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Design And Performance Evaluation Of A Carbon Capture Unit For A Combined Cycle Power Plant

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ABSTRACT

The examination of carbon dioxide capture systems is motivated by growing apprehensions regarding global greenhouse gas emissions as a viable method for mitigating climate change. This study examines the extraction of carbon dioxide (CO_2) from the Bismayah Power Plant in Baghdad, Iraq. The system consists of six stages, each generating 750 MW, resulting in a total power output of 4500 MW, and utilizes a natural gas combined cycle system. The impact of carbon capture on plant efficiency and power generation is under investigation. The post-combustion method, reliant on the absorption and adsorption capabilities of amines, is recognized as one of the most prevalent techniques owing to its high efficiency in carbon capture. The research utilized Thermo-flow and Aspen HYSYS 14 software® for analysis. The study concluded that the average carbon dioxide release to the ocean from the plant is 2.26 Mt CO_2 per year for each stage. The estimated total quantity of released CO_2 is approximately 14 Mt CO_2 per year. The incorporation of a carbon capture unit, achieving a capture efficiency of 90%, will lead to a 14% reduction in the overall efficiency of combined cycle power production, culminating in a net power decrease of 13.6%. This method has the potential to reduce annual carbon dioxide emissions to 0.22 Mt CO_2 per year. The emissions associated with electricity production are 40.6 grams of CO_2 per kilowatt-hour (g CO_2/kWh) with carbon capture and 376.85 g CO_2/kWh without it.

Kombine Çevrim Santrali İçin Karbon Yakalama Ünitesinin Tasarımı Ve Performans Değerlendirmesi

MAKALE BİLGİSİ

Anahtar Kelimeler:
Thermoflow®,
CO_2 giderimi,
Monoetanolamin,
Absorpsiyon,
Ayırıcı.

ÖZET

Karbondioksit yakalama sistemlerinin incelendiğinde, İklim Değişikliği zararlarını azaltmanın etkili bir yolu olarak artan küresel sera gazı emisyonlarının azaltmak olduğu net bir şekilde görülmektedir. Bu çalışma, Bağdat yakınlarındaki bir Elektrik Santrali'nden (Bismayah) karbondioksitin (CO_2) sistemsel olarak azaltılmasını analiz etmektedir. Sistem altı aşamadan oluşmaktadır; her aşama 750 MW, toplam 4500 MW güç üretmektedir. Santral doğal gaz kombine çevrim sistemiyle çalışmaktadır. Karbonun santralin verimliliği ve güç üretimi üzerindeki etkisi detaylı incelenmiştir. Amin kullanımı, yöntem olarak yanma sonrasında absorpsiyon ve adsorpsiyon ünitelerinde, karbon yakalamadaki yüksek verimliliği nedeniyle en yaygın yöntemlerden biri olarak kabul edilmektedir. Çalışma, Thermo-flow ve Aspen HYSYS 14 yazılımları® kullanılmıştır. Çalışma ile, santralden okyanusa salınan karbondioksit miktarı, ortalama 2.26 (Mt CO_2/yıl) değerine sahip olduğu ortaya çıkmıştır. Toplam salınan CO_2 miktarı yaklaşık 14 Mt CO_2/yıl olarak tahmin edilmiştir. %90 yakalama verimliliğine sahip bir karbon yakalama ünitesinin eklenmesi, kombine çevrim elektrik üretiminin genel verimliliğini %14 oranında düşürecek ve bu da %13.6'lık net bir güç azalmasına yol açacaktır. Bu yaklaşım, yıllık karbondioksit emisyonlarını 0.22 Mt CO_2/yıl'a kadar düşürmüştür. Karbon yakalayarak ve karbon yakalamaksızın elektrik üretimi için özgül emisyon değerleri sırasıyla herbir kilovatsaat için 40.6 gram CO_2 (g CO_2/kWh) ve 376.85 g CO_2/kWh'dir.

NOMENCLATURE

ACC	Air-cooled condensers	IEA	International Energy Agency
Ar	Argon	EPA	Environmental Protection Agency
CAPEX	Total capital cost	IGCC	Integrated gasification combined cycle
CC	Combined cycle	IRR	International rate of return
CCGT	Combined cycle gas turbine	LCOE	Levelized cost of electricity
CCPP	Combined cycle power plant	LHV	Lower heating value
CCS	Carbon capture and storage	LP	Low-pressure
CCUS	Carbon capture, utilization, and storage	MEA	Monoethanolamine
CMMS	Computerized maintenance management system	Mt CO2 yr^{-1}	Million tone CO2 per year
CO	Carbonmonoxide	MW	Megawatt
CO2	Carbondioxide	N2	Nitrogen
GE	General electric	NETL	National Energy Technology Laboratory
GHG	Greenhouse gas emission	NGCC	Natural gas combined cycle
Gt	Gigatons	NPV	Net Present Value
H2	Hydrogen	O2	Oxygen
H2O	Water	OPEX	Annual operating cost
H	Hour	PCC	Post-combustion capture
HP	High-pressure	PSA	Pressure swing adsorption
HRSGs	Heat recovery steam generators	ST	Steem turbine

INTRODUCTION

In light of the increasing evidence concerning the impacts of global warming, initiatives are being implemented to reduce direct greenhouse gas emissions, particularly carbon dioxide (CO2). The capture of carbon dioxide from power stations, refineries, and industrial exhaust has been acknowledged for its critical role in mitigating climate change over an extended timeframe (Shirmohammadi et al., 2020).

The International Energy Agency (IEA) report highlights the significance of carbon capture, utilization, and storage in facilitating the transition to a low-carbon energy economy (IEAGHG, 2023). The global estimate for carbon capture, utilization, and storage (CCUS) is projected to reach between 4 and 6 gigatons (Gt) of CO2 by 2050 (Razzaghianarmarzi, 2023). Fossil fuel-powered units release significant amounts of direct and indirect greenhouse gases into the atmosphere (Amed et al., 2021). Methane, carbon dioxide, nitrous oxides, and F-gases significantly contribute to environmental challenges. The implementation of carbon capture systems by 2030 is essential for addressing these issues (Guidehouse, 2023).

Global warming is exacerbated by human activities, resulting in unprecedented levels of greenhouse gas emissions (GHGs) (Ma et al., 2022). A method known as Carbon Capture, Utilization, and Storage (CCUS) was developed to mitigate climate change. The main goals of CCUS include capturing CO2 emissions prior to atmospheric release, repurposing the captured CO2 for beneficial uses, and ensuring its safe storage to reduce its impact on climate change (Kammerer et al., 2023). In 2019, the combustion of coal, natural gas, and oil for heating and electricity generation constituted 34% of global greenhouse gas emissions. The United States Environmental Protection Agency (EPA, 2024) indicates that reliance on fossil fuels persists in fulfilling global energy demands, despite the rapid advancement of renewable technologies. It is projected that by 2040, 78% of global energy consumption will continue to derive from fossil fuels, including oil, coal, and natural gas (Cao et al., 2020). While renewable energy technologies develop to effectively supplant fossil fuels, carbon capture, storage, and the utilization of fossil-based emissions are essential as a transitional strategy (Zhang et al., 2021).

