MARMARA UNIVERSITY
INSTITUTE FOR GRADUATE STUDIES IN PURE AND APPLIED SCIENCES

Simulation and Enhancement of the Carbon Capturing for Combined Cycle Power Plant with Concentrated Solar Power System

YASSER ABBAS HAMMADY AL-ELANJAWY

Ph.D. THESIS

Department of Mechanical Engineering

Thesis Supervisor

Prof.Dr. MUSTAFA YILMAZ

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I dedicate this research.

Istanbul, Turkey, June 2025

YASSER ABBAS HAMMADY AL-ELANJAWY

Özet

Bu araştırma, güneş destekli karbon yakalama sonrası teknolojilerinin Irak'ın ağırlıklı olarak gazla çalışan enerji sektörüne entegre edilmesinin uygulanabilirliğini araştırıyor. Karbon yakalama süreçlerini desteklemek için güneş enerjisinden yararlanan bu yenilikçi yaklaşım, sera gazı emisyonlarını azaltırken potansiyel maliyet tasarruflarını açığa çıkarmayı ve enerji verimliliğini artırmayı amaçlıyor. Bu entegrasyonun teknik ve ekonomik boyutlarını kapsamlı bir şekilde inceleyerek, çalışma Irak'taki politika yapıcılar ve endüstri paydaşları için değerli içgörüler sunmayı ve sürdürülebilir bir enerji geleceği teşvik etmek için bilinçli kararlar almalarını sağlamayı amaçlıyor.

Doğal gaz kombine çevrim (NGCC) santralleri alanında, çevresel sürdürülebilirliği sağlamak için CO_2 emisyonlarının azaltılmasına öncelik vermek hayati önem taşır. Yanma sonrası karbon yakalama teknolojilerinin entegrasyonu, sera gazı emisyonlarının azaltılmasında önemli bir rol oynar ve karbon ayak izini en aza indirerek NGCC'nin çevresel profilini iyileştirir. Bu araştırma, Irak, Bağdat'ta bulunan Besmaya Doğal Gaz Kombine Çevrim (NGCC) santraline güneş termal enerjisinin entegrasyonuna ilişkin kapsamlı bir inceleme sunmaktadır. Aspen Plus yazılımını kullanan gelişmiş proses simülasyonu ve modelleme tekniklerinden yararlanan çalışma, karbon yakalama sonrası için mevcut NGCC tesisinin güneş enerjisi yardımıyla güçlendirilmesinin performansını ve uygulanabilirliğini değerlendirmeyi amaçlamaktadır. Bu araştırmanın temel amacı, Besmaya NGCC santralinin mevcut işletme koşulları altında kapsamlı bir simülasyonunu yürütmek ve böylece sonraki analizler için bir temel oluşturmaktır. Daha sonra, güneş enerjisi destekli bir yanma sonrası yakalama (PCC) santrali simüle edilir ve mevcut güç altyapısına sorunsuz bir şekilde entegre edilir. Bağdat koordinatlarında güneş termal güç potansiyelini doğru bir şekilde tahmin etmek için Sistem Danışmanı Modeli (SAM) kullanılır. Güneş termal enerjisinin NGCC santraline entegrasyonu titizlikle incelenir ve ortaya çıkan hibrit sistemin teknik uygulanabilirliği ve performans ölçütleri titizlikle değerlendirilir. Araştırma, özellikle Bağdat'taki Besmaya NGCC santrali bağlamında, güneş termal enerjisini geleneksel doğal gaz güç üretim altyapısına dahil etmenin teknik uygulanabilirliği ve potansiyel faydaları konusunda değerli içgörüler sağlayarak alana katkıda bulunur. %49,8'lik net santral verimliliği ile karbon yakalama olmadan yapılan temel simülasyon, 751 MW'lık güçlü bir toplam güç üretim kapasitesi gösterdi. Bununla birlikte, yanma sonrası yakalama (PCC)

entegrasyonu, verimlilikte %44'lük bir düşüşe ve genel güç kapasitesinde mütevazı bir azalmaya, 682 MW'a neden oldu. Baca gazlarından gelen CO_2'nin yaklaşık %99'unun metanole başarılı bir şekilde dönüştürülmesi, bu yaklaşımın sera gazı emisyonlarını azaltırken aynı zamanda değerli bir kimyasal hammadde üretmedeki uygulanabilirliğini vurgular. Bu kapasiteyle, yıllık CO_2 üretiminin 2.119.318 ton/yıl olduğu tahmin edilirken, MEA emilim sistemiyle 18.064 ton/yıl (%99 azalma) ve CO_2-metanol dönüşüm sistemiyle 16.069 ton/yıl (%99,2) düşürüldü. Bulgular, bölgedeki hem çevresel endişeleri hem de enerji güvenliğini ele alarak sürdürülebilir ve verimli enerji çözümleri arayışında gelecekteki kararları bilgilendirmeyi amaçlamaktadır.

Yoğuşma suyundan hidrojen üretmek için güneş enerjisinin kullanılması, sürdürülebilir enerji teknolojisinde önemli bir ilerlemeyi temsil etmektedir. Güneş ışığının gücünden yararlanarak, su moleküllerini hidrojen ve oksijene verimli bir şekilde ayırabilir, temiz ve yenilenebilir bir yakıt kaynağı sunabiliriz. Bu süreç, yalnızca geleneksel hidrojen üretim yöntemleriyle ilişkili çevresel etkiyi azaltmakla kalmaz, aynı zamanda endüstriyel ortamlarda sıklıkla göz ardı edilen bol miktarda bir kaynak olan su yoğuşmasını da kullanır. Yenilikçi güneş enerjili su ayırma teknolojileri sayesinde, merkezi olmayan hidrojen üretiminin potansiyelini açığa çıkarabilir, toplulukların daha yeşil ve daha kendi kendine yetebilen bir enerji altyapısına geçişini sağlayabiliriz.

Anahtar Kelimeler: Karbon yakalama, Metanol, Doğal Gaz Yanma Döngüsü, Sistem Danışmanı Modeli, Güneş Enerjili Su Ayırıcı.

Abstract

This study investigates the viability of integrating solar-supported post-carbon capture technology into Iraq's largely gas-based energy matrix. Utilizing solar power to supplement carbon capture schemes, this revolutionary strategy seeks to minimize greenhouse gas emissions while releasing economic potential and improving the efficiency of energy consumption. By extensively analyzing the technical and economic aspects of this integration, this study intends to provide useful information to policymakers and industry players in Iraq in order to enable them to make better-informed decisions towards realizing a sustainable energy future.

In the world of Natural Gas Combined Cycle (NGCC) power plants, it is highly important to have the reduction of CO2 emissions as a high priority to allow for environmental sustainability. The coupling of post-combustion carbon capture technologies is instrumental in reducing greenhouse gas emissions, as it improves the NGCC's environmental image through the reduction of its carbon footprint. This study offers an extensive examination of the integration of solar thermal power into the Besmaya Natural Gas Combined Cycle (NGCC) power plant in Baghdad, Iraq. Utilizing sophisticated process simulation and modelling tools using Aspen Plus software, the study seeks to assess the performance and viability of supplementing the current NGCC plant with solar support for post-carbon capture. The main task of this work is to run a complete simulation of the Besmaya NGCC power plant according to its actual operational status and thereby set the stage for subsequent calculations. Afterward, the Post-Combustion Capture (PCC) plant with solar assistance is simulated and effortlessly connected to existing power networks. For proper assessment of solar thermal power potential in the Baghdad location, the System Advisor Model (SAM) tool is utilized. The incorporation of solar thermal energy into the NGCC power plant is carefully analyzed, and the technical feasibility and performance characteristics of the resulting hybrid system are critically assessed. The research contributes to the discipline by including a valuable observation regarding the technical feasibility and potential benefits of using solar thermal energy in conventional natural gas-based power generation facilities, for the instance of the Besmaya NGCC plant in Baghdad with net plant efficiency of 49.8%, the baseline simulation without carbon capture indicated a strong total power generation capacity of 751 MW. Post-combustion capture integration, on the other

hand, led to a reduction in efficiency to 44 % and a slight decrease in net power capacity to 682 MW. The efficient conversion of nearly 99% of CO2 from the flue gases into methanol highlights the potential of this methodology in reducing greenhouse gas emissions while at the same time yielding a useful chemical feedstock. With this ability, the CO2 production annually was estimated at 2119318 tons/year which was minimized to 18,064 tons/year (99 % reduction) using MEA absorption system and 16069 tone's/year (99.2%) using CO2-to-Methnol conversion system. The results are meant to guide future actions in the quest for sustainable and efficient energy options, taking into consideration both environmental issues and energy security in the region.

The use of solar energy to split hydrogen from condensate water is a major breakthrough in clean energy technology. Through the energy of the sun, we are able to effectively split the molecule of water into hydrogen and oxygen and thus provide a clean and sustainable fuel source. This method not only reduces the environmental footprint involved in traditional methods of hydrogen production but also taps into a widespread resource—water condensate—that is normally underutilized in industrial processes. With emerging solar water splitting technologies, we can realize the potential for decentralized hydrogen production and enable communities to shift towards a cleaner and more autonomous energy infrastructure.

Keywords: Carbon capture, Methanol, Natural Gas Combustion Cycle, System Advisory Model, Solar Water Splitter

Claim For Originality

“Simulation and Enhancement of the Carbon Capturing for Combined Cycle Power Plant with Concentrated Solar Power System”.

This work is my own and no portion of this work is borrowed either in full or in part from the prior research. This work is unique in combining solar-assisted post-carbon capture technologies into the Besmaya NGCC power plant in Baghdad, Iraq, using advanced simulation (Aspen Plus) and solar thermal analysis (SAM). The study singularly analyzes the technical and economic viability of the hybrid system, with 99% reduction of CO2 and converting the emissions into methanol. It also investigates the new application of solar power to produce hydrogen from condensate water, presenting new avenues of sustainable energy alternatives for Iraq's gas-based economy.

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Symbols

a : Attraction parameter .
b : Repulsion parameter .
CH3OH : Methanol
CO : Carbon Monoxide
CO2 : Carbon Diaoxide
GW : Giga Watt
GWp : Giga Watt Power
H2 : Hydrogen gas
H2O : Water
k : Rate constant
kg : Kilogram
kJ : Kilo joul
km : Kilometer
KOH : Potassium Hydroxide
kW : Kilo Watt
kWe : Kilo Watt Electrical
kWh : Killo watt hour
kWth : Kilo Watt Thermal
MW : Mega Watt
N2 : Nitrogen
O2 : Oxygen
p : Partial pressure
P : Pressure
R : Universal Gas constant
T : Temperature
$\bar{v}$: Molar volume (volume per mole)

Abbreviations

CCPP : Combined Cycle Power Plant

CCS : Carbon Caputre and Storage

CCUS : Carbon Caputre, Utilization and Storage

CDR : Carbon Dioxide Removal

CSP : Concentrated Solar Power

DNI : Direct Normal Irradiance

EOS : Equation of State

GCAM : Global Change Assessment Model

GHGs : Green House Gases

HHV : Higher Heating Value

HP : High Pressure

HRSG : Heat Recovery Steam Generator

HSGT : Hybrid Solar Gas-Turbine

HTF : Heat Transfer Fluid

IRR : Internal Rate of Return

LHHW : Langmuir-Hinshelwood-Hougen-Watson

LLE : Liquid-Liquid Equilibrium

LP : Low Pressure

LSPV : Large Scale Photovoltaic

MEA : Monoethanol Amine

MPPT : Maximum Power Point Tracking

NGCC : Natural Gas Combined Cycle

NPV : Net Present Value

PCC : Post-combustion Carbon Capture

PTC : Parabolic Trogh Collector

PV : Photovoltaic

SACC : Solar Assisted Combined Cycle

SAM : System Advisory Model

SEGS : Solar Energy Generating Systems

SLE : Solid-Liquid Equilibrium

SPCC : Solar-Assisted Post-combustion Carbon Capture

STG : Steam Turbine Generator

VLE : Vapor-Liquid Equilibrrium

Cum/s : Cubic meters per second

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Chapter 1

Introduction

1.1. Introduction

The world energy scene is undergoing a revolutionary change as nations struggle to address the twin issues of fulfilling rising energy demand while reducing the environmental effects of traditional energy sources [1]. Fossil fuels are critical to driving economic growth and have been known for decades as significant sources of greenhouse gas emissions, driving climate change and its related effects. In this multifaceted setting, natural gas has become a key bridging energy source, being a cleaner option to coal and oil. Its burning, however, still involves high carbon dioxide (CO2) emissions, which call for the creation of new technologies to capture and reduce these environmental effects [2].

