat and mass balance constraints using robust numerical solution algorithms. For simulation study, Thermodynamic model is integrated and developed using embathed each mathematical component within EBSILON®. EBSILON® utilizes standard thermodynamic property libraries from REFPROP [16], and CO<sub>2</sub> properties is derived from REPROP, providing high flexibility for modeling complex energy systems. For water and steam properties, the IAPWS-IF97 formulation was adopted [17], ensuring compliance with internationally recognized standards for H<sub>2</sub>O thermodynamic behavior.

The gas turbine performance is derived from the ENEXSA Gas Turbine Library [18] as shown Figure 5 (a). The library referrer Gas turbine data from each OEM manufacturer, for SGT-800, it is mentioned that its reference is Siemens Plant Performance Estimation Program. For information, this correction curve has the limitation of power output under  $-5\text{ }^{\circ}\text{C}$ , however, If this constraint were removed—idealized gas turbine without low-temperature output restrictions—both power augmentation and efficiency improvement would be significantly greater, highlighting the potential benefits of TIAC integration under sub-ambient conditions. For information, the gas turbine curve with restriction is derived from same company difference model SGT-5000F.

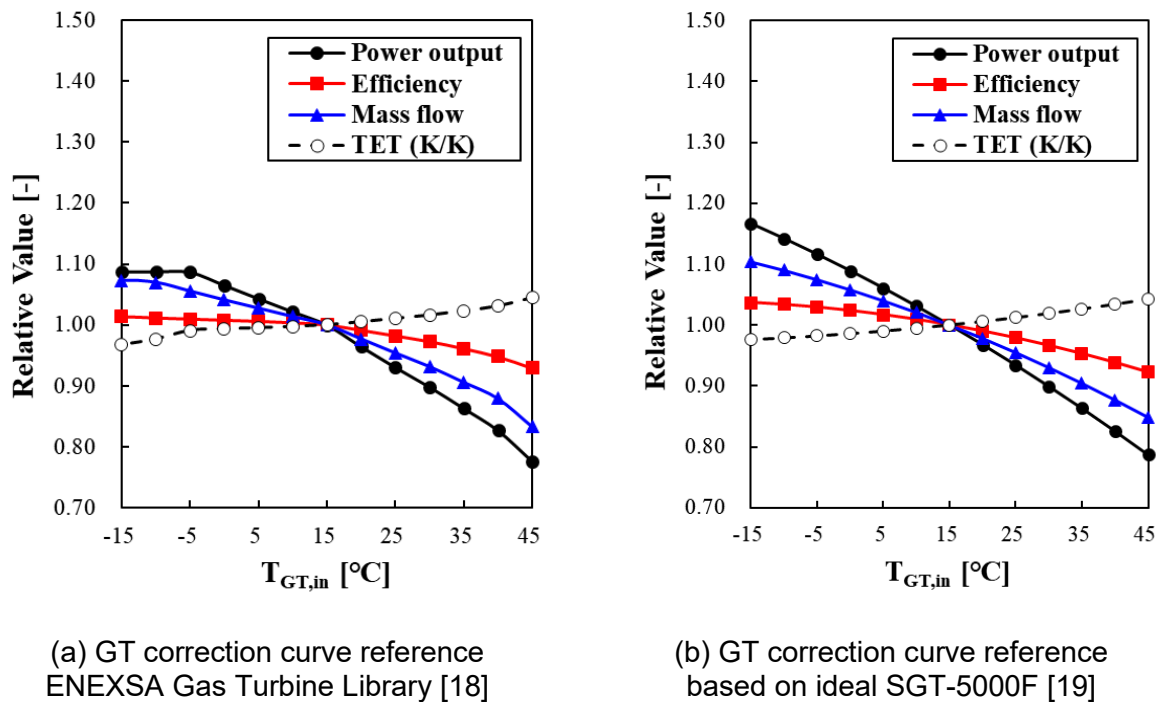


Figure 5. Gas turbine performance correction by compressor inlet air temperature

## RESULTS AND DISCUSSION

### Influence on the CO<sub>2</sub> bottoming cycle performance utilizing LNG cold energy

Figure 6 presents the T-s and P-h diagrams of the CO<sub>2</sub> bottoming cycle under conditions where LNG cold energy is available. The integration of LNG cold energy significantly enhances the thermodynamic performance of the CO<sub>2</sub> cycle. By utilizing LNG cold energy, the heat rejection temperature is reduced from 44 °C to -38 °C, enabling a substantial increase in the expansion ratio, which rises from 4 to 23. This improvement in pressure ratio directly translates into higher specific work output, which increases from 120 kJ/kg to 307 kJ/kg, representing a major performance gain compared to the baseline configuration.