Four techniques exist for addressing global warming: reducing greenhouse gas emissions, increasing employment in clean energy sources, enhancing energy efficiency, and implementing climate policies related to national strategies. Research output on carbon capture began to increase in 2008, coinciding with the implementation of global warming mitigation laws and heightened awareness among the public and businesses regarding clean fossil energy sources. Incentivized by these factors, 55 nations engaged in the pursuit of carbon capture technologies and related research, with the United States at the forefront of research output, succeeded by China and the United Kingdom. Post-combustion capture is the predominant carbon capture technology, representing around 80.9% of all published research (Omoregbe et al., 2020). Post-combustion CO2 capture is a method designed to reduce greenhouse gas emissions, particularly carbon dioxide (CO2), generated from the combustion of fossil fuels in power generation and industrial operations. This method removes CO2 from the exhaust gases generated during combustion, thus preventing its emission into the environment. The system can be integrated into existing facilities with minimal infrastructure modifications, making it a viable and cost-effective solution. There are three categories of carbon capture technologies: post-combustion, pre-combustion, and oxyfuel combustion (Olayebi, 2022). The predominant method for large-scale post-combustion CO2 capture from exhaust gas involves the absorption of CO2 using an amine-based solvent, specifically monoethanolamine (MEA) (Aforkoghene Aromada & Øi, 2015; Mahdi et al., 2021; Dehghanizadeh, 2023).

Figure 1. Bismayah 4500 MW combined cycle power facility.

Not all alkanol amines, despite their diversity, are suitable for carbon capture and storage (CCS) applications. Monoethanolamine (MEA), a straightforward alkanol amine, is commonly employed as a benchmark solvent in the development of new CCS solvents (Spuhl et al., 2011; Chu et al., 2016; Mangalapally & Hasse, 2011). Monoethanolamine (MEA) is favored as a solvent for CO2 capture from flue gas at low partial pressures due to its rapid reaction time (Vinet and Zhedanov, 2011; Gaspar et al., 2016). MEA exhibits the lowest cost and molecular weight among alkanol amines. The maximum potential for CO2 absorption by MEA arises from its lower molecular weight within chemical absorption systems. Amines can chemically absorb carbon dioxide (Anselmi et al., 2019).

At this juncture, CO2 is treated with an aqueous amine solvent. This chemical process results in the production of a water-soluble molecule (Figueroa et al., 2008). The relatively elevated vapor pressure of the MEA compound may lead to considerable losses due to evaporation, especially in low-pressure applications (Kohl and Nielsen, 1997). The degradation of MEA increases the demand for new MEA, incurs waste management costs, and may exacerbate corrosion problems (Merikoski, 2012). The integration of amine mixes can significantly reduce capital and operational expenses, as stated by Gaspar and et al., (2016). Alkanolamines has numerous drawbacks in the management of flue gas, despite their prevalent application as solvents for CO2 scrubbing. The primary disadvantages of utilizing alkanol amines as post-combustion capture (PCC) absorbents are the dimensions of the capture facility and the considerable energy required to renew the CO2-laden solvent (Ahmed Qamar et al., 2020).

Besides its significant energy consumption, the most commonly utilized amine, MEA, presents further disadvantages. MEA solutions exhibit a tendency to degrade over time and demonstrate a higher level of corrosiveness compared to the majority of other amines. The MEA compound exhibits a relatively high vapor pressure, leading to considerable vaporization losses, especially in low-pressure operations (de Riva et al., 2017). MEA degradation not only introduces waste disposal costs and potentially worsens corrosion issues but also heightens the need for replacement MEA (Flo, Kvamsdal, and Hillestad, 2016). Post-combustion carbon capture (PCC) is a crucial technique for mitigating CO2 emissions from power plants (Chao et al., 2021). PCC offers two primary advantages: its established technology and the capacity to retrofit existing power plants for prompt implementation (Notz et al., 2010). Although it may result in marginally reduced efficiency compared to pre-combustion capture and oxyfuel methods, it remains a viable option. Alternative PCC techniques, such as adsorption and membrane separation, are presently being developed for wider application (Chao et al., 2021). Monitoring metrics such as energy intensity and efficiency, as well as benefits like reduced energy costs and improved energy independence, can aid in redefining policy objectives (Kuzemko et al., 2016). Therefore, developing more efficient natural gas power plants equipped with CO2 capture technologies is essential. The combined cycle (CC), in conjunction with various CO2 collection techniques, has garnered significant attention (Marchioro Ystad et al., 2013; Kvamsdal et al., 2007). This study uniquely applies the well-documented technique of carbon capture using MEA to the Bismayah Combined Cycle Power Plant, the largest power plant in Iraq and one of the largest in the Middle East. This plant exhibits unique operating conditions, such as a hot, dry climate and limited emissions processing infrastructure, which render the integration of a carbon capture system a technical and economic challenge that differs from conventional published experiments. This research employs an integrated model that merges the simulation of the thermodynamic performance of the capture system (utilizing Aspen HYSYS) with a comprehensive assessment of the plant's performance (using Thermoflow), accounting for the impacts of steam extraction and variations in efficiency. The model was developed in conjunction with plant engineers, enabling the formulation of realistic operational scenarios that are practically applicable. This study offers a significant contribution that goes beyond theoretical frameworks to inform national energy and sustainability policies in Iraq. This research quantitatively assesses the effects of post-combustion carbon capture technology at the Bismayah combined cycle gas turbine facility. It employs thermal and chemical simulation tools to analyze the effects on thermal efficiency, CO_2 emissions, and both investment and operating costs.

MATERIALS AND METHODS

Combined cycle systems exhibit considerable potential for technological advancement and diverse applications. The main advantages consist of reduced investment costs, enhanced fuel efficiency, environmental sustainability, and a quicker return on investment. Advancements in gas turbine technology enable a range of outputs, accommodating various applications across multiple industries. Applications encompass industrial power plants, district heating utilities, and smaller in-plant power supply units for businesses necessitating process heat. This discussion includes both the construction of new power or heating facilities and the renovation or retrofitting of existing ones (Taner Elmas, 2024; Elmas 2024; Nord and Bolland, 2013; Ibrahim and Rahman, 2012).