The increasing awareness of the imperative to act on climate change has accelerated worldwide efforts to shift towards cleaner energy systems. Renewable energy sources like solar, wind, and hydroelectric power are being incorporated into the energy mix in growing proportions, providing clean and renewable alternatives to fossil fuels. But the uncertainty of renewables and their scalability and integration challenges into the grid emphasize the need to have a mix of energy sources that includes renewables as well as low-emission fossil fuels such as natural gas.

Against this background, carbon capture, utilization, and storage (CCUS) technologies have received much attention as a major avenue towards energy sector decarbonization. Specifically, post-combustion carbon capture holds great potential for mitigating CO2 emissions from combustion cycle units of natural gas. Through CO2 capture from flue gases produced when burning fuel, post-combustion capture technologies facilitate the separation and consequent storage or utilization of CO2, hence avoiding release into the atmosphere.

Solar-powered post-combustion carbon capture technologies are a cutting-edge and eco-friendly method for increasing the efficiency and economics of carbon capture technologies. By using solar energy to power the carbon capture process, these technologies can provide such advantages as less energy use, reduced operating expenses, and higher process efficiency. Furthermore, the incorporation of solar power into carbon capture technologies supports international initiatives towards developing a low-carbon economy and fostering sustainable energy solutions.

Yet, deployment of solar-supported carbon capture strategies encounters a number of technical, financial, and legislative hurdles that will need to be overcome if they are to realize their maximum impact. Technical ones involve optimizing design and operation of solar collectors, creating efficient systems for heat transfer and storage, and ensuring interfacing with incumbent carbon capture technology. In addition, financial factors like capital expenditure, running expenses, and payback periods are key in ascertaining the feasibility of solar-assisted carbon capture projects. Policy incentives and regulatory environments also impact the deployment and uptake of these technologies, emphasizing the importance of supportive policy instruments and incentives in promoting their commercialization and mass deployment.

In conclusion, solar-assisted post-combustion carbon capture technologies have considerable potential to decrease CO2 emissions from natural gas combustion cycle facilities and move toward a cleaner energy future. However, overcoming their technical, economic, and regulatory hurdles is important to achieve their maximum potential and drive the world toward a low-carbon future. Through the utilization of solar energy to power carbon capture techniques, these new methodologies provide a window of opportunity towards decarbonization of the energy industry while guaranteeing energy security, economic growth, and environmental sustainability for the generations to come.

1.1.1. Background

The Role of Natural Gas in the Global Energy Mix:

Natural gas, which is mainly made up of methane, has become less carbon intensive than other fossil fuels. In a future world transitioning towards low carbon, natural gas becomes an important part of offering a bridge between old energy sources and a cleaner energy mix. The clean burn of natural gas creates less quantity of pollutants and less CO2 emissions per amount of energy created relative to oil or coal [3]. The natural gas-powered plants have consequently become an inherent part of the energy infrastructure that is flexible with comparatively cleaner power production Mokrani [4]. Natural gas plays a critical role in Iraq's energy basket as it forms an important share in electricity production. The nation, rich in natural gas resources, depends on the fuel to cover the increasing electricity needs of its population and industries. The strategic value of natural gas in the energy mix of Iraq

underlines the necessity of searching and using technologies that improve its environmental performance [5].



Figure 1. 1 Combined Cycle Power Plants.

1.2. Carbon Capture Technologies

With the increasing concern over climate change and the need to cut greenhouse gas emissions at a faster pace, carbon capture technologies have become an essential area of research in the fight against global warming. Carbon capture, utilization, and storage (CCUS) technologies hold the potential to reduce CO2 emissions from industrial activities, power generation, and other human activities, thus helping to combat the pressing issues of climate change and environmental degradation.

Carbon capture technologies refer to a wide range of techniques and methodologies for capturing CO2 emissions from different sources such as power generation, industrial processes, and natural gas processing plants. Carbon capture technologies have been classified into broad categories such as pre-combustion, post-combustion, and oxy-fuel combustion capture processes with their respective advantages, limitations, and applications.

Pre-combustion capture is the removal of CO2 from fuel gases prior to combustion, often by gasification or reforming processes. Post-combustion capture is the separation of CO2 from flue gases released during combustion by means of sorbents, solvents, or membrane-based separation. Oxy-fuel combustion is the combustion of fuel in a mixture of oxygen and recycled flue gases, producing a concentrated stream of CO2, which is more easily captured.

One of the major challenges for carbon capture technologies is the cost of capturing, transporting, and storing CO2, which is very high. Nevertheless, research and development activities are ongoing to minimize these costs through technological advancements, process improvements, and economies of scale. Furthermore, the possibility of CO2 utilization and storage presents opportunities to develop value from sequestered CO2 by converting it into useful products like chemicals, fuels, and construction materials or by sequestering it underground in rock formations.

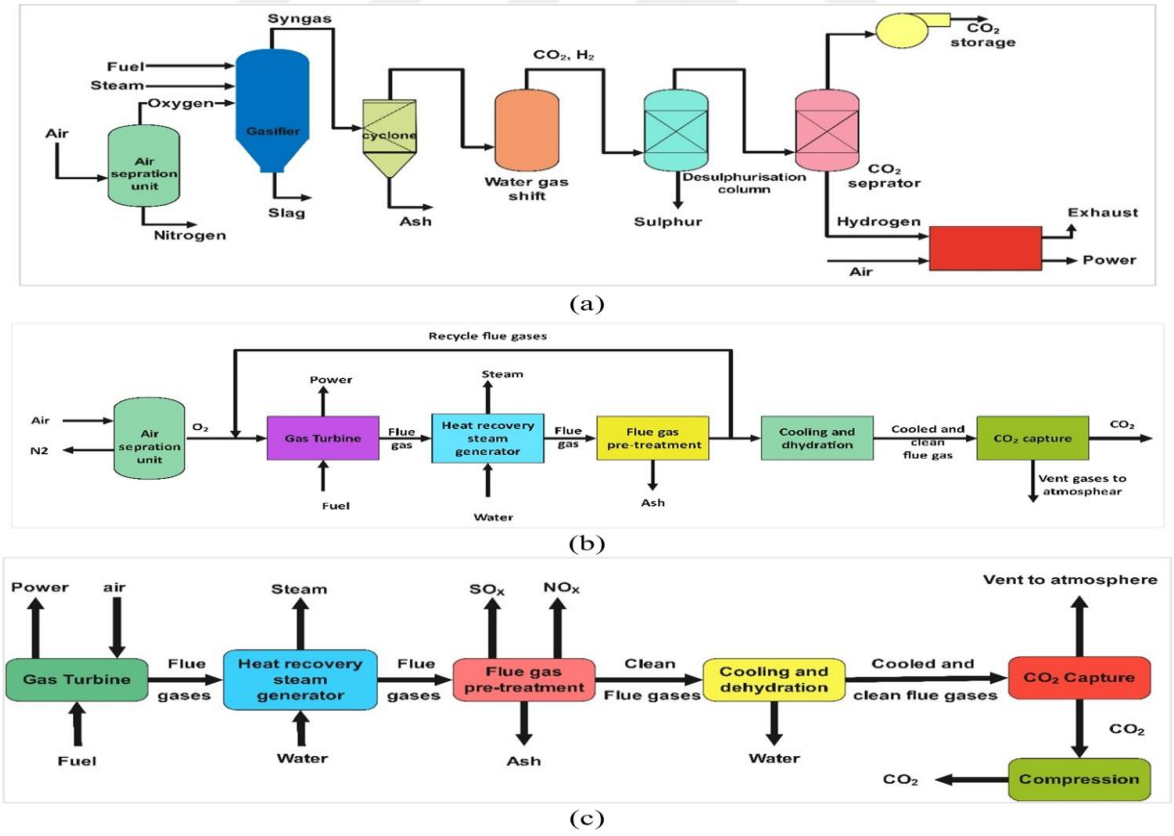


Figure 1. 2: Different Carbon Capturing Techniques (a) Pre-Combustion Carbon-Capturing, (b) Oxy-Fuel Combustion Carbon-Capturing, (c) Post-Combustion Carbon-Capturing [128].

The application of carbon capture technologies is not only vital in minimizing the emissions of CO2 from current fossil fuel-based infrastructure but also in facilitating the utilization of fossil fuels while taking the world to a low-carbon energy future. In industries like power generation, where fossil fuels are still a prevalent source of energy, carbon capture technologies can be instrumental in realizing deep decarbonization and emission reduction goals.

Additionally, carbon capture technologies can aid in integrating the renewable energy resources into the power system through their provision of grid stability, balancing loads, and energy storage services. For example, carbon capture can be utilized to produce low-carbon hydrogen from biomass or natural gas to serve as clean fuel for industrial purposes, power generation, or transportation.

1.2.1. Addressing the carbon footprint of natural gas

The burning of hydrocarbons, such as natural gas, releases CO2 into the environment, which causes the greenhouse effect and global warming. In order to reduce the environmental footprint of power generation based on natural gas, carbon capture technologies have been considered as one solution [6]. Post-combustion capture is among the technologies that can be used as a viable option for in-service natural gas combustion cycle units. This process comprises capturing CO2 from the combustion flue gases and avoiding release into the environment [7]. Several techniques that are in existence, including chemical absorption, adsorption, and membrane separation, have been considered for post-combustion capture. These processes aim to trap CO2 while permitting other gases to pass and obtaining a stream of CO2 in its purified form for transportation and storage [8]. The deployment of post-combustion capture technologies is vital in minimizing the carbon footprint of natural gas-fired power plants and aiding global endeavors to cap warming and counter the effects of climate change [9].

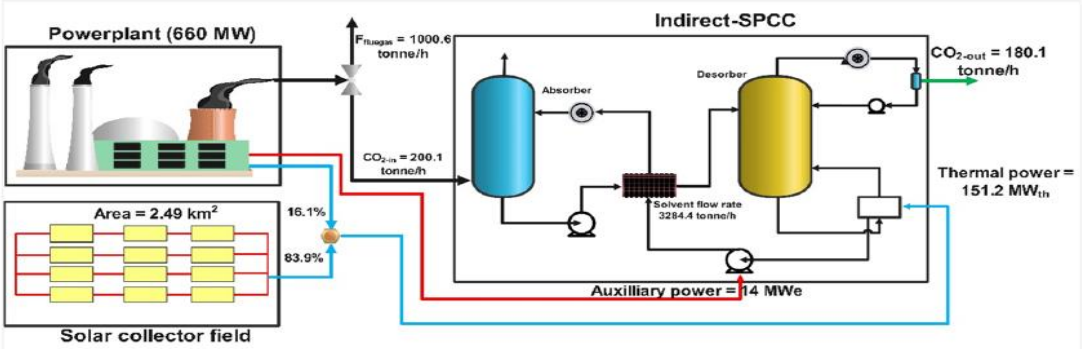
1.2.2. Process of carbon capture

According to Fig.1.1, the capture process usually comprises three major stages: (1) capture, (2) transport, and (3) storage. Capturing phase technologies employed include post-combustion capture, pre-combustion capture, and oxyfuel combustion capture. The CO2

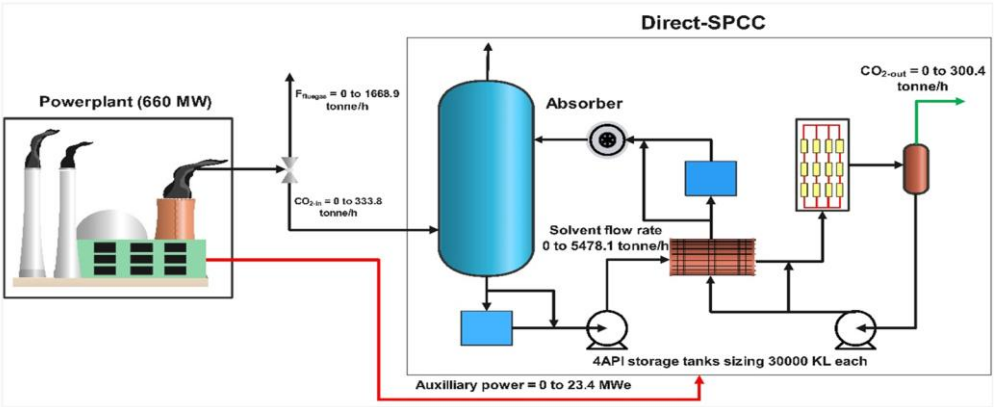
captured is further purified and compressed. Finally, the pure CO2 is passed to a turbine, from where it may be utilized as a working fluid in power generation. This mechanism affects CO2 in generating power, thus addressing a double advantage of avoiding greenhouse gas emissions and generating power. Carbon capture along with turbine technology is an innovative method of minimizing environmental footprint and ensuring sustainable energy sources [10].