The results confirm that deep sub-ambient heat rejection facilitated by LNG cold energy not only improves the second-law efficiency of the bottoming cycle but also unlocks a high-pressure ratio regime that is unattainable in conventional CO<sub>2</sub> cycles (typically limited to 2–5). This demonstrates the strong potential of LNG cold energy integration for next-generation combined cycle systems.

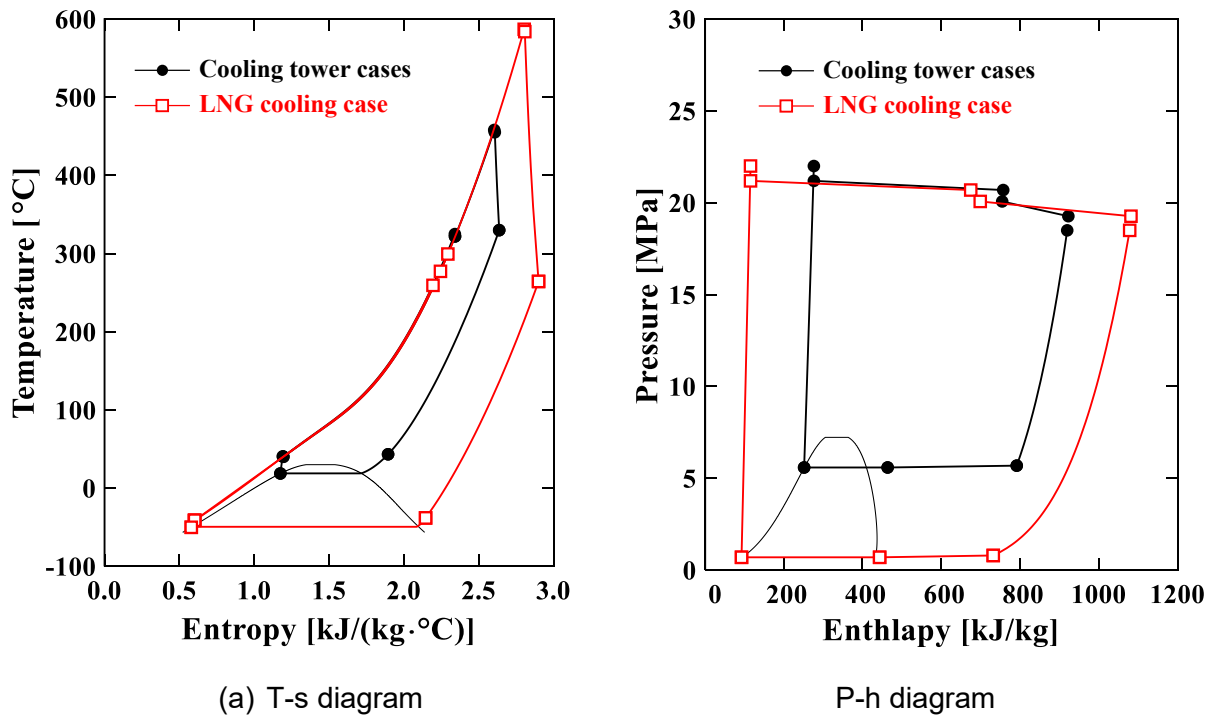


Figure 6. Influence on T-s and P-h diagram in the tCO<sub>2</sub> cycle according to the working fluid cooling option

## Influence on the GT-CO<sub>2</sub> CCPP performance according to TIAC & HR system

The application of Turbine Inlet Air Cooling (TIAC) enables a lowering in gas turbine inlet air temperature, thereby increasing air density and improving power output. This section evaluates the effect of recovering thermal energy absorbed during TIAC and integrating it into the CO<sub>2</sub> bottoming cycle.

Figure 7 illustrates the impact of TIAC cooling degree on the GT-CO<sub>2</sub> CCPP net output and the CO<sub>2</sub> cycle contribution under ISO conditions. Due to the gas turbine correction curve constraints, performance begins to deteriorate below -5 °C, making -5 °C the optimal inlet air temperature, as shown in Figure 7(a). At this condition, corresponding to a 20 °C cooling degree, the TIAC system recovers approximately 4.5 MW<sup>th</sup> of thermal energy, which is utilized to increase the CO<sub>2</sub> bottoming cycle net output by 2.1 MW.

In contrast, previous literature [1] reported continuous performance improvement down to -15 °C, highlighting the influence of power restriction in the correction curve on the present results. Figure 7(b) shows the effect of cooling degree on combined cycle efficiency. Without the proposed TIAC & HR system, the GT-CO<sub>2</sub> CCPP efficiency declines sharply beyond -5 °C, whereas with the system applied, the efficiency decrease is more gradual. At -5 °C, the recovered 4.5 MW<sup>th</sup> improves overall efficiency from 63.9% to 65.1%, a 2 % gain. Further cooling degrees of 25 °C and 30 °C yield efficiency improvements of 2.5% and 3.0%, respectively.