Case Study: Power Plant Description

The Bismayah Power Plant is a significant modern power generation facility managed by the Iraqi Ministry of Electricity. Situated to the east of the capital, Baghdad. The project consists of six phases, each having a capacity of 750 MW. The facility utilizes a combined cycle system that includes 18 production units, which are made up of 12 gas turbines and 6 steam turbines. The plant's total capacity is 4500 MW (Bismaya, 2022). The gas generating units are of the 9F-frame type, produced by General

Electric (GE), and primarily utilize natural gas, with diesel fuel serving as a backup when required. The Power Plant commenced operations in early 2017 and has notably enhanced the electrical supply to Baghdad and adjacent governorates, especially during peak demand periods, such as summer. This facility employs steam units C-7 and D-200 from General Electric (GE) in conjunction with various equipment sourced from Europe. This comprises four vertical two-stage high-pressure (HP) and low-pressure (LP) heat recovery steam generators (HRSGs) from CMI Belgium, featuring diverter dampers and a bypass stack with a capacity of 101.48 kg/s at 536.53°C, ensuring a rating of 7.08 kg/s at 242.16°C. The plant incorporates air-cooled condensers (ACC) manufactured by the German company ENEXIO, along with main and sub-transformers supplied by Siemens, also located in Germany. Emerson, an American firm, supplies the central control system, whereas the gas pressure reduction and conditioning system is sourced from Petrogas in the Netherlands (Besmaya 1,500 MW Combined Cycle Power Plant - ENKA İnş. San. A.Ş., n.d.). In the combined cycle system, the high heat generated by exhaust from gas generation units is utilized to heat water in the HRSG boilers, resulting in the production of high-temperature and high-pressure steam. This steam powers steam turbines to generate electricity, employing waste heat without the need for additional fuel. This process improves energy generation and decreases thermal emissions, thereby benefiting the environment.

The production units of the power plant have demonstrated efficiency in delivering high productivity and readiness for electrical energy throughout all seasons. The Power Plant employs contemporary techniques for operation and maintenance activities, including the utilization of established maintenance management systems (CMMS) and adherence to maintenance and operation protocols in accordance with international guidelines and standards. The emphasis is on improving preventive and predictive maintenance to decrease the need for corrective maintenance. Figure 2 illustrates the details of each stage, presenting a comprehensive block diagram of the natural gas combined cycle (NGCC) process without a carbon capture unit.

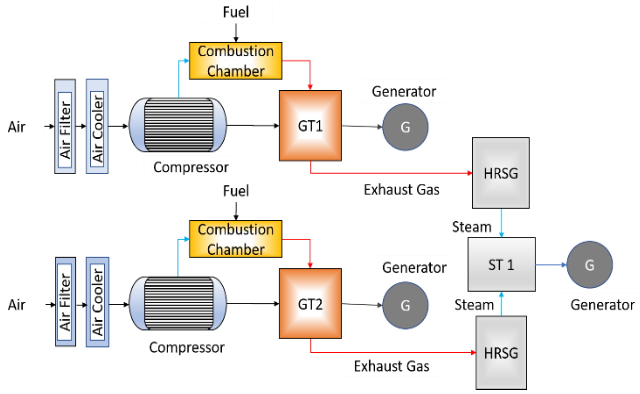


Figure 2. A comprehensive block diagram for the 750 MW NGCC process excluding a carbon capture unit.

Simulation Tools and Methodology

This study utilized two advanced software tools, Aspen HYSYS and Thermoflow (Thermoflex), recognized for their efficacy in the design and analysis of carbon capture systems in power plants. Aspen HYSYS was chosen for its sophisticated capabilities in simulating complex chemical and thermal processes, particularly in post-combustion capture systems that employ amine solvents such as MEA. HYSYS effectively models thermal and chemical equilibrium through the application of the Li-Mather and e-NRTL electrolyte models. Recent studies published in esteemed scientific journals, substantiate the model's efficacy in characterizing CO_2–MEA–H_2O systems under realistic industrial operating conditions (Øi et al., 2023; Li et al., 2021).

The simulation was conducted with a design capture efficiency of 90%, including a thorough analysis of key variables such as the number of absorption and reactivation stages, steam consumption, column efficiency, and regeneration energy requirements. The outputs from HYSYS included CO_2 capture rates, solvent consumption, and energy requirements, which served as input parameters for the system analysis.

In contrast, Thermoflow (Thermoflex) software was chosen to assess the overall performance of the power plant due to its advanced capabilities for developing integrated models for combined-cycle plants. This enables the simulation of the effects of integrating carbon capture units on steam consumption and power distribution, thereby influencing plant efficiency. Thermoflow is widely employed by global corporations and research institutions to evaluate technical and economic solutions in power plants, ensuring the reliability and accuracy of analyses (Nguyen et al., 2023).

The use of HYSYS for holding unit design and Thermoflex for plant performance analysis provides a thorough approach that considers both micro-level and system-level factors, consistent with recent research methodologies developed after 2020. This approach underscores the study's dedication to remaining current with scientific advancements, thereby enhancing the quality and relevance of results in relation to regional infrastructure challenges.

The design model features a theoretical 10-stage absorber column with a Murphree efficiency of 0.25. This selection aligns with research recommendations advocating for the use of intermediate-performance packing columns in post-combustion applications employing MEA solvent (Zhang et al., 2020; Khan et al., 2022). A theoretical six-stage design was utilized for the desorber unit, with the assumption of an ideal Murphree efficiency of 1.0. This method corresponds with several established models that utilize maximum efficiency as a primary criterion for evaluating the upper limits of heat recovery performance and solvent efficiency (Ali et al., 2024; Al-Mamoori et al., 2023).

A few secondary system components, such as the acid gas pretreatment and water treatment units, were streamlined to correspond with similar studies aimed at evaluating the thermal and economic performance of the primary system. This method circumvents the complexities of secondary effects, especially considering that their quantitative influence on total energy consumption in these models has been demonstrated to be relatively minor (Zhang et al., 2023).

Carbon Capture Process

Conversely, Figure 3 presents a detailed block diagram of the NGCC process, which incorporates a carbon capture unit.

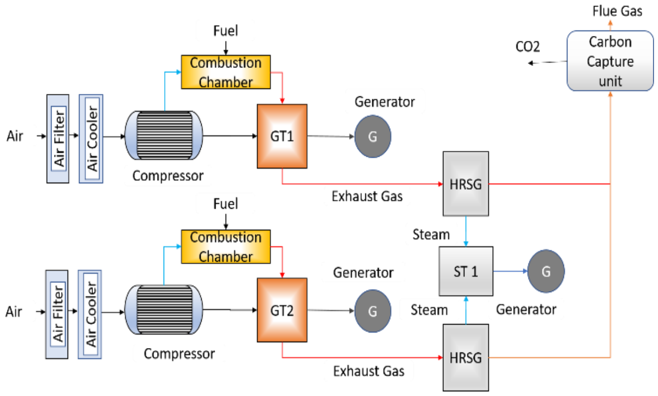


Figure 3. A comprehensive block diagram for the 750 MW NGCC) process, incorporating a carbon capture unit.