(a) General Overview



(b) an indirect SPCC system [128]



(c) a direct SPCC system [128]

Figure 1. 3: Process Flow Of Carbon Capture.

1.3. Integration of solar energy: enhancing efficiency and sustainability

The post-combustion capture deals with the environmental effects of the combustion of natural gas. It brings about energy-consuming processes that can undermine the overall power plant efficiency. To address this discrepancy, the incorporation of solar power in post-combustion capture processes provides a strong rationale [11]. Solar energy is plentiful available and it is renewable which means there is a chance to counteract the energy needs of capture technologies to make the system more efficient overall. The synergistic potential between solar energy and post-carbon capture technologies leads to a new level for cleaner energy options. By using the power of the sun to drive or augment the carbon capture processes, it is possible to have a more sustainable and even energy creation. This integration, in addition to meeting the energy requirements of the capture process, also serves to further the aims of shifting toward a low-carbon energy sector [12].

1.3.1. Sustainability approaches

Fig. 1.2 illustrates the recurring and interdependent parameters of solar applications. The sustainability can be obtained by economic, environment and sustainable development pillars Wikström [13].

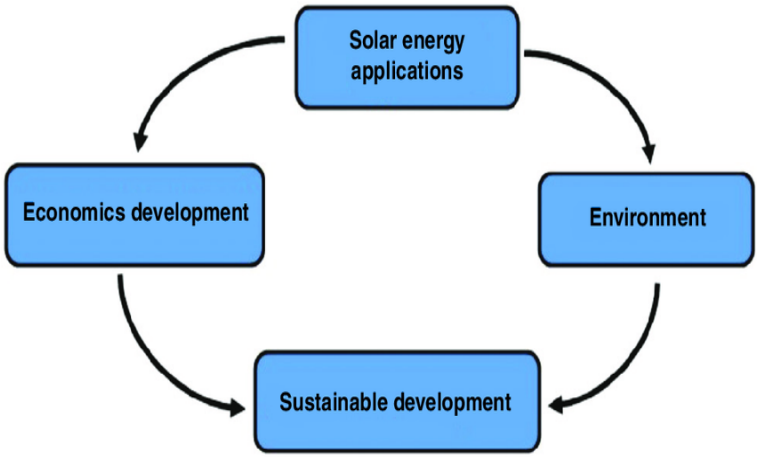


Figure 1. 4: Diagram of Sustainability.

1.4. Research Gap: A Holistic Techno-Economic Comparison

The advancements in post-combustion capture technology and integration of renewables into power generation, the literature gap becomes apparent. While separate studies delve into the nature of post-combustion capture or integration of solar energy, there exists no techno-economic comparison of several solar-assisted post-carbon capture methods for natural gas combustion cycle units [14]. Lack of such a comparison prevents the formulation of rational plans for their deployment at a scale. Filling this void, this research project intends to carry out an exhaustive and systematic review of various solar-assisted post-carbon capture methods. Taking into account technical feasibility as well as economic viability, the research intends to develop a general insight into the possibilities as well as issues with these hybrid systems.

1.5. Significance Of the Study: Guiding Sustainable Energy Development

This research work has invaluable insights into the sustainable development of energy, and most importantly, in the case of Iraq's reliance on natural gas to generate power. The results of the research can enlighten policymakers, professionals in the industry, and researchers on the most efficient and cost-effective ways to minimize carbon emissions from natural gas combustion cycle units [15].

1.5.1. Policymakers

The findings of this study can guide the formulation of policies that encourage and facilitate the integration of solar-assisted post-carbon capture technologies in Iraq's natural gas power plants. Policymakers can use the design regulations and frameworks that replace the uptake of sustainable energy solutions Pillar [16].

1.5.2 Industry Professionals

Industry players, such as power plant operators and engineers, can gain from the pragmatic advice produced by this research. Economic and technical insights can inform decision-making procedures regarding technology investments, project planning, and operational issues, achieving a balance between economic feasibility and environmental sustainability.

1.5.3. Researchers and academia

The study adds to the body of knowledge in academia by presenting an in-depth techno-economic analysis that can be used as a benchmark for future research. It provides methodologies and insights that can be further developed and applied, posing a cumulative trajectory of knowledge in solar-assisted post-carbon capture.

1.5.4. Global energy transition

In the wider context of the global energy transition, the research adds to the debate concerning the role of natural gas and the integration of renewables in cutting carbon emissions. As countries globally aim to support their energy system with climate objectives. The results of the research provide an outlook on the prospects and challenges with solar-assisted post-carbon capture strategies.

1.6. Aims Of the Project

This study is intended to create unique methods using advanced Aspen HYSYS/Aspen Plus software. The primary goal is to make a detailed comparison of these technologies, to assess their technical performance. Yet, the research does not only end with technical analysis, but it also analyzes the sustainability and environmental performance improvement for Natural Gas Combined Cycle (NGCC) plants. The second method get on a new solution for sustainability quotient and environmental footprint of NGCC plants. It is based on utilizing the potential of CO2 as a valuable feedstock for methanol production to fill in modern carbon capture and utilization approaches. By converting CO2 into methanol, an all-purpose and common chemical, the suggested system not only caters to the environmental issue but also adds value to the emergent trend of circular economy methods. The additional energy required in the production of hydrogen from water splitting systems is provided by solar energy. This novel integration is intended to increase the economic feasibility of the whole process, creating a closed-loop system in which methanol is used as an auxiliary fuel in addition to natural gas. The suggested system, thus, transcends a simple juxtaposition of technical advantages; it seeks to maximize the energy efficiency of the NGCC plant while simultaneously reducing greenhouse gas emissions. This two-pronged approach not only

aligns with international sustainability objectives but also works towards the general shift towards cleaner, more eco-friendly energy of the future.

1.6.1. Carbon utilization and emission reduction

The essence of this study is in the complex evolution of two unique models. The first model is based on the incorporation of solar thermal energy to boost the efficiency of Natural Gas Combined Cycle (NGCC) plants, combined with a CO2 capture plant using amine absorption technology. This multi-faceted model not only aims to maximize the overall performance of NGCC through the utilization of solar thermal energy but also tackles the imperative requirement of carbon capture. Concurrently, the second model ventures into the field of high-performance catalytic conversion processes, leveraging the direct use of captured CO2 from NGCC flue gas emissions for methanol synthesis. This new method goes beyond the traditional paradigm of simple CO2 capture and storage. Rather, it is a dynamic system where CO2, a historically regarded pollutant, is utilized as a valuable resource in the manufacture of methanol—a chemical with many uses and applications.

1.6.2. Assessing greenhouse gas emission reduction potential

A key component of this research effort is the comprehensive evaluation of the possibility of substantial greenhouse gas emission reduction by integrating solar thermal energy and catalytic conversion for methanol production. By strategically integrating these two models, the research seeks not only to capture CO2 emissions from NGCC flue gases but also direct them into a value-added process, thus making a contribution towards a circular and sustainable process.

The use of solar thermal energy plays a double role here. It not only increases the overall efficiency of NGCC plants but also supports the integration of renewable energy, a major aspect of modern-day sustainable practices. At the same time, the catalytic transformation of sequestered CO2 into methanol not only avoids emissions but also converts them into a high-market chemical, incorporating an economic value into the environmental advantages.

Greenhouse gas emission reduction potential assessment is a key component of managing climate change and moving towards a more sustainable future. It entails an examination of the viability and efficacy of different strategies, technologies, and policies

for mitigating emissions of greenhouse gases (GHGs) like carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O).

One way of evaluating emission reduction potential is by applying carbon accounting and lifecycle assessment techniques. These techniques entail measuring GHG emissions from particular activities, processes, or systems across their whole lifecycle, from extraction or manufacturing to end-of-life waste disposal or recycling. Through the systematic examination of emissions at various lifecycle phases, decision-makers can determine hotspots, inefficiencies, and areas where emission reduction is possible.

In addition, developments in technologies are important for quantifying emission reduction potential. Cleaner energy technology developments, renewable energy, efficiency gains in energy, and carbon capture and storage (CCS) technologies provide potential for emissions reduction in many sectors including energy, industry, transport, and agriculture. Determining technical and economic viability of these technologies, and their scalability and deployment potential, is important for establishing their contribution to emission reduction.

Policy settings and regulatory actions also have a crucial role in determining emission reduction potential. Governments, international institutions, and regulatory agencies adopt policies like carbon pricing, emissions trading schemes, renewable energy standards, and emission standards to encourage emission reductions and the use of low-carbon technologies. Determining the effectiveness of these policies in encouraging emission reductions and meeting climate goals is critical to informing future policy choices and improving policy effectiveness.

Furthermore, measurement of the emission reduction potential considers socio-economic parameters, stakeholder support, and public acceptability. Understanding socio-economic impacts of emission reduction actions, their influence on jobs, economic development, and social equity, is also vital to inform the formulation of efficient and equitable policies as well as an inclusive transition towards a low-carbon economy. In addition, the involvement of stakeholders such as businesses, communities, and civil society organizations in the decision-making process and promoting public awareness and support are needed for effective implementation of emission reduction measures.

1.7. Objectives

- To develop a steady state model for the integration of solar thermal energy to improve NGCC with CO_2 capture plant through amine absorption.
- To develop a steady state model for the integration of catalytic conversion of carbon dioxide (CO_2) into methanol within the context of an NGCC power generation system.
- To optimize the models and conduct parametric evaluation of various important operating parameters.
- To compare the models with each other and with existing methods for post carbon capture.

1.8. Tools Used in The Project

The implementation of the present project will be coordinated using the high-end features of ASPEN PLUS software, i.e., Version 11. ASPEN PLUS, which is well known for its strong simulation features, will be used as the main tool for designing and modeling different process components that are part of the project. This all-encompassing software will be used for the careful design of essential components like the power generation cycle, MEA absorption cycle, catalytic conversion steps, and the combustion system. Nevertheless, the solar thermal analysis module brings a sophisticated aspect to the project. Although ASPEN PLUS does not necessarily carry with it solar thermal analysis functions, a strategic solution will be adopted in order to include the effect of solar heating as part of the overall system dynamics. The problem is that of properly integrating solar thermal factors, and to rectify this, accurate Direct Normal Irradiance (DNI) data becomes critical. In overcoming such, DNI data, critical in conducting proper solar thermal analysis, will be drawn from trusted external databases. Ansys FLUENT, being adept in fluid dynamics simulations, presents itself as an applicable solution. This program can offer precise DNI values using given coordinates in terms of latitude and longitude data for the chosen project location. This combined application of ASPEN PLUS for the majority process modeling activities and Ansys FLUENT for detailed solar thermal analysis provides a thorough and advanced framework for the project. The synergistic combination of these tools provides a careful investigation of the complex interactions within the suggested system, providing a refined

understanding of the technological and environmental aspects of the solar-assisted post-carbon capture methods for natural gas combustion cycle units.