Compared to the idealized scenario in [1], where power restrictions are absent, the present results shows smaller gains, indicating that gas turbine output limitations significantly influence the performance benefits of the proposed system.

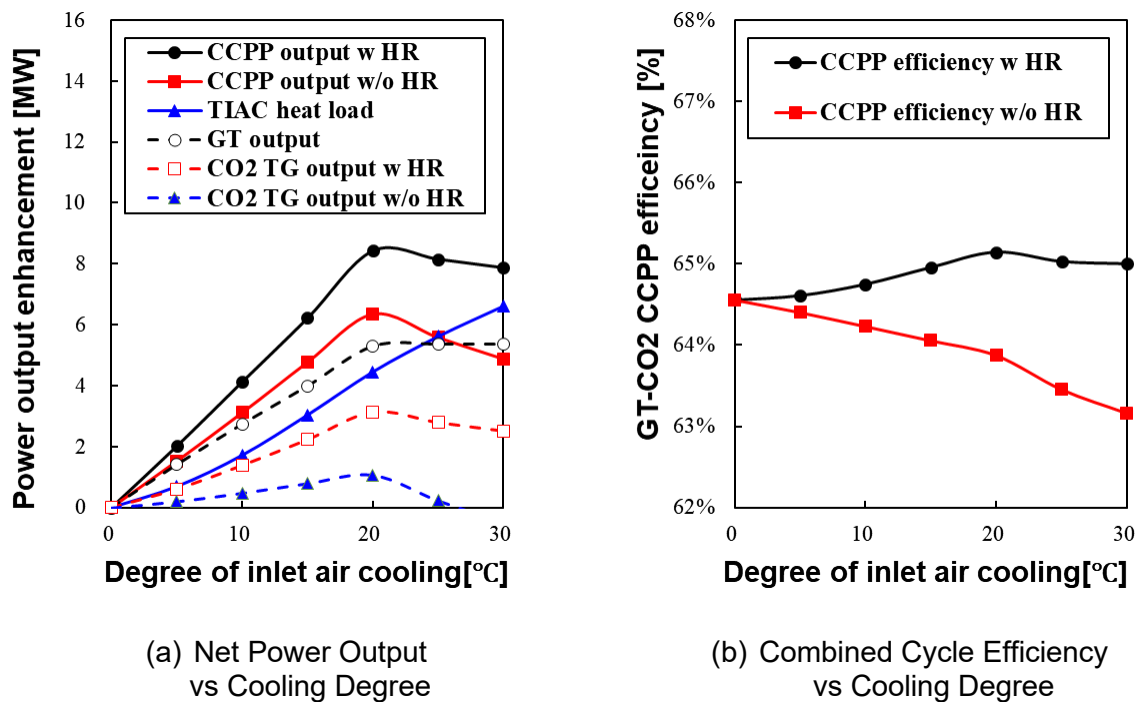


Figure 7. Influence on the GT-CO<sub>2</sub> CCPP performance according to TIAC & HR system

## Influence on the GT-CO<sub>2</sub> CCPP performance according to Ambient Temperature

Figure 8 illustrates the variation in net power output and overall efficiency according to ambient temperature. The reference GT-ST CCPP (Case 1) exhibits the lowest performance across all conditions due to the use of a cooling tower, which increases condenser vacuum pressure and heat rejection temperature as ambient temperature rises. Consequently, both gas turbine output and combined cycle efficiency decline with increasing ambient temperature. In Case 2 (GT-CO<sub>2</sub> CCPP utilizing LNG cold energy), the bottoming cycle benefits significantly from the sub-zero heat sink, improving efficiency compared to Case 1. In Case 2, similarly to Case 1, as ambient temperature increases, gas turbine inlet air density decreases, reducing GT output.

In contrast, Case 3 (GT-CO<sub>2</sub> CCPP with TIAC & HR) maintains stable GT output across the entire ambient temperature range. Moreover, higher ambient temperatures enable greater thermal energy recovery from the inlet air cooling process, resulting in progressive improvements in both output and efficiency. For example: At ISO conditions (15 °C), Case 3 achieves 106.6 MW net output and 65.6% efficiency, compared to Case 1, which is 18.7% lower in power and 10.3% lower in efficiency. At 30 °C ambient, Case 3 maintains 106.6 MW output and improves efficiency to 66.7%, corresponding to 30.8% higher power and 14.6% higher efficiency than Case 1. Relative to Case 2, Case 3 delivers 8.5% more power and 0.9% higher efficiency at ISO, and 17.2% more power and 2.6% higher efficiency at 30 °C. Case 4 show performance based on idealized Gas turbine, without low-temperature output restrictions, correction curve mentioned in Figure 5. (b), the CCPP performance would improve further.