There are three primary methods for capturing CO2 in combustion: pre-combustion capture, oxy-fuel combustion, and post-combustion capture. Post-combustion capture is the most prevalent and efficient method for fossil fuel power plants and various industries (Sciences, 2022).

The pre-combustion capture method involves the extraction of carbon dioxide (CO_2) from fuel prior to combustion. This method is frequently employed in Integrated Gasification Combined Cycle (IGCC) plants. Gasification converts fuel into a mixture of carbon monoxide (CO) and hydrogen (H_2). CO_2 is subsequently extracted from this mixture through various techniques, such as membrane separation and pressure swing adsorption (PSA) (Shaw and Mukherjee, 2022; Yusuf and Ibrahim, 2023). The post-combustion capture method involves the removal of CO_2 from flue gases produced by power plants and industrial facilities after fuel combustion. The primary technique for post-combustion capture involves amine-based absorption, employing a solvent such as monoethanolamine (MEA) to capture CO_2 (Hack et al., 2022; Laribi et al., 2019). Oxy-fuel combustion represents a specific method of post-combustion capture, utilizing a mixture of recirculated flue gases and pure oxygen for fuel combustion. The process produces flue gas primarily composed of CO_2. The method efficiently separates CO_2 from flue gas, while preserving water vapor. Oxy-fuel combustion combines the advantages of post-combustion capture with those of oxy-fuel combustion (Al Baroudi et al., 2021; Becattini et al., 2022).

The post-combustion process comprises several essential components: an absorber, a heat exchanger for rich or lean amine, a cooler, pumps, a reboiler, a desorber (commonly referred to as a stripper), and a condenser (Oh S. et al., 2016). In the absorption column, carbon dioxide (CO2) from flue gas is absorbed by a monoethanolamine (MEA) solvent. The concentrated amine solution that emerges from the base of the absorption column is transferred to the lean/rich amine heat exchanger for heating.

The rich amine is introduced into the stripper, where CO2 is separated and exits from the top. The regenerated lean amine is discharged from the bottom of the stripper following processing in the reboiler. The lean amine is subsequently recirculated to the absorption column for reuse through a lean amine pump. The lean amine passes through the lean/rich amine heat exchanger before re-entering the absorption column, where it heats the rich amine solution stream and is then cooled in the lean amine cooler.

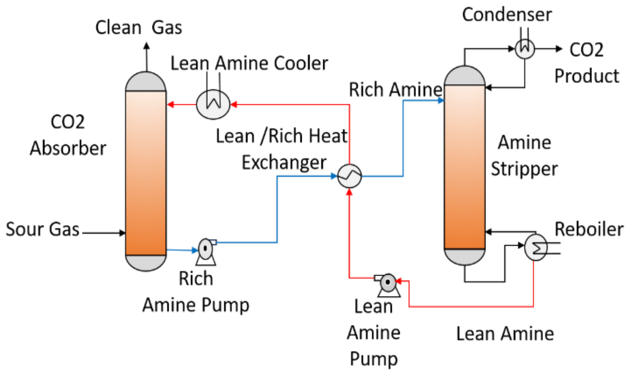


Figure 4. Principle of the standard carbon dioxide absorption and desorption process.

Figure 4 represents the elements and principles underlying the standard carbon dioxide absorption-desorption process.

The Li-Mather equilibrium models were utilized in Aspen HYSYS to simulate the configurations, incorporating a non-ideal gas phase (Øi et al. 2014). The CO2 removal efficiency was established at 90%, signifying that the absorption column captures 90% of the CO2 from the flue gas, with the remaining 10% being emitted from the top of the column. The minimum approach temperature in the rich/lean heat exchanger varied between 5 and 10°C.

The absorber was maintained at a pressure of 1.1 bar, whereas the desorber was operated at 2 bar. The reboiler temperature was established at 120°C, while the designated reflux ratio in the desorber was 0.3. This simulation excludes the water cleansing process, flue gas pretreatment, and distillation product treatment. This decision was made in consultation with the superintendent, as the energy potential will influence energy reduction, though it is not anticipated to affect the potential for energy reduction. The standard procedure for CO2 capture was simulated using Aspen HYSYS V14.0, as illustrated in Figure 5, with specific specifications summarized in Table 1 (Aforkoghene A. & Øi, 2015; Razzaghianarmarzi, 2023).

Figure 5 indicates the process flow, highlighting the essential components and movements within a CO2 absorption plant utilizing flue gas. It has been constructed utilizing data from various credible sources. The gas conditioning section is emphasized, which includes the transport fan and the direct contact cooler, ensuring that the flue gas attains the requisite pressure and temperature prior to entering the absorption column. The flue gas containing CO2 is then introduced to the absorber liquid. This liquid efficiently dissolves gaseous CO2. Consequently, it enhances the mass transfer process. The storage of CO2 in the solvent occurs via chemical or physical bonding or mixing, which is essential for the efficiency of the absorption process.

Table 1. Specifications for the input of a process simulation for a 750 MW carbon capture unit with an efficiency of 90%.

Parameter	Value	Unit	Parameter	Value	Unit
Flue gas			**Absorber**		
Inlet temperature	57.24	°C	Number of Absorbers	5	-
Inlet pressure	1.138	Bar	stages Number	10	-
Inlet flowrate	170000	kmole/h	Murphree efficiency	0.25	-
CO_2 concentration	3.81	mole %	**Desorber**		
H_2O concentration	8.2	mole %	Number of Desorbers	5	-
Lean amine temperature	40	°C	Number of Stages	6	-
Lean amine			Reflux ratio	0.3	-
Inlet temperature	40	°C	Murphree efficiency	1	-
Inlet pressure	1.1	Bar	Reboiler temperature	120	°C
Inlet flowrate	201900	kmole/h	**Rich/lean heat exchanger**		
MEA concentration	30	Mass %	Rich amine to desorber temperature	104.5	°C
CO_2 concentration	5.5	Mass %	Approach temperature	10	°C