1.8.1. Capabilities of Aspen plus simulation process and its user interference

Aspen Plus is a process simulation software that is used extensively in the chemical engineering field for process design, optimization, and analysis. It has the capabilities to reach from conceptual design through detailed engineering and optimization. Below are some of the main capabilities of Aspen Plus and their usage in process design:

Process Modeling: Aspen Plus enables engineers to simulate intricate chemical processes with a broad variety of unit operations, such as reactors, separators, distillation columns, heat exchangers, and others. It offers an extensive library of pre-designed components and thermodynamic models, making it easy to develop precise process models.

Thermodynamic Modeling: Aspen Plus has a large library of thermodynamic models and property methods available for the purpose of describing phase equilibria, vapor-liquid equilibrium (VLE), liquid-liquid equilibrium (LLE), and solid-liquid equilibrium (SLE). Several equation-of-state (EOS) models, activity coefficient models, and mixing rules are available that engineers can choose from depending on the unique demands of their process.

Process Simulation: Steady-state and dynamic behavior of chemical processes can be simulated by engineers using Aspen Plus. Aspen Plus enables the simulation of different operating conditions, process configurations, and feed compositions in order to evaluate the performance of the process and the optimum operating conditions.

Heat and Material Balances: Aspen Plus facilitates the calculation of heat and material balances for chemical processes, enabling engineers to track the flow of energy and materials throughout the system. This capability is essential for understanding process behavior, identifying bottlenecks, and optimizing process performance.

Process Optimization: Aspen Plus provides robust optimization capabilities to enable engineers to optimize process design and operating conditions. It enables process variables including temperatures, pressures, flow rates, and equipment size to be optimized for maximum process efficiency, cost reduction, or achievement of certain performance criteria.

Sensitivity Analysis: Sensitivity analysis may be carried out by engineers employing Aspen Plus in order to investigate the effect of process parameter variations, feed stream compositions, or operating conditions on process performance. The ability thus facilitates the location of key parameters and process designs' optimization with various scenarios.

Process Integration: Aspen Plus allows engineers to integrate multiple process units and streams and design integrated process flowsheets. The ability is specifically beneficial for the design of complicated processes with several unit operations, recycle streams, and heat integration.

Environmental Analysis: Aspen Plus contains environmental analysis features to determine the environmental effect of chemical processes, such as emissions of greenhouse gases, air pollutants, and waste streams. Engineers can utilize these features to analyze the sustainability of process designs and determine opportunities for environmental improvement.

Fig: 1.3 depicts the user interference of Aspen HYSYS software, which displays iteration simulation results. The software is equipped with graphical design features of simulation models and obtain results on excel sheets, graphs. Furthermore, the software has pre-programmed some importance in learning model templates.

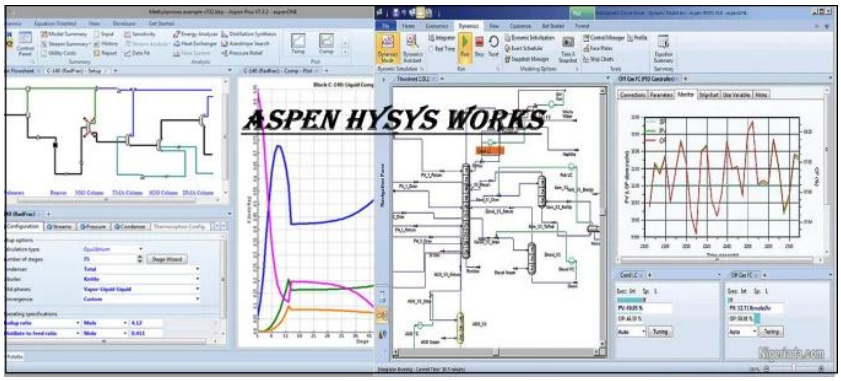


Figure 1. 5: Aspen plus simulation process user interface

1.8.2. Graphical fluid diagram

According to Fig. 1. 4, all simulation model fluids are connected according to program setup. User interference is user friendly in which each and everything is clearly visible.

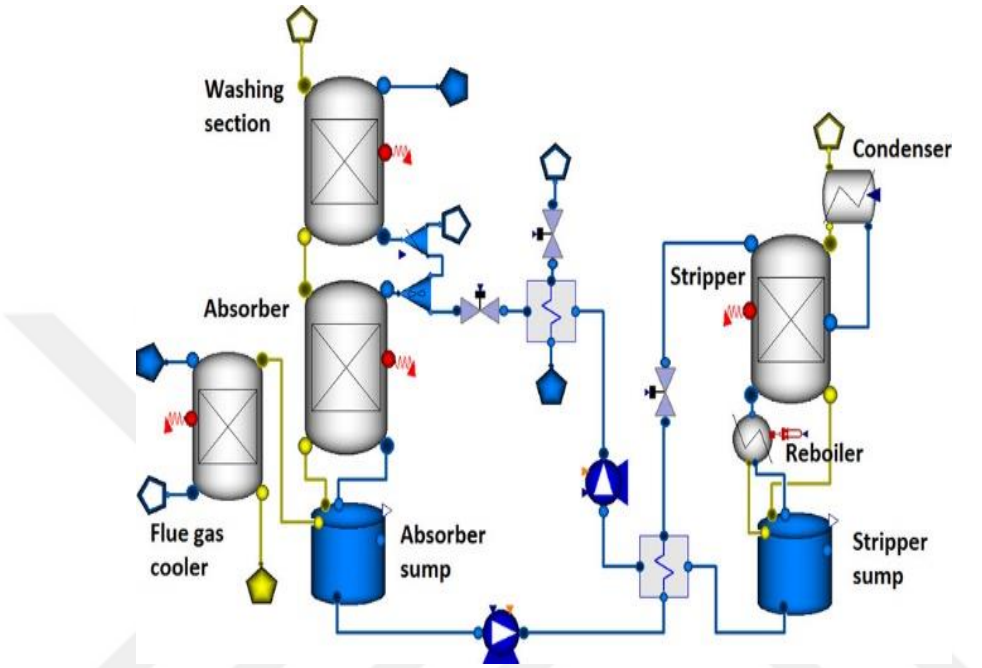


Figure 1. 6: Graphical Fluid Diagram

1.9. Thesis Organization

The thesis, "Techno-Economic Comparison of Solar Assisted Post-Carbon Capture Approaches for Natural Gas Combustion Cycle Units Installed in Iraq," offers a detailed examination into the use of solar-assisted technologies in post-combustion carbon capture processes in natural gas combustion cycle units with an emphasis on the feasibility of implementing them and the economic attractiveness thereof in the case of Iraq's energy industry.

The introduction primes the reader by pointing out the importance of carbon capture technologies in reducing greenhouse gas emissions and dealing with environmental issues related to power generation from fossil fuels. The rich natural gas resources of Iraq and its increasing energy requirements place emphasis on developing efficient and sustainable methods to limit emissions while fulfilling energy requirements.

The literature review explores current studies on technologies for carbon capture, highlighting both traditional post-combustion processes and futuristic solar-aided techniques. Through integrating existing studies, the literature review isolates knowledge gaps and establishes the basis of comparative analysis and assessment undertaken in chapters that follow.

Chapter on methodology describes the research design and strategy, explaining the evaluation criteria to compare various carbon capture methods and simulation methods used for techno-economic assessment. The chapter describes the assumptions that were made and sensitivity analysis carried out to test the robustness of the results.

Chapter 4 provides the techno-economic comparison results, giving insights into the performance and cost-effectiveness of different solar-assisted post-combustion carbon capture methods in the context of natural gas combustion cycle units in Iraq. Based on extensive data analysis and discussion, this chapter explains important findings, determines cost drivers, and discusses policy and industry stakeholders' implications.

Lastly, Chapter 5 summarizes the thesis with a summary of findings, conclusions based on the research, and practical recommendations for future research paths and implementation strategies. By combining the research findings and providing insights into the prospects for benefits and challenges associated with the incorporation of solar-assisted carbon capture technologies into the energy sector of Iraq, the thesis adds to current knowledge in sustainable energy technology and informs decision-making by policymakers and industry professionals.

Chapter 2

Literature Review

2.1. Introduction to The Literature Review

Literature review is pivotal in creating a foundation for a comprehensive investigation of solar-aided post-carbon capture measures in natural gas combustion cycle units in Iraq. Its intention is to provide the background by putting recent studies in perspective, identifying knowledge gaps, and highlighting the technological, economic, and environmental aspects of carbon capture technologies when combined with solar energy, all specifically addressing the Iraqi context. By integrating earlier studies, the literature review intends to build a strong framework. This structure not only clarifies understanding of the challenges and opportunities associated with the integration of carbon capture technology and solar energy but also provides precious insights into possible avenues for creating sustainable and economically viable solutions within the one energy regime of Iraq.

2.2. Solar Integration in Natural Gas Combustion Cycle Units

The solar gas-turbine systems hybrid (HSGT) in technologies of solar power plants is expanding. The use of hybrid systems to generate electricity is essential [17]. Combined cycles minimize water use and maximize the conversion efficiencies. The outcomes are translated into simulation tools to produce high performance cycles with a thermal energy storage device. The storage method provided a benefit in maintaining the air stabilized temperature at the inlet of the combustion chamber, hence the design perspective the combustion chamber operating conditions remain in balance. This work establishes stable electricity production. It raises the daily average solar contribution of the power plant. [18] analyzed the outcomes of Solar Thermal Systems that turned out to be novel solar technology intended for electric power generation by heating a working fluid to high operating temperatures (≥300°C) and combining it with a thermodynamic power cycle. The system performance analysis outcomes suggested that the integrated solar combined cycle operating mode increases the plant capacity. Raised it from 503 MW to 555.23 MW in summer season. Annual contribution of solar energy to electricity totals around 85.77 GWh, supported by an annual decrease in CO2 emissions by around 51670.8 tons. Integrated Solar Combined Cycle

configurations that not only enhance economic feasibility, expressed in terms of Net Present Value, but also help reduce mean CO2 emissions concentration, hence supporting sustainable and environmentally friendly power generation options Brodrick, Brandt [19]. The Integrated Solar Combined Cycle power generation process can facilitate combining solar thermal and natural gas systems. In this research, focus has been laid on creating bi-objective Pareto faces that provide two conflicting objectives: Net Present Value and average CO2 emissions intensity of power produced. In order to find an optimum setup, several Integrated Solar Combined Cycle configurations were thoroughly examined. Nonetheless, given physically feasible yearly solar contributions of as much as 20%, which represents a significant increase over existing designs documented in the literature.

2.2.1. Overview of solar integration technologies

Solar power is highly marketed as a reliable alternative energy source to conventional fossil fuels. Owing to its convenience of use together with sustainability issues advantages. Photovoltaic devices provide fascination options for energy supplies of buildings, which represents most energy consumption in most cities. To offset in the unpredictable and unreliable nature of solar photovoltaic power production, the electric energy storage systems were being constructed to correspond power production with building demand Liu, Chen [20].Concentrated Solar Power had been getting much notice for its probable application in large-scale energy production and addressing solar resource intermittency. The united countries of Spain, India and China expressed interest in Concentrated Solar Power parabolic trough collectors and solar power towers Islam, Huda [21]. The twin issue of reducing carbon emissions and electricity costs in industry is essential to competitiveness and meeting climate policy. Although photovoltaic power holds promise, wide-scale application raises operational issues, including unsatisfied demand and electrical instabilities. Polleux, Guerassimoff [22] reviews challenges from fossil engine thermodynamics to control system theory in the industrial context and emphasizes the necessity of reliability-constrained micro grids. It identifies gaps in accommodating dynamic behavior of fossil equipment, PV, and storage systems, stressing the demand for tailored modeling approaches. Wang, Zhao [23] developed a pilot system of solar thermal energy-assisted chemical absorption to analyze system performance, with the use of parabolic trough and linear Fresnel reflector collectors.