Results show in Table 3 as well. These results show that the TIAC & HR integration not only mitigates the adverse effects of high ambient temperatures but also leverages them to enhance combined cycle efficiency, making the proposed configuration advantageous for hot-climate LNG terminal applications.

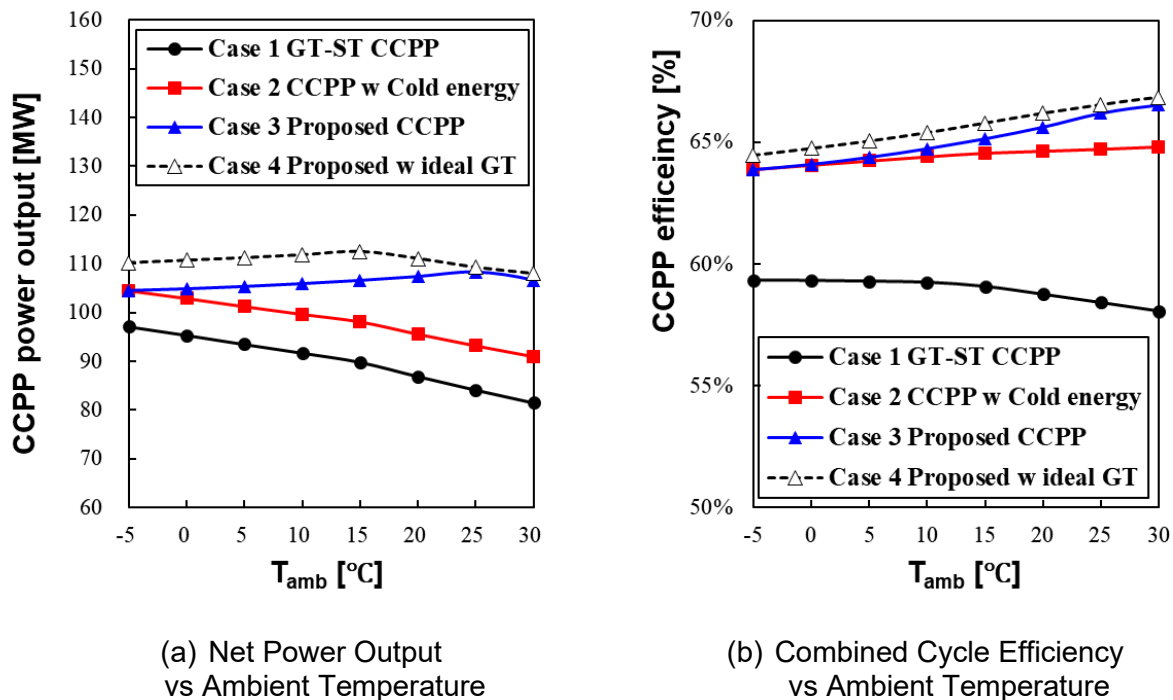


Figure 8. Influence on the CCPP performance according to ambient temperature

**Table 3. Performance Summary**

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 <sub>2</sub> Cycle	Partial Heating CO <sub>2</sub> Cycle	Partial Heating CO <sub>2</sub> 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%)

## CONCLUSION

This study investigated the performance enhancement potential of a GT–CO<sub>2</sub> Combined Cycle Power Plant (CCPP) equipped with a Turbine Inlet Air Cooling and Heat Recovery (TIAC & HR) system, leveraging LNG cold energy. Three case studies were conducted to validate the thermodynamic advantages of the proposed configuration. Compared to the reference GT–ST CCPP, the proposed system achieved 18.7% higher power output and 10.3% higher efficiency under ISO conditions. Relative to the baseline GT–CO<sub>2</sub> CCPP without TIAC & HR, the improvements were 8.6% in power output and 0.9% in efficiency, primarily due to maintaining gas turbine inlet air density and recovering thermal energy from the cooling process to generate additional bottoming cycle power.

The performance benefits increase with ambient temperature, making the system particularly advantageous for hot-climate LNG terminal applications. At 30 °C ambient, the proposed configuration delivers 30.8% higher power output and 14.6% higher efficiency compared to the GT–ST CCPP, and 17.2% higher power and 2.6% higher efficiency compared to the GT–CO<sub>2</sub> CCPP without TIAC & HR. These findings show that integrating LNG cold energy with TIAC & HR in GT–CO<sub>2</sub> CCPPs offers a significant effect for efficiency improvement and power augmentation, addressing Synergy between LNG receiving terminal and NG Combined cycle Power Plants.

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