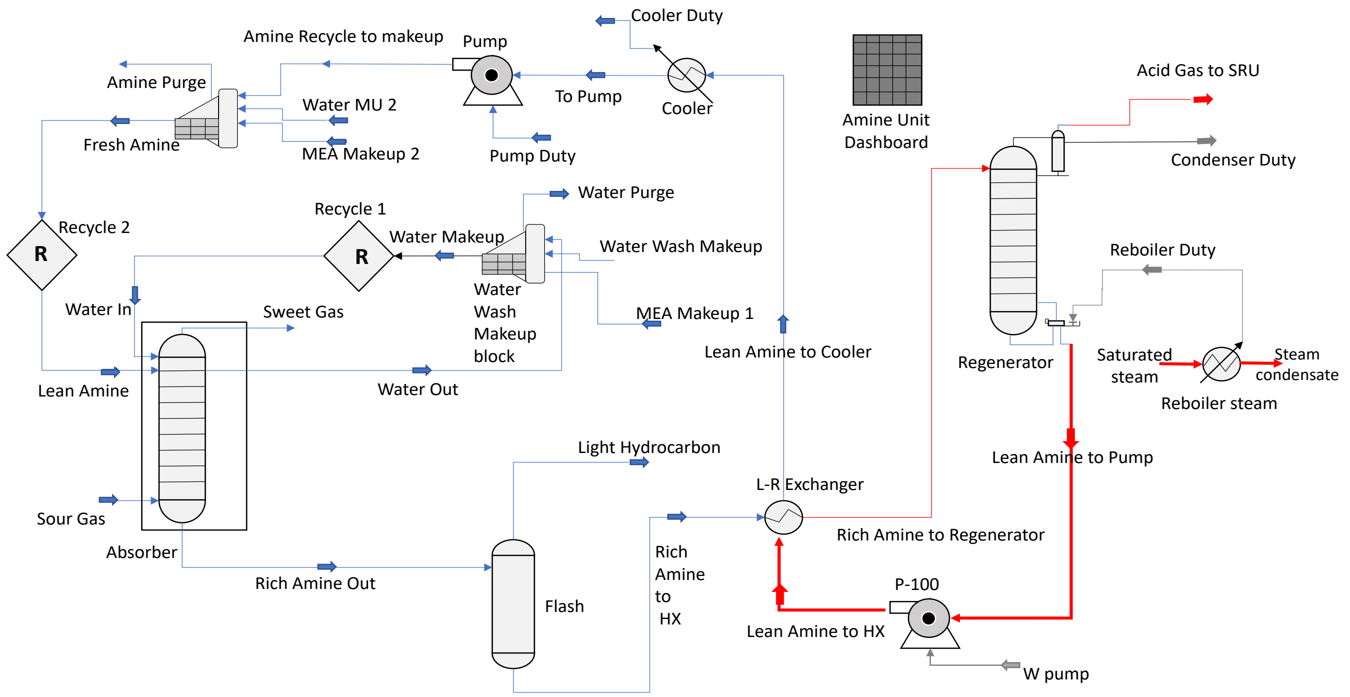


Figure 5. Aspen HYSYS model of CO_2 removal.

RESULTS AND DISCUSSIONS

The subsequent operating conditions were analyzed to effectively assess the station's performance utilizing natural gas as fuel:

- An ambient pressure of 1.013 bar,
- The temperature of 15 degrees Celsius,
- The relative humidity of 60%.

The energy outputs from gas and steam turbines are quantified and documented as presented in Table 2. This analysis evaluates the station's performance under two conditions: one without a carbon capture unit and the other with a carbon capture unit functioning at 50% and 90% capture efficiencies.

The findings demonstrate that the incorporation of a carbon capture unit into a combined cycle power plant (CCPP) significantly affects net power generation. Net power output declines by 8.6% at a carbon capture efficiency of 50% and by 13.6% at a capture efficiency of 90%. Higher carbon capture efficiency leads to a more substantial decrease in the net power output of the plant.

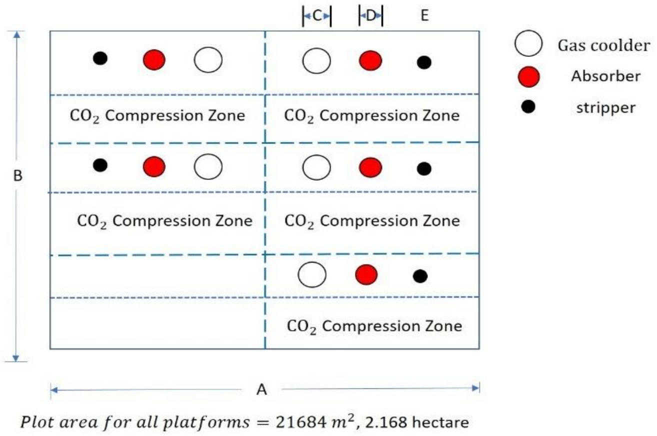
The total electrical power produced at the terminals of all generators indicates the gross power output of the Combined Cycle Gas Turbine (CCGT). To ascertain the net power production of the CCGT, one must deduct the auxiliary power consumption, which includes energy used by fans, the natural gas compressor, cooling systems, and process water pumps.

Table 2. Compares the station's performance with and without a carbon capture unit.

Item	Unit	CCGT		
		without CCS	**with CCS (50%) capture**	**with CCS (90%) capture**
Technology	-	CCGT	CCGT	CCGT
Carbon capture and storage	-	No	Yes	Yes
Make Model	-	GE 9F.03	GE 9F.03	GE 9F.03
Number of units	No	2 GT +2 HRSG +1 ST	2 GT +2HRSG +1 ST+CCS	2GT+2HRSG +1ST+CCS
Performance				
Total plant size (Gross)	MW	764.4	737.3	713.2
Auxiliary power consumption	MW	24	60.7	73.5
Total plant size (Net)	MW	740.4	676.6	639.7
Heat rate LHV Net	(MJ/KWh)	6.73	7.38	7.78
Thermal Efficiency	%, LHV Net	0.535	0.488	0.46
CO2 emission	Mtonne	2.26	1.121	0.22
Flue gas constriction				
N2	V%	74.51	78.31	79.66
O2	V%	12.57	13.22	13.44
CO2	V%	3.81	2.002	0.407
H2O	V%	8.2	5.528	5.53
SO2	V%	0	0	0
Argon	V%	0.896	0.94	0.958

The reduction in net power output is mainly attributed to the heightened steam demand for the regeneration of the solvent monoethanolamine (MEA) in the stripper. The incorporation of the carbon capture unit does not influence the power output of the gas turbines; however, the total net power output from the combined cycle power plant diminishes as a result of its impact on the steam turbines. In steam turbines, a portion of the steam produced in the steam generator is redirected to the carbon capture unit for solvent regeneration, which diminishes the power output from the steam turbine.

Figure 7 illustrates that the carbon capture unit comprises five trains, each containing an absorber, stripper, and cooler. The exhaust gas flow rate processed by each platform is 224.9 m^3/s, leading to a daily CO2 capture of 1214.7 tons. The total area necessary for the installation of the carbon capture unit is 21684 m^2 for all five platforms.