Operating parameters satisfied the design requirements, and solar collectors provided thermal energy for the reboiler, which was based on solar irradiation. Wang, Zhao [24] learned through the experimental setup with parabolic trough and linear Fresnel collectors for understanding the solar-assisted post-combustion carbon capture system to mitigate coal-fired plant energy penalties due to absorbent regeneration. Dynamic performance was influenced by parameter changes and solar collector fluctuations. Mokhtar, Ali [25] suggested a solar-assisted Post-combustion Carbon Capture (SPCC) system to minimize the Output Power Penalty (OPP) in fossil-fuel power plants. The system sought to employ solar thermal energy for some of the PCC energy input, ideally coinciding with peak electricity prices. Li, Yan [26] investigated solar-assisted post-combustion CO2 capture (SCC) in an amine-based power plant. Local conditions significantly affected SCC performance, determining costs. Cohen [27] surveyed solar thermal technologies for CO2 capture, finding parabolic troughs and central receivers technically viable. Several studies investigated solar-assisted PCC as an alternative for the reduction of the energy penalty of fossil-fuel power plants. Ampah et al., [28] used the Global Change Assessment Model for Carbon dioxide removal (GCAM-CDR) to simulate five CDR strategies in four deployment scenarios for China's climate objectives. Findings indicated that relying exclusively on land-based biological CDR techniques might result in significant decreases in fossil fuel use, greenhouse gas emissions, and air pollutants, with varied implications for China's carbon neutrality ambitions.

2.2.2. Importance of understanding the existing research on solar-assisted PCC approaches for NGCC units

Carbon dioxide capture from natural gas-fired power plants is challenging due to the high flow rate and low concentration of carbon dioxide in the flue gas. The new design was proposed to decarbonize a natural gas-fueled combined cycle power plant using a solar-assisted hybrid membrane-amine system for carbon capture and storage Asadi and Kazempoor [29]. A detailed process modeling and simulation framework was established to accurately study the interaction between different components of the integrated process. Power plant efficiency penalty can be compensated for by integrating solar energy to improve solvent regeneration in post-combustion CO2 capture (PCC). Since solar energy is a naturally intermittent and fluctuating form of energy, solar-assisted post-combustion CO2

capture (SPCC) power plants are expected to be operated in a flexible manner in order to optimize their techno-economic efficiency [30]. Supercritical carbon dioxide cycle coupled with a multi-generation gas turbine system was incorporated with an Al-Hamed and Dincer [31] solar-powered carbon capture system. The combined configuration is intended to produce electricity, create a cooling effect, generate freshwater, and produce ammonium bicarbonate. The results of the analysis reveal that the combined system can produce ammonium bicarbonate at 1.30 kg s−1 and generate 2,280 kW of electricity at the same time. The overall energy and exergy efficiencies of this combined system are found to be 22.3% and 11.9%, respectively. The carbon capture process from post-combustion is dynamically controlled and combined with a solar power system based on parabolic trough collectors Alzhrani [32]. The Aspen plus Dynamic software was used in performing dynamic simulation, in addition to an initial stringent design done using Aspen Plus software. Two scenarios Investigated: one for low-pressure steam and the other with a Parabolic Trough Collector (PTC). During steady-state design, the CO2 capture process showed the capability to remove up to 89.4% of CO2, using a certain reboiler energy of 4.64 GJ/tone's CO2.

2.3. Solar Thermal Technologies

Description of different solar thermal technologies available for use in air conditioning or cooling applications. Parameters considered for simulation model analysis for the cooling system were collector area, per unit capacity of chiller, Coefficient of Performance, per unit area storage tank volume and per unit capacity of chiller. Market-dominant absorption chillers have a Coefficient of Performance range between 0.40 and 0.85 for experimental set-ups and between 0.6 and 0.8 for simulation for different attribution for raising inlet temperature between 70 and 100 °C. Adsorption chillers, even though they contain lower Coefficient of Performance from 0.2 to 0.6, have a low inlet temperature (45 to 65 °C). The collector unit area per unit chiller capacity ratio ranges widely from 1.5 to 11.5 m^2 $kWch^{-1}$, which points to varied installations and resultant thermal energy loss and upfront system costs implications. Likewise, the storage tank volume to collector area ratio shows considerable range from 5 to 130 l m^{-2}, with most systems falling within 20–80 l m^{-2} range. Although a range of storage volume 50–110 l m^{-2} is recommended, storage volume is constant, being correlated with collector area may not be the optimum solution for large collector areas. Even though originally designed for solar cooling or air-conditioning

purposes, the feasibility of integrating the systems for sanitary hot water and space heating as Multi-Purpose Solar Thermal Systems. Which promises primary energy savings, Ghafoor and Munir [33]. The Various concentrated solar thermal technologies that were parabolic troughs, central receivers using different heat transfer media, and Coefficient of performance were taken into commercial phase for large power generation. Yet data on the cost, performance, and environmental effects of these systems presently defined by uncertainty Cavallaro [34]. The European FP7 Project In Sun was directed towards demonstrating collector technologies' efficacy and reliability suitability for providing industrial process heat for different climatic area locations. The initial system layouts, description of the intended operating conditions, and the type of industrial process involved were shown in the early design of the three installations. The demonstration collectors vary from flat-plate collectors providing temperatures up to 95 °C in the moderate north European climate to concentrating collectors, such as parabolic trough collectors and linear Fresnel collectors. The collectors are intended for supply temperatures between 160 and 250 °C in the dry Mediterranean and warm climates of Spain and Italy. The biggest challenge to rapid market development of this new technology is in putting the performance of the production process for industrial companies ahead of energy savings realized. Therefore, only proven and standardized solutions not to exceed 3 to 5 years payback time that are to be considered. Apart from the cost factors, which are subject to fluctuations in energy and collector manufacturing processes. There is an urgent need to prove the reliability of technology. Smart control plan strategies required for smooth integration into various industrial processes and methods for automation performance monitoring are required. In Sun project partnered with ZAFH-NET and scientific research inputs with EURAC and industrial collaborations with Solera, Solid, and Soltigua are given high priority [35]. Parabolic trough solar collectors are a proven technology for solar energy harvesting.

They are comprised of arched, reflective troughs that focus the sunlight into a focal line along which is positioned a receiver tube. A heat transfer fluid in the receiver tube, generally oil or molten salt, captures the concentrated light and achieves hot temperatures. Heated fluid subsequently creates steam used to generate electricity by driving the turbine in CSP facilities. Parabolic trough collectors are highly efficient and scalable, which makes them applicable to both utility power generation and industrial process heat. With years of

successful operation, parabolic Trough technology remains a key player in the shift towards clean and renewable energy sources. Several commercial parabolic solar collectors exist, among which a few of them are presented in Table 2.1.

Table 2. 1: Commercial Technology for Parabolic Trough Solar Collector Technologies

Sr. #	Technology	Some features
1	SkyTrough by SkyFuel	This is a highly efficient and cost-effective parabolic trough solar collector used in concentrated solar power (CSP) plants.
2	SCHOTT PTR 70 by SCHOTT Solar	SCHOTT offers high-performance parabolic trough receivers designed for use in large-scale solar thermal power plants.
3	Aalborg CSP HTS-P30 by Aalborg CSP	Aalborg CSP provides parabolic trough collectors suitable for both power generation and industrial applications.
4	SEGS (Solar Energy Generating Systems) by BrightSource Energy	While not a specific product name, SEGS represents a series of parabolic trough solar power plants utilizing BrightSource Energy's technology.
5	Ultima® by Solar Millennium (now Siemens Energy)	Ultima® is a type of parabolic trough collector developed for solar thermal power plants.
6	Infinia Solar System by Infinia Corporation	This company offers innovative parabolic trough solar systems for various applications, including electricity generation and industrial processes.
7	HelioTrough by Solar Trust of America	HelioTrough is a line of parabolic trough solar collectors designed for utility-scale solar power plants.

2.3.1. Solar thermal integration

In Fig: 2.1, the process of solar thermal integration is depicted. The process of solar thermal integration begins with Capture solar energy using solar collectors. Such as mirrors or parabolic racks to focus sunlight on a receiver. Absorb and transform sunlight to heat energy at the receiver through the use of a fluid or material. The stored heat energy for future use allows for constant utilization, even during cloudy weather. The thermal energy stored is utilized in various industrial processes like manufacturing, heating, etc.

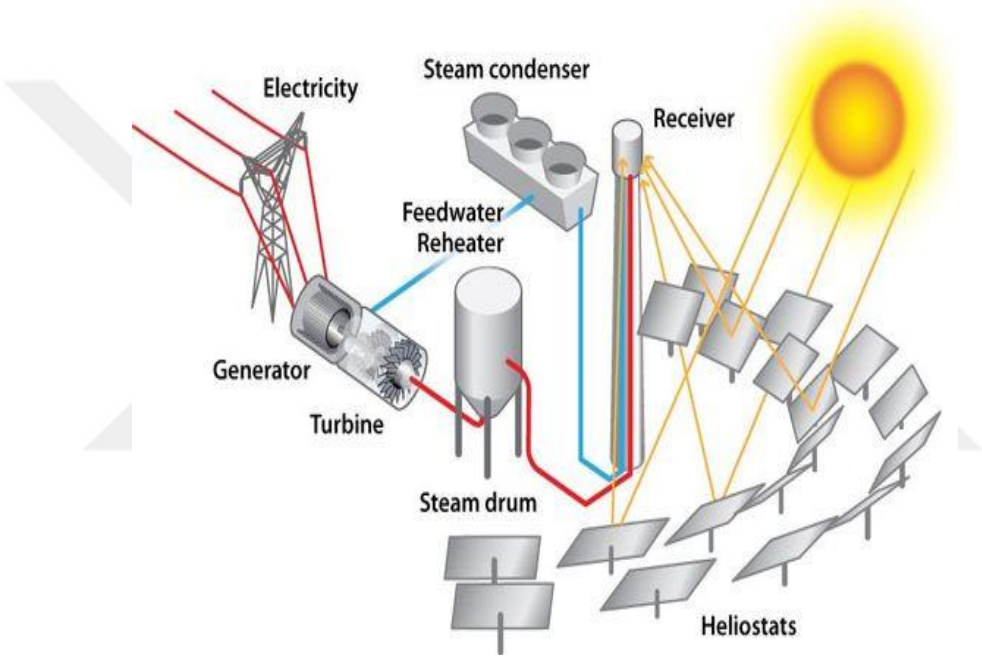


Figure 2. 1: Solar Thermal Integration Flow Diagram

2.3.2. Photovoltaic integration

Photovoltaic (PV) systems are becoming increasingly integrated into larger segments of power generation. The PV systems are the fastest-growing generation technology that witnessed a growth around 30% since 2015 and achieved a global capacity of 509.3 GWp. As of the end of 2018 with expectations to rise further to 1000 GWp by 2022 [36].China is identified as the world's most rapidly growing nation in the photovoltaic (PV) sector, and it has particularly eminent challenges in this field Ding, Xu [37]. The research examines the applications of large-scale photovoltaic (LSPV) power generation using the modeling and

simulation methods. It investigates the impact of combining LSPV on the static and dynamic power system characteristics. It also specifying key technologies in terms of LSPV-delivered power and consumption from a power system planning perspective. Alquthami, Ravindra [38] carried out research on large solar panel impacts. The study looks primarily at the substantial influence of large solar plants on power systems, with an emphasis on the rapid swings in power injection. Factors used such as intermittent sun radiation, temperature changes, and potential converter tripping were investigated. The job started with designing a comprehensive mathematical model of an array-based photovoltaic (PV) solar plant that has the Maximum Power Point Tracking (MPPT) technique to reflect DC power output changes accurately. The mathematical model was then incorporated into the PSS/E dynamic simulation program by a user-programmed model integration technique in a very efficient way. The research seeks to give a comprehensive insight into the dynamic problems associated with large-scale solar integration in power systems. To demonstrate high PV penetration, PV power generation was precisely increased up to 20%, spread randomly across three plants. The findings give precise insight into the perceived increase in system vulnerability with the precisely increased penetration of PV power.