A	B	C	D	E
150.1 m	173.4 m	11.01 m	9.974 m	2.197 m

Figure 6. Plot of the designated area for all platforms within the carbon capture unit

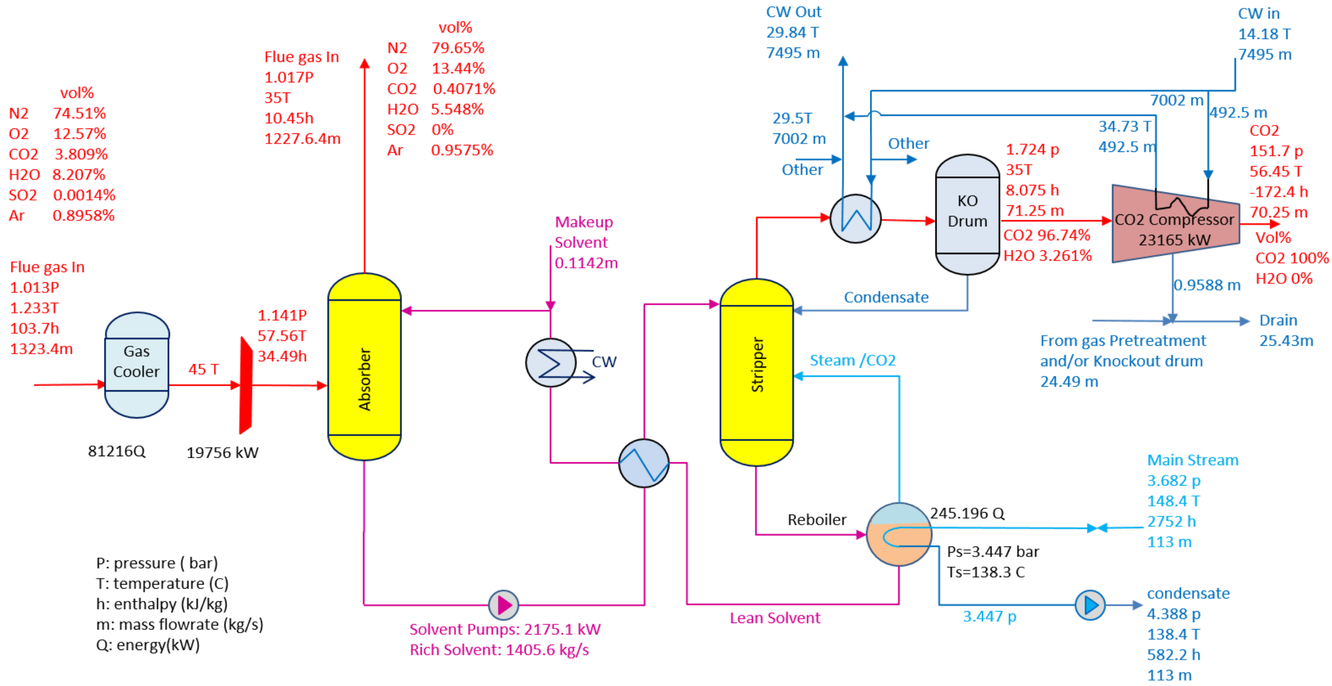


Figure 7. Summary of simulation outcomes for CO2 absorption and desorption processes (entire plant).

The main objective of this study is to reduce CO2 emissions from the Power Plant by integrating a carbon capture unit. Following the combustion process, the CO2 captured is approximately 2.26 from each stage of the plant, resulting in a total annual capture of 13.56 million tons per year from the power plant. The captured CO2 will be pressurized to 151.7 bars, subsequently transported, and stored underground, as depicted in Figure 8.

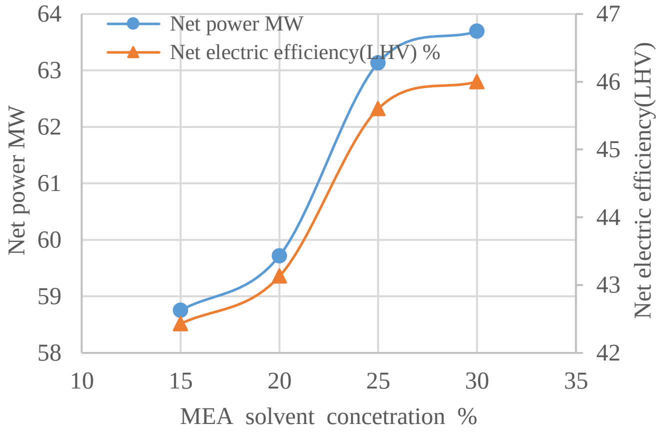


Figure 8. Impact of MEA Solvent Concentration (%), Net Power (MW), and Net Electric Efficiency (LHV)

The amine-based CO2 capture process exhibits a mass flux capacity of 70.29 kg/s, equivalent to 6073 tons/day, with a CO2 capture efficiency of 90%. This study reveals that the average daily consumption of monoethanolamine (MEA) is approximately 9.8 tons per day for a 750 MW combined cycle power plant with a post-combustion carbon capture unit. The consumption rate is roughly 1.48 kg of MEA for each ton of CO_2 captured. The comparison of these results with existing literature demonstrates that the calculated values conform to established reference ranges. Specifically, data from the US Department of Energy – NETL Laboratory (DOE & NETL, 2015) suggest that MEA consumption varies between 0.5 and 3.1 kg/ton CO_2, whereas the IECM (2018) utilizes an average reference value of 1.5 kg/ton CO_2. The model's results correspond with established technical values, enhancing the reliability of the implemented numerical representation. An applied study in a master's thesis indicated that the offset consumption of MEA was 325.8 kg/h, or 7.82 tons/day, in a gas plant utilizing a conventional carbon capture system. This finding corroborates the accuracy of the results in this research and affirms their alignment with the actual operational performance of industrial capture units.

The thermal energy consumption rate of the CO2 capture system was approximately 3489 kJ per kilogram of captured CO2, consistent with the typical range observed in absorption systems employing a 30% monoethanolamine (MEA) solution under stable operating conditions. This finding is consistent with recent studies, which indicate that thermal energy consumption typically ranges from 3000 to 4200 kJ/kg CO_2, depending on operating conditions and regeneration efficiency.

The thermal energy consumption is documented at 3886 kJ/kg CO_2 within a 30% MEA system, under conditions representative of a standard industrial scenario. The recorded values in this study are within the acceptable range, thereby supporting the system's effectiveness regarding energy and performance (Adu et al., 2020).

The CO2 concentration in the flue gas entering the carbon capture unit is 3.81%, decreasing to 0.4072 % upon exit. The CO2 balance shows a total inlet of 78.1 kg/s, which includes 70.29 kg/s captured and 7.81 kg/s retained in the flue gas. The total electrical power consumption amounts to 45309kW, which includes 23171 kW for CO2 compressors, 19,250 kW for booster fan(s), and supplementary power for solvent recirculation. The pumps have a power consumption of 2175.5 kW, the condensate pumps utilize 15.06 kW, and miscellaneous power requirements total 697.4 kW. The heat rejection to the cooling water is 497410 kW, while the estimated heat loss is 4000 kW.

This analysis focuses on the multi-shaft configuration of a combined gas turbine power plant, which includes two gas turbine units and one steam generator unit. The results are derived from a single stage of 750 MW. The annual electricity export amounts to 5997*106 kWh. The specific emissions, in the absence of the carbon capture unit, amount to 376.85 g CO2/kWh. When the carbon capture unit is incorporated, the annual electricity exported reduces to 5181*106 kWh, resulting in specific emissions of 40.6 g CO2/kWh. The electricity production decrease is 816 million kWh, resulting in an estimated 89.4 % reduction in CO2 emissions. This quantity is an important improvement for climate change mitigation strategies. The countries can be ready for the future with modern and eco-friendly facilities. Most facilities don't want to set up such systems for economic reasons. However, it is essential to acknowledge that collective responsibility will be shared for the well-being of future generations.

The world needs more CO2 reduction than before. The current situation is progressively worsening and poses a significant concern for the future of our planet. Energy is a vital resource that signifies power, and it is crucial to prioritize effectively and to invest in energy facilities. The results of this study could be conducted to keep CO2 emissions to a minimum for an indispensable electricity production facility. It is also an important step for the future of the country. Modelling is only a tool in this study; however, it has shown the possible CO2 reduction quantity. In this systemic approach, this study is considered the most important modelling study conducted for the region. The results will be valuable for decision-makers in guiding their strategic choices.

Sensitivity Analysis

A sensitivity analysis was performed to assess the influence of two critical variables on the performance of the combined cycle plant: MEA solvent concentration and CO_2 capture efficiency. As depicted in Figure 8, augmenting the MEA concentration from 15% to 30% resulted in a substantial increase in net electrical power, escalating from 58.75 MW to 63.69 MW. Thermal efficiency (LHV) enhanced from 42.43% to 46%. The improvement results from a decrease in the steam required for solvent reactivation, which lessens with higher MEA concentrations, thus reducing the thermal load on the system (Zhang et al., 2020). Additionally, a decline in the specific energy of CO_2 capture was observed, decreasing from 6.039 kJ/kg to 3.564 kJ/kg, which correlates with a reduction in the volume of steam entering the capture unit, as illustrated in Figure 9.

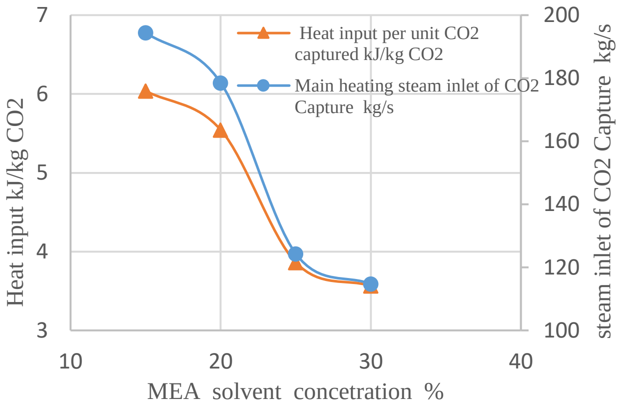


Figure 9. Impact of MEA solvent concentration percentage on heat input in kJ/kg CO2 and main steam extraction intake for CO2 capture

In contrast, as CO_2 capture efficiency rose from 50% to 90%, net power diminished from 68.3 MW to 64.0 MW, and thermal efficiency decreased from 49.4% to 46.2%, as illustrated in Figure 10. This decrease is ascribed to heightened steam usage during the absorption and regeneration processes, which reduces the energy accessible to the turbines. The findings correspond with data from NETL and IEAGHG, demonstrating that enhanced capture efficiency leads to a net efficiency reduction of 6 to 8 percentage points in combined gas plants (IEAGHG, 2023; NETL, 2023). A recent study in Frontiers in Energy Research (2023) indicates that a system utilizing a 30% MEA concentration attains a specific energy yield of 3.5 to 3.9 MJ/kg CO_2, marking a substantial enhancement over lower concentrations and aligning with prior findings (Al-Mamoori et al., 2023). Moreover, Zhang et al. (2023) illustrated that a coal- and biomass-fired facility employing approximately 30% MEA concentration and achieving around 90% capture efficiency realized a specific energy yield of 3.39 MJ/kg CO_2, while encountering an approximate 20% decline in electrical performance relative to operations devoid of carbon capture and storage (CCS), corroborating the findings of this study.

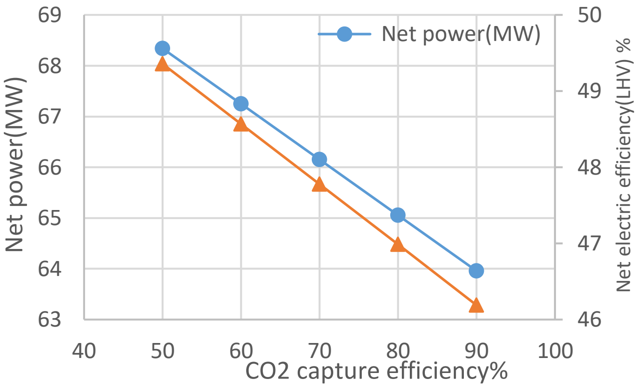


Figure 10. Efficiency of CO2 capture (%), net power (MW), and net electrical efficiency (LHV)

The improvement results from a decrease in the steam required for solvent reactivation, which lessens with higher MEA concentrations, reducing the thermal load on the system. Figure 11 illustrates that enhancing efficiency from 50% to 90% progressively elevates the steam flow rate and the thermal input to the regeneration unit.

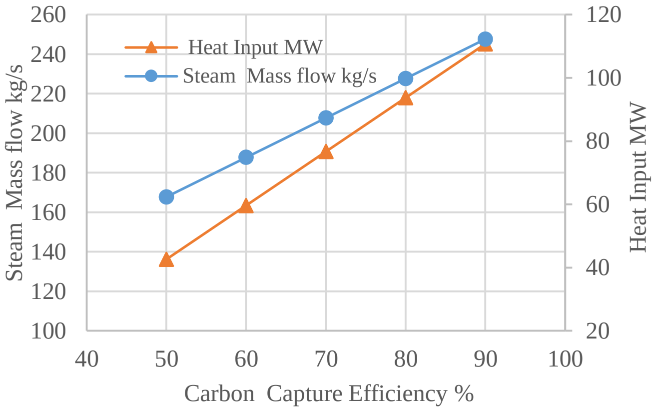


Figure 11. Carbon Capture Efficiency (%), Steam Mass Flow (kg/s), and Heat Input (MW)

At 50% capture efficiency, the necessary steam flow rate was roughly 62.4 kg/s, and the heat input was 136.2 MW. Upon elevating the efficiency to 90%, the steam flow rate rose to 112.3 kg/s, and the heat input escalated to 245.2 MW. This exponential growth illustrates a nearly linear correlation between capture efficiency and the requisite heat quantity. This indicates that improved efficiency increases energy requirements due to the need to regenerate larger quantities of CO2-saturated solvent.