2.3.3. Hybrid solar-gas systems

The hybrid solar gas turbine power plant dynamic model utilized a tower-driven method. It has benefits of hybrid operation and demonstrates a distinct formation [39]. The hybrid system increases solar to electric efficiency by 30% compared to a solar-only plant using packed-bed thermal energy storage. Despite low improvement in packed-bed thermal energy storage being passive, the one-of-a-kind formation, characterized by a recycle stream for thermal energy storage charge, realizes in a 10.8% increase in annual solar to electric and an 11.3% increase in solar percentage over a system in the absence of this control mechanism. Hybrid modeling of thermodynamic for solar power plants involves various components' cycles, including energy, energy and emissions. Both solar gas turbine and organic Rankine cycle were examined from energy and exergy standpoints. How wind speed, air pressure, and ambient temperature affect heat loss from the solar receiver was considered. Analysis consists of emissions, working fluid mass flow rate, pressure ratio, and concentration ratio, and all are compared with a typical fossil-fueled power plant. The results indicate a significant enhancement in the system's energy efficiency and energy as a function of solar

radiation intensity. Interestingly enough, the organic Rankine cycle shows a greater output power than that of the Rankin steam cycle. As a result, solar energy utilization reduces carbon dioxide emissions by a significant amount of 150% compared with a typical fossil-fueled power plant [40].

2.3.4. Comparative investigation of solar collectors

Table 2. 2 illustrates various studies were carried out on simulation models employed that were (T*SOL, TRNSYS, EES, RET Screen Graphical tool, Nomograph, and F-Chart Solar collectors' efficiency was obtained with the aid of T* SOL simulation model that is 86 % by utilizing solar fraction. Evacuated solar collectors employed in TRNSYS AND EES simulation model where factors employed flow rate through the cycle, storage tank size, solar collector size, type solar collector, area, storage tank size, and area.

Table 2. 2: Comparative investigation of solar collectors' impacts on solar fraction also decreases in CO2

Solar Collectors	Simulation Model Software	Factors	Region	Results of simulations	CO_2 emission	Ref.
Evacuated tube collectors (ETC), flat plate collectors (FPC), and unglazed collectors (UnGC)	Simulation (T*SOL)	Hot water demand, solar irradiance, economic feasibility	Pakistan (Gilgit-Baltistan)	ETC has the highest solar fraction	ETC saves the highest CO2 emissions compared to FPC and UnGC.	Arif, Waqas [41]
evacuated tube	TRNSYS and EES software	solar collector type, area, storage tank size, and flow rate through the cycle	Jordan	0.52–0.542	-	[42]
Domestic Solar Water Heaters (DSWH)	RETScreen software	Solar collector gross area, aperture area, Fr (tau alpha) coefficient, UL coefficient, number of collectors, and electricity rate.	Benghazi, Libya	-	CO2 emissions (kgCO2/kWh): gas (20518), light fuel oil (20764), heavy fuel oil (185). Social cost of CO2 emissions: 220$/ton CO2.	[43]
-	Graphical tool, Nomograph, and F-Chart method	exact costs, supplementary fuel, solar thermal systems performance and size	Italy	-	-	[44]

2.4. Carbon Capture Technologies for Natural Gas Combustion

Carbon capture technologies for natural gas combustion have an essential role to reduce greenhouse gas emissions and meet the environmental challenge from power generation based on fossil fuels. Natural gas, though a cleaner option for coal and oil because it is less carbon-intensive, still emits high volumes of carbon dioxide (CO2) when burned to produce electricity or industrial purposes. Carbon capture technologies provide an effective means to trap and sequester CO2 emissions associated with natural gas combustion, minimizing the carbon impact of such activities.

Among the first-generation carbon capture technologies being applied in the combustion of natural gas is post-combustion carbon capture. Post-combustion capture involves capturing CO2 from the flue gases produced during combustion through solvent-based absorption, adsorption, or membrane-based separation technologies. The captured CO2 can be compressed, transported, and injected underground into geologic formations for storage or applied for enhanced oil recovery (EOR) or industrial uses. Post-combustion carbon capture technologies can be added to existing natural gas power plants and industrial processes, allowing for emissions reductions without the need for extensive changes to existing infrastructure.

Another technology that hold great promise for natural gas combustion carbon capture is pre-combustion carbon capture. For pre-combustion capture, natural gas is first converted to syngas (a hydrogen-carbon monoxide mixture) via steam methane reforming (SMR) or autothermal reforming (ATR). CO2 is removed from the syngas stream prior to combustion, yielding a high-purity CO2 stream that is ready for capture and storage or use. Pre-combustion carbon capture is more efficient in terms of capture and has smaller energy penalties than post-combustion capture and is thus a desirable choice for new industrial and natural gas power plants.

In addition, technological developments in oxy-fuel combustion have made it possible to design carbon capture systems in conjunction with natural gas power plants. In oxy-fuel combustion, natural gas is burned in a blend of oxygen and recycled flue gases, producing a flue gas stream that mainly comprises CO2 and water vapor. This highly concentrated CO2

stream can be captured with ease by employing standard post-combustion capture technologies, which enable effective carbon capture with minimal energy penalties.

2.4.1. Review existing methods and technologies for carbon capture

Current carbon dioxide (CO2) capture technologies include pre-combustion, post-combustion using chemical absorption, physical and membrane separation, chemical looping combustion, calcium looping, and oxycombustion. The operational mechanism of each method highlights their relevance to future low-emission energy technologies. Operational demonstrations of these CO2 capture technologies are given, highlighting their application [45].Solid adsorbents for post-combustion and direct air capture (DAC) carbon capture were applied to several new emerging technologies Lai, Ngu [46]. NaX@NaA core-shell microspheres show the greatest DAC CO2 adsorption capacity of 5.60 mmol g−1, whereas MOF-177-TEPA shows the greatest under post-combustion conditions with a capacity of 4.60 mmol g−1, thanks to tetra ethylene pentaamine properties. Pre-combustion capture at oxy-combustion process conditions provides adsorption capacities between 0.0000026 and 48.71 mmol g−1.

The vast overview of Carbon Capture and Utilization (CCU) technologies were discussed from lab-scale research to commercial use. Carbon dioxide is an economical carbon source, which is investigated for uses like solvents, fuel production, carbonates, polymers, chemicals, and recovery agents for improved oil and coal bed methane. The recent upgrading in every technology, culminating with major Life Cycle Assessment [47]. Interestingly, carboxylation reactions, including the formation of carbonates and carboxylates, stand out as major, with salicylic acid manufacture and dimethyl carbonate synthesis being cited as short-term opportunities for carbon dioxide use. Hekmatmehr, Esmaeili [48] they evaluated carbon capture possibilities, wherein including pre/post-combustion, oxyfuel, and chemical looping combustion, across various technological readiness levels (TRL).The organized survey contrasted methods that were enzyme-accelerated solvents, such as enzyme-catalyzed aqueous salt, pointed out their benefits, drawbacks, and technical-economic to summarized essential characteristics of traditional physicochemical solvents. Technology maturity levels led to conclusions, and prospective carbon mitigation paths are suggested.

2.4.2. Evolution of carbon capture approaches in the context of NGCC units

Carbon capture, utilization, and storage come out as key measures to counter Environmental problems [49]. The largest sources of carbon dioxide release into the environment are largely attributed to human activities, particularly the use of nonrenewable fuels in the generation of energy, industrial activities like cement production, and tree cutting. It is evaluating two of the front-runner technologies for carbon capture that are direct methods pre and post combustion, oxy-combustion and indirect carbon capture. Nowadays for commercial applications post combustion is utilized predominantly, particularly in industries. The technology, which is for Readiness Level analysis, shows pressure-vacuum, swing adsorption, amine solvents and gas separation membranes have the maximum value of Readiness Level analysis 9. Environmental impact assessments rank these procedures according to their sustainability levels, showing a maximum global warming of 219.53 kgCO2 potential eq. /Mwah for post-combustion. [50] reviewed an entire comparison between the procedures for Carbon Capture, Storage, and Utilization, and how their effects relate to the environment in collaboration with existing life cycle assessments. 11 of 27 studies researched correspond to Carbon Capture and Storage while 16 work on Carbon Capture and Utilization. In Carbon Capture and Storage, the results predicted a global warming potential reduction of 63–82% from power plants, with oxy-fuel combustion in pulverized coal and integrated gasification combined cycle) plants producing the highest reductions and post-combustion capture in combined cycle gas turbine) plants having the lowest.

Yet, some of the other environmental effects, for instance, acidification and human toxicity, were significantly increased using Carbon Capture and Storage. When it comes to Carbon Capture and Utilization, the changes in global warming potentials are scenario specific. Mineral carbonation would lower the global warming potential by 4–48% compared to zero Carbon Capture and Utilization, whereas using CO2 for chemicals production, such as dimethyl carbonate, has a 4.3-fold lower global warming potential and 13-fold lower ozone layer depletion than the traditional dimethyl carbonate process. Carbon dioxide (CO2) is not necessarily the strongest greenhouse gas in terms of triggering intense global warming, but its consistently high annual releases make it the most significant anthropogenic greenhouse gas. Currently, CO2 removal technologies are mostly based on

solvent-based sorbents such as ionic liquids and amine solutions. It discusses the development of nanomaterials as next generation CO2 removal sorbents. Nanomaterials show potential in CO2 capture because they have a high surface area and can have adjustable properties Lee, Lee [51].

2.4.3. Chemical absorption

Chemical absorption has emerged as one of the prominent technologies for CO2 capture in coal-fired large stationary power plants Fang, Liu [52]. The process took advantage of CO2 solubility, mass transfer, and chemical reaction principles. Ammonia based processes, amine scrubbing, biphasic processes, and membrane absorption were investigated regarding their processes and mechanisms. The primary emphasis of this research was on process modification, equipment, including absorbents, amine scrubbing, and integration technologies. The research investigated the significant effects of economic as well as environmental of amine scrubbing, gaining insights into its industrial applications for efficient CO2 capture. [53] employed absorption by chemical processes to recover carbon dioxide from power plant. First introduced at ICCDR-2 in Kyoto, the KS-1 absorbent stimulated further endeavor to improve energy efficiency. Eventually, a new absorbent, KS-2, was agreed and tested experimentally in a plant.

KS-2 is as efficient as KS-1, both of which together use 20% less energy than MEA. KS-2 has the advantage of greater stability over KS-1 and hence is a better absorbent for low CO2 content flue gas. Post-combustion CO2 capture had received widespread interest for its ease of retrofitting to new and old power and industrial facilities. Recent developments in chemical absorption-desorption systems were emphasized, including CO2 absorption studies, high pressure operation, absorber configuration advancements, and stripper heat duty reduction methods [54]. Post-combustion CO2 chemical capture utilized [P2228][CNPyr] and [P66614] [CNPyr] Aprotic Heterocyclic Anion Ionic Liquids (AHA ILs) properties in aspen plus for simulation [55]. Multiscale COSMO-RS methodology was used in Aspen Plus for simulation, incorporating AHA ILS within the database of the simulator. The operation comprised chemical absorption of multicomponent flue gas with a RADFRAC packed column model in Rate-based as well as Equilibrium modes. Tetralayer

was proposed as a co-solvent for increasing CO2 concentration and easing mass transfer constraints. Desorption, using recirculation of CO2 as a stripping fluid, at 115 °C and 1 bar.

2.4.4. Physical absorption

The efforts needed to challenge the emissions, emphasizing cost-efficient methods where physical absorption was a major technology ([Ban, Keong [56], 57] .The method had a simple installation of gas-liquid contactor and flash tanks for the regeneration of the solvent. Physical solvents, selected for being free of chemical reactions, captured CO2, which was easily stripped by pressure reduction and mild heat regeneration. Physical absorption optimum conditions were high pressure and low temperature. The study focused on the improvement of solvents, process optimization, and mathematical modeling for increased CO2 removal efficiency.

2.4.5. Adsorption

In critical phenomenon at different interfaces Adsorption, found extensive applications in technology, environment, and biology, Dąbrowski [58]. It is an important component in catalytic processes in the separation of mixtures on laboratory as well as industrial levels. Adsorption is vital in water, sewage, air, and soil cleaning. Recent developments have bridged the gap between theory and practice, with advances in molecular-level theoretical techniques, computer simulations, and novel methods. New generations of solid adsorbents, such as nanostructured materials, had emerged, which improved the knowledge and fields of application of adsorption in science and technology. The technology of adsorption's porous nanomaterial is extremely effective at environmental clean-up, and thus it is an essential and timely topic nowadays [59]. Hybrid inorganic–organic porous materials, also referred to as metal–organic frameworks (MOFs), contain a metal–oxygen cluster and organic molecules. Because of their effective properties, MOFs are now potentially looked at as substitutes for conventional inorganic porous materials such as zeolite and silica for environmental remediation.

2.4.6. Membrane separation

The techniques have been developed from the laboratory scale to industrial processes as well as with significant technical and commercial impact on membrane separation Strathmann [60]. Membrane technology has evolved during the past two decades due to multi-disciplinary cooperative efforts, extending its applications and diversifying its uses. This examines the underlying principles of several separation processes, such as microfiltration, ultrafiltration, and reverse osmosis, electrodialysis, and gas separations. It examines current applications both in the laboratory and industrial environments. Providing insights into the structure and transport characteristics of widely available membranes. New developments, including liquid membranes and carrier-facilitated transport for selective chemical species removal, are treated widely as well.

2.4.7. Cryogenic separation

The innovative Pre-Purification Unit (PPU) named SS-TSA for cryogenic oxygen production. Unlike traditional FULL-TSA, SS-TSA combines a supersonic separator (SS) prior to temperature-swing adsorption (TSA), significantly reducing TSA costs. The SS-TSA system with an alternate named TSA-HI for heat recovery, was compared with FULL-TSA and another alternate SS-SS-TSA-HI. HYSYS simulations, adding a new SS-UOE for challenging modeling, demonstrated greater performance for SS alternatives. With respect to breakeven prices after 20 years at an interest rate of 10%, SS-TSA and SS-TSA-HI performed better than FULL-TSA, setting the strengths of the supersonic separator idea (Brigagão, de Oliveira Arinelli [61]. Those economic and technical aspects of a complete-scale cryogenic air separation unit analyzes including feasibility of recent replacements like multistage compression with and without an organic Rankine cycle, integrated PSA unit, energy recovery systems, and argon column to CO2 removal. Stringent simulation and economic analysis pinpoint major bottlenecks, highlighting compression and refrigeration stage importance in capital cost, in addition to the influence of electricity and maintenance costs on economic feasibility (Young, Villardi [62]).

2.4.8. Carbon technology with their cost benefit and carbon reduction

In Table 2.3, two various carbon capture technologies employed for electricity production with carbon reduction. In (NGCC) carbon is reduced by as much as 17 percent when implementing this technology. In (SSFCC) Process marginally 1.9% of carbon cost penalty reduced due to additional processing of carbon utilization.

Table 2. 3: Carbon Technology with Cost Benefit and Carbon Reduction

CARBON CAPTURE TECHNOLOGY	Costs of electricity analysis	Reduction in cost	Carbon cost reduction	Ref.
Natural Gag Combined Cycle (NGCC)	Costs of electricity from 5.6 €ct/kWh to 4.5 €ct/kWh	1.1 €ct/kWh	45 €/tCO_2 to 28 €/tCO_2	Peeters, A.,A.Faaij [63]
Sequential Supplementary Firing Combined Cycle (SSFCC)	Compared with a conventional NGCC at 49.5-31.7 $/MWh.	47.3-26 $/MWh and 44.6-25 $/MWh respectively	8.2% to 5.7% carbon cost penalty reduced	González Díaz [64]

2.5. Co_2 Conversion to Chemicals

Carbon capture, utilization, and sequestration (CCUS) is important for the reduction of CO2 emissions. CO2 electro reduction, a significant carbon utilization technology, is attracting considerable attention. It electro synthesizes valuable chemicals directly from CO2 with renewable electricity. Improved catalysts, scale-up reactors, process models, and insights into the mechanics of the reduction reaction hold promise for commercial use and rapid incorporation of CO2 electro reduction in chemical production Overa, Ko [65].

2.5.1. Catalytic conversion of CO_2 into useful chemicals

The eco-risk of elevated atmospheric CO2 by its transformation into value-added chemicals Taheri Najaf abadi [66]. Chemical reduction of CO2, in which the problematic breaking of stronger energy bonds C=O is done without impress potential. The Progressed applied reducing agents and catalysts, homogeneous and heterogeneous, with nucleophilic

addition reactions in mind. The initial section of the discussion outlined several homogeneous catalytic processes to produce pharmaceutical industry-applicable products. The second section reported attempts with heterogeneous catalysts, focusing on the requirement of selective, active and stable catalysts on a plant type experimental scale. Exploration of reaction mechanisms with different active sites was deemed. The advances and challenges in CO2 reduction processes, with a focus on activating the CO2 molecule. [67] disclosed the excess CO2 emissions from sources points that were industries, and transport had impacts enormously to the earth due to climate changes. Metal organic proved to be effective catalysts for the conversion of CO2 into useful products. Their stable structures, high porosity, and tenability rendered them active for CO2 conversion processes like electro catalysis, cycloaddition, and photo catalysis.

2.5.2. Non-catalytic conversion of CO_2 into useful chemicals

Olive mill waste studied by simulation model approach, where catalytic and non-catalytic rapid pyrolysis features employed for results in fluidized bed reactors employed in model to yield biofuel oil [68]. Global reaction was represented by pyrolysis process with experimentally measured kinetics. Aspen Plus models is employed in two pyrolysis schemes: one without catalyst and the other with red mud used as catalyst. There were three temperatures used for fast pyrolysis: 400, 450, and 500°C. For all the simulation stages, the maximum yield of bio-oil was obtained at 450°C for non-catalytic and 400°C for catalytic fast pyrolysis. The simulation results provide precise readings like experimental results with an absolute deviation mean of 2.78% and 3.54% for non-catalytic and catalytic fast pyrolysis respectively. Techno-economic analysis of catalytic fast pyrolysis for plant capacity of 100 ton's/day wet biomass (93 ton/day dry biomass) revealed a total project investment of €17.9 million and operating cost of €4.9 million, establishing the minimum fuel selling price of bio-oil as €3.02/gallon gasoline equivalent. Energy efficiency of the plant was estimated at 52.9%, and sensitivity analysis indicated that the minimum selling price of the fuel fluctuated wildly with variation in the income tax, rate of return, and fuel yield.[69] conducted a comprehensive evaluation of the methane chemical looping combustion and sensitivity analysis process in computer program Aspen Plus. Employed a micro-reactor system with alumina supported nickel oxide as the oxygen carrier. Number of factors investigated provided valuable information for the improvement of the methane chemical looping

combustion process with an oxygen carrier based on nickel. By modifying the reactor temperature from 700 °C to 1200 °C the maximum conversion of methane to carbon dioxide that could be attained was determined to be 61.19%. The fuel reactor pressure was maintained between 20 bar and 40 bar and did not affect the methane conversion. However, when the fuel reactor pressure varied from 20 to 40 bar, the reduction of the oxygen carrier by hydrogen occurred more slowly compared to methane. Further, changing the entering carrier flow rate (1×10-8 kmol/s to 1 kmol/s) produced a reduction of methane modification from 100% to close to 50%.

2.5.3. CO_2 electro-reduction flowchart

In Fig. 2.2 chemical conversion of CO2 electrolysis process illustrated. In initiation of the process by the application of electrical power to CO2. Employ electrodes and electro-catalysts often made up of metals in order to facilitate electrochemical reactions. Ensure that the electro-catalysts selectively facilitate the reduction of CO2 into desired chemical products. Such as carbon monoxide (CO), methane (CH4) and ethylene (C2H4). The formation of valuable chemicals and fuels via the electro-reduction of CO2. The process of CO2 electro-reduction effectively reduced CO2 to valuable chemical products.

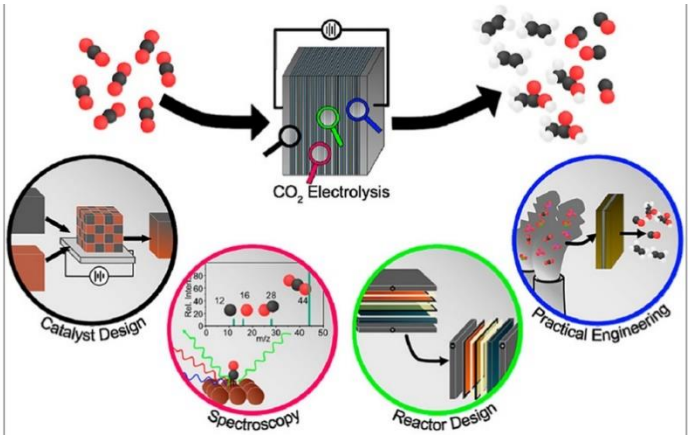


Figure 2. 2: CO2 electro reduction flowchart

2.6. Existing Applications In Iraq's Energy Sector

Current uses in Iraq's energy arena are largely based on traditional fossil fuel-powered generation, where natural gas and oil form central elements of electricity generation. There is also growing interest and investment in renewable resources, including solar and wind power, as part of a move to diversify the energy mix and increase sustainability.

2.6.1. Review studies and projects related to solar-assisted and carbon capture technologies in Iraq

Iraq's renewable energy potential focused on harnessing solar energy to ramp up power capacity [70]. Iraq could heavily benefit from solar energy, though its world mean daily radiation remains suboptimal. The article highlighted Iraq's limited solar energy activities as well as the governmental push to bring solar energy aboard, especially using concentrated solar power projects aimed to generate thermal electricity. Without the incorporation of energy storage, cost research indicated that Iraq's 50 kW concentrated solar power had an approximate production cost of about 0.23 cents/kWh. The study highlighted the very expensive nature of photovoltaic power plants among the challenges for the utilization of solar energy. The government of Iraq should initiate measures to facilitate the utilization of renewable energy, such as solar energy. It also discussed the use of combined heat and power systems, particularly the use of hot water storage tanks and flat plate solar collectors as an effective means to store both thermal and electrical energy. The proposed integrating solar power with electrochemical batteries and heat storage could enhance the technical and economic merits of stand-alone PV power plants. Increased CO2 emissions were due to conventional vapor compression cycles (VCCs), which demand environmentally damaging refrigerants and conventional power to function. Sun-powered cooling cycles appeared to be an effective alternative, particularly in those areas in the Middle East and North Africa that receive intense solar radiation. The sun cooling methods in the MENA region, with a focus on cycles such as adsorption, absorption, solid desiccant, liquid desiccant, ejector, and solar electric-driven cycles. The Middle East and North Africa took interest in solar cooling technologies in the late 2000s according to research by [71]."Evaluating the Performance of a Solar Water Heating System Utilizing CO2 through Various Climate Conditions". An efficiency of a solar water heating system based on CO2 was examined under a variety of

climate conditions in order to produce hot water without emitting greenhouse gases into the atmosphere [72]. Long-term development is based on that, especially in regions with less sunlight. Solar power is a sustainable and effective alternative to traditional water and space heating equipment. Despite synthetic refrigerants' efficiency, global institutions such as the Paris Accord have lobbied for their phased-out elimination due to environmental reasons. Low global warming potential (GWP) refrigerants were employed within this work in modeling an evacuated glass tube solar water heater system using TRNSYS®. The optimum sizes and configurations were identified through parametric analysis, and dynamic simulations for Pakistan, Australia, and China were conducted for a range of weather conditions. The outcomes reflected improved thermal performance and justified the application of natural refrigerants, i.e., hydro fluor olefins (HFOs) R-1234yz and R-1234yf. With CO2 and R-410a, the highest annual sunlight fraction values were achieved. Natural refrigerants are more environmentally friendly and have a better environmental footprint, our study recommends their use.