The augmented steam extraction immediately affects the efficiency of the steam turbines, diminishing the steam available for electricity generation and thus reducing the plant's net electrical power output. Consequently, whereas enhanced capture efficiency leads to significant decreases in carbon dioxide emissions, it adversely affects plant output. Consequently, choosing an optimal capture efficiency necessitates a meticulous equilibrium between minimizing emissions and preserving the plant's economic and performance.

Economic Assessment

A comprehensive techno-economic evaluation of the Bismayah Combined Cycle Power Plant was performed to analyze the financial and environmental outcomes of two scenarios. The initial scenario employed traditional technology devoid of carbon capture, but the subsequent scenario utilized a carbon capture system proficient at sequestering 90% of emissions. The research postulated a functional lifespan of 25 years, with an annual operational duration of 8000 hours, mirroring the real-world conditions of combined cycle power plants. In the base scenario, the project-level (or "hard") capital expenditures for plant construction were around $699 million. The incorporation of the carbon capture unit augmented the overall expenditure by 81%, elevating it to $1.26 billion. As a result, the investment cost per kilowatt-hour (kWh) increased from $956.80 to $1981.40. The increase was primarily due to expenses associated with the capture, compression, transportation, and storage of CO2, along with the necessary infrastructure.

The plant's annual operating expenses were considerable, primarily attributed to fuel use, leading to a mere rise of 39800 terajoules in yearly fuel usage. However, total expenses rose significantly due to the use of chemicals, particularly the monoethanolamine (MEA) solvent used in adsorption. The yearly MEA use for carbon capture was around 3291 tons. Based on February 2025 export data (IndexBox, 2025) and a price of $1 238 per ton, the yearly solvent expenditure would be around $4.07 million.

In June 2025, natural gas prices were established at $2.86 per gigajoule, consistent with the global market average (U.S. Energy Information Administration, 2025). The substantial annual fuel usage directly influenced the operational costs in both cases. Nevertheless, the impact was more significant in the carbon capture scenario owing to the plant's diminished efficiency. Net electrical efficiency declined from 53% in the traditional scenario to 46% with carbon capture technology, mainly due to the increased energy requirements of the capture and compression systems. Total yearly electricity generation decreased from 5846 GWh to 5095 GWh. The levelized cost of electricity (LCOE) in the carbon capture scenario was $53.40 per megawatt-hour, in contrast to $34 per megawatt-hour for the conventional case, indicating a 57% increase. This increase corresponds with global projections for the expense of carbon capture and storage (CCS), generally fluctuating between $50 and $120 per megawatt-hour (Hayat, 2024; Belfer Center, 2025).

From an environmental standpoint, CO2 emissions decreased from 2225 kilotons annually in the baseline scenario to 208 kilotons in the carbon capture scenario, resulting in a reduction of about 2025 kilotons. The disparity in emissions and costs between the two scenarios resulted in an estimated cost of avoided carbon at $40.80 per ton of CO2, aligning with the commonly advised range for carbon capture technology (IEA, 2023; IMF, 2023). Concerning economic feasibility, the indicators demonstrated considerable advantages for the typical scenario devoid of carbon capture.

The net present value (NPV) rose to $647.9 million in the conventional scenario, whereas it amounted to just $41.9 million in the carbon capture and sequestration (CCS) scenario. The internal rate of return (IRR) decreased from 24.15% to 10.7%, and the payback period lengthened from 2.05 years to 7.54 years. The data suggests that the project is comparatively unviable when utilizing carbon capture technology because of their elevated expenses. This prompts inquiries on its feasibility unless accompanied by carbon payments or subsidies, notwithstanding the evident environmental advantages.

Table 3. Comparative Analysis of Performance and Economic Metrics

Indicator	Unit	Without Carbon Capture	With Carbon Capture (90%)	Difference / Notes
Annual electricity generation	(GWh)	5 846	5 095	↓ 12.9%
Annual fuel consumption	TJ	39 720	39 898	Slight increase due to efficiency loss
Annual CO_2 emissions	kt	2 225	208	↓ 90.7%
Captured CO_2 amount	kt	—	2 025	Effective capture rate
Natural gas cost	$/GJ	—	3	Global average (EIA, 2025)
MEA solvent cost	$/ton	—	1 238	Source: Index Box, 2025
Annual MEA consumption	tons	—	3 291	$4.07 M$
Annual operating cost (OPEX)	M$	216	245	↑ $29 M$ (13.4%)
Total capital cost (CAPEX)	M$	699	1 262	↑ ~81%
Specific investment cost	$/kW	956. 8	1981. 4	Nearly doubled
Levelized Cost of Electricity (LCOE)	$/kWh	0.0340	0.0534	↑ ~57%
Net Present Value (NPV)	M$	647. 9	41. 9	Significant reduction
Cost of CO_2 avoided	$/ton CO_2	—	40. 8	Within global benchmark range

CONCLUSION

This study assessed the technical, economic, and environmental performance of a natural gas-fired combined cycle gas turbine (CCGT) power plant, while examining the effects of including post-combustion carbon capture (PCC) technology with a MEA solvent. The analysis utilized integrated simulations using Thermoflow and Aspen HYSYS to deliver a thorough quantitative assessment of the effects of this integration on plant efficiency, emissions, and costs.

The results demonstrated that the integration of a carbon capture unit with high capture efficiency significantly reduced carbon dioxide emissions by 90%, decreasing annual emissions from 2225 kt to 208 kt, so improving adherence to international climate regulations. A 12.9% decrease in net electricity output was observed, accompanied by a rise in fuel consumption and operating expenses. The implementation led to a substantial rise in investment costs by around 81%, an increase in the Levelized Cost of Energy (LCOE) by approximately 57%, and a notable decline in the net present value (NPV), underscoring the economic difficulties linked to the adoption of this technology in existing power plants.

Regarding the adverse effects on economic viability metrics, the prevented carbon cost of $\$40.8/\mathrm{tCO_2}$ aligns with the suggested worldwide range, thereby enhancing the project's environmental and strategic feasibility, particularly when integrated with carbon pricing frameworks or green policy endorsement.

When assessing technologies to reduce emissions, the findings highlight the requirement of a consistent and equitable approach that balances ecological performance with economic efficiency. It offers a reproducible simulation framework suitable for future research on low-carbon energy systems, especially in the context of developing countries. The report advocates for ongoing research that includes long-term dynamic analysis, scenario assessment under various carbon subsidy frameworks, and the incorporation of renewable energy sources to mitigate the economic effects of adopting carbon capture technology.

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