2.6.2. Case studies of implemented projects

The opportunities and challenges in the adoption of building information modeling for large architectural projects in Iraq was undertaken as a case study [73]. Large architectural projects impact society, the environment, and the economy. There was a need to examine the challenges affecting the operation and realization of such projects. The Building Information Modeling had emerged as a significant instrument in the Architecture, Engineering, and Construction sector with its wide international application especially in mega-scale projects. This was with a view to explore the causes behind the low adoption of Building Information Modeling in mega-scale architecture projects in Iraq as well as the ways in which these projects utilize it. Through expert interviews and surveys, the research gathered opinions from consultants, clients, contractors, and Building Information Modeling practitioners. Several significant BIM-related projects in Iraq were selected to be used as case studies. Based on the findings of the study, there are several challenges preventing large-scale projects in Iraq from utilizing extensively Building Information Modeling for project implementation and design. The principal obstacle was the absence of laws or other government or private-sector policies that enabled the integration of Building Information Modeling into project planning and construction work.

Building Information Modeling in projects on large scale in Iraq is an effective means for administrators and experts. It delivers suitable information on project characteristics limitations. Which is more understandable to stakeholders and project owners. [74] carried out surveys to gather data for study of the energy crisis. Climate change effects and conflicts arose due to exhaustion of energy sources. There is a severe electric crisis resulting from these issues, which are caused by various factors such as declining fossil fuel availability, increasing world population, climate change, and growing quantities of solid and liquid waste. The crisis has fragile socioeconomic and technological issues in most developing countries, resulting in industrial shutdowns and job loss. Waste disposal is a peculiar issue in the context of Najaf City. The Najaf city is a holy sites and tourism city in Iraq. The objective of the study was to identify how much and what type of garbage Najaf generated in a year. To find out the feasibility of generating electricity from municipal solid waste (MSW), data on the waste compositions were needed. A cost-analyzed simulated model was employed in Homer Pro simulation software. The findings proved the viability and competitiveness of the suggested power plant's cost of production compared to conventional energy production techniques in Iraq. The suggested strategy is an effective and economical means of using waste materials.

2.6.3. Challenges and opportunities specific to Iraq

The renewable energy is a strategic and efficient approach to attain sustainable development in Iraq. It will address the urgent power requirements as well as offer solutions to climate change issues. Iraq is facing a decades-long electricity shortage. In order to ease this shortage, there is an increasing focus on investigating renewable energy opportunities. This research critically analyzes Iraq's current and future electricity requirements, discussed current plans and challenges. The purpose is to increase understanding of the potential for investing in renewable energy and securing extensive energy access in Iraq. The present study offers significant information for researchers in search of an integrated view of existing research in this area and guidance for future investigation [75]. Competitive performance is a central aspect for businesses, and most struggle to maximize economic resources to generate added value. This, in turn, affects their contribution to the gross domestic product. Knowing the strengths and weaknesses of a company is necessary to design strategies that improve productivity and reduce losses. This study sought to come up with solutions to

improve the competitive performance of a company in line with its goals [76]. The research was divided into two parts: the first defined what competitive performance is, what it consists of, and how it can be measured. It also analyzed the competitive environments that both internally and externally exist. In the second part, the Iraqi Company for Seed Production (ICSP) was analyzed internally and externally based on the Porter model. Recommendations for improving and recovering the company's competitive performance were proposed. The study resulted in various findings and recommendations. Al-Elanjawy, Mustafa Yilmaz in Integrated Systems of a Solar Thermal Energy Driven Power Plant [77] Essential receivers in current solar thermal power plants can endure high temperatures. This ensures funding for green thermal power generation. Regular solar thermal power plant testing is arduous and time-consuming. They need expensive installation and take up much space. Many free software and tools can model and simulate solar thermal-producing systems. Some techniques can evaluate and predict the plant's performance, while others can investigate specific components. Nothing using research tools has ever reached the top. Simulated testing may precede power plant construction. This research requires basic visual help. A rudimentary plant model was developed when computational calculations for thermal performance were obtained. Plus, it may estimate how much power the facility would produce. The program includes hydraulic heat transport fluids, ambient factors, a database, and user input parameters. Free hourly weather data from anywhere is available from the simulator. The simulator calculates the thermal power delivered by each component while running constituent simulators.

2.7. Techno-Economic Analysis In Energy Systems

Techno-economic analysis of energy systems entails assessment of the economic feasibility and cost-effectiveness of the application of diverse technologies and policies aimed at maximizing energy generation, transmission, and consumption. By combining technical and economic insights, the analysis provides insights to inform decision-making, leading investments and policy measures towards securing sustainable and economically desirable energy options.

2.7.1. Methodologies for techno-economic analysis in the context of energy systems

Intelligent energy services and technologies have a vital contribution to make in energy changeover and decarburization approaches within the built environment. Technical potential for the energy, emissions, and cost savings of building stock was not fully utilized. The availability of data from devices, sensors, smart meters, and smart meters facilitated transparent monitoring of improved energy performance. Energy modeling and data analytics brought standardization of energy performance measurement and reporting with empirically found approaches. Techno-economic analysis guaranteed the financial viability of pioneering business models. The central importance of energy modeling and techno-economic analysis makes possible next-generation energy services and technologies Manfren, Nastasi [78]. Price instability of fossil fuels has major economic impacts, especially for oil-importing nations. To counteract these issues, nations ventured towards augmenting the use of renewable energy sources. Earlier studies considered technical as well as economic viability of hybrid RES but never together. The techno-economic comparison of solar photovoltaic (PV) and wind, and hybrid PV/wind systems with the objective of optimizing RES fraction while maintaining the levelized cost of electricity (LCOE) at or less than the local grid tariff in Gwanda, Zimbabwe. The methodology suggested was to improve the use of renewable energy economically and enhance energy security by minimizing import dependency [79].

The results reported that the PV/wind hybrid system, more specifically a 2 MW wind and 1 MW PV, exhibited the optimal economic advantages and technical performance. The system reached a 65.07% RES fraction, LCOE of 0.1 USD/kWh, payback period of 3.94 years, internal rate of return of 14.04%, and a net present value of 3.06 × 106 USD. It has the potential to lower energy costs substantially and bring energy security to the country by implementing similar infrastructure in various Zimbabwean cities. The UK heat network system facilitated the distribution of energy made its way into popularity as a pragmatic way of decarbonizing the heating sector primarily at the neighborhood level up to many megawatts. But the assessment of techno-economic performance of heat network solutions at a strategic level in most regions was hindered by a deficiency of suitable modeling tools research's Ahmed and Mancarella [80].A general and comprehensive model for heat network

design and evaluation was outlined in this research. It considered pre-specified input criteria and evaluated the overall, capital, and operational costs of various alternatives. The developed model considered multiple operating network lengths, cost conditions, temperatures, pipe types, load densities, dwelling connection types provides data on the feasibility and performance of heat network solutions. For strategic purposes, generic test networks representing typical topologies of electrical networks in urban, semi-rural, and rural areas of the UK were used. The smart framework was advanced to analyze the impacts of solar uncertainty, explore stochastic reliability, explore biomass planning profiles, and achieve optimal-economic decisions.

A bi-level programming interface was the target of the proposed meta-heuristic algorithm, with the aim of creating a versatile, trustworthy decision-making tool for techno-socio-economic planning. A random forest methodology was first employed to train nine different solar probability classes for assessing the impacts of climatic and seasonal changes in solar radiation. With the aid of 20 standard and 4 global benchmark functions, the ability of the FO-JAYA algorithm was tested in exploitation, exploration, convergence, and local minima. For the optimal techno-economic solutions for a hybrid renewable energy system to electrify villages in Eastern India, further research was conducted on the bi-level typology. The statistical analysis of the proposed FO-JAYA optimization showed a reduced cost of energy (COE) for the best system at Rs. 3.933/kWh, worst at Rs. 4.201/kWh, mean at Rs. 4.222/kWh, and standard deviation at 0.277 after 15 iterations. The COE calculated using the JAYA algorithm was Rs. 4.232949783/kWh, whereas the COE calculated using class-topper optimization (CTO) was Rs. 4.120555094/kWh [81].

2.7.2. Economic viability models

Energy influences primary production and consumption globally and it is a primary driver of social and economic development. Solar home systems are advantageous to small industries; they meet their energy requirements and reduce their energy expenses. The central theme of this research is to understand how the development of Pakistan's small-scale enterprises is influenced by the adoption of solar home systems [82].They explored the relationship between the financial success of small-scale enterprises and the adoption of Small Hydropower Systems and the moderating influence of technology awareness by

surveying 357 specifically chosen individuals. Partially smallest squares structural equation modeling (PLS-SEM) was applied to test the model. The findings demonstrated a positive and significant relationship between the performance of small-scale enterprises and the cost-effectiveness of solar-heated electricity. Small-scale industry performance improved energy supply through solar home systems and were highly moderated by solar home system awareness and understanding. These findings identify the importance of focusing on solar home systems to improve the performance of small-scale firms, which is important in providing regulatory bodies with useful insights.

[83] conducted research on power generation to substitute nonrenewable source to renewable source. Renewable sources of energy have been identified as a competitive alternative to traditional power systems, providing lower-loss, more reliable, and environmentally benign electricity with the additional advantage of reducing network congestion. A grid-connected solar PV system with battery backup was demonstrated in an earlier study in the hilly state of India. In case of grid operation, a systematic evaluation of solar system resources was undertaken, and total load contributed by the battery system and the PV system was determined. A techno-economic evaluation was carried out of the proposed idea, and also feasibility estimates were carried out. It was determined with a net present value of $37,433.87 in the study that the system involving grid operation along with storage will save $3,923,394.00 year. Further, the cost of energy required for stand-alone operation was reduced to $0.21/kWh from $0.30/kWh.

2.7.3. Economic viability implementation

In Fig. 2.3, steps are laid down for the implementation of economic viability. It begins with observing the ground conditions of the project, followed by observing its primary characteristics which impact the economy. The report observed is submitted to the decision makers in order to make a feasible decision on it. Following that sources will be utilized for the commencement of the project. In the final project progress should be reported so that steps should be taken to address the problems.

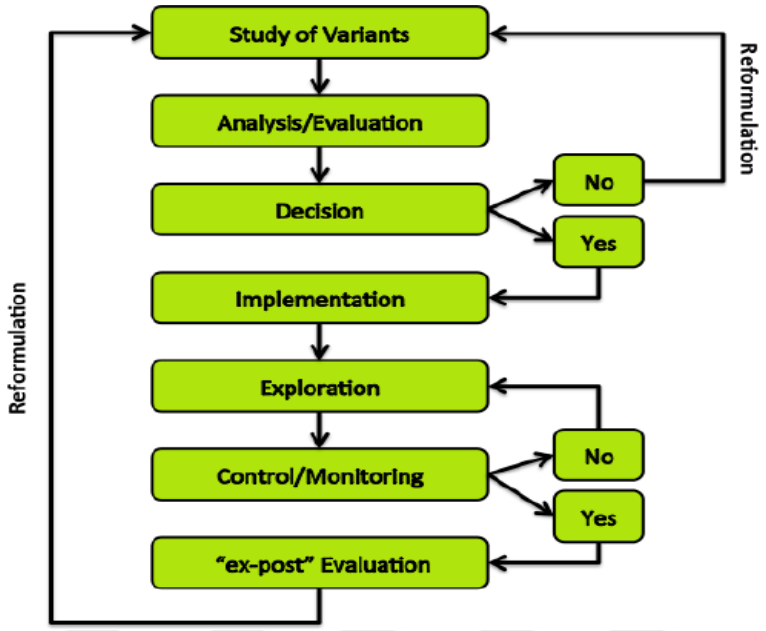


Figure 2. 3: Economy viability implementation

2.7.4. Cost-benefit analysis

Fig. 2.4 shows how the cost benefit ratio is calculated. The cost of each parameters should be calculated for its optimum benefits. The cost-benefit analysis is crucial to any investment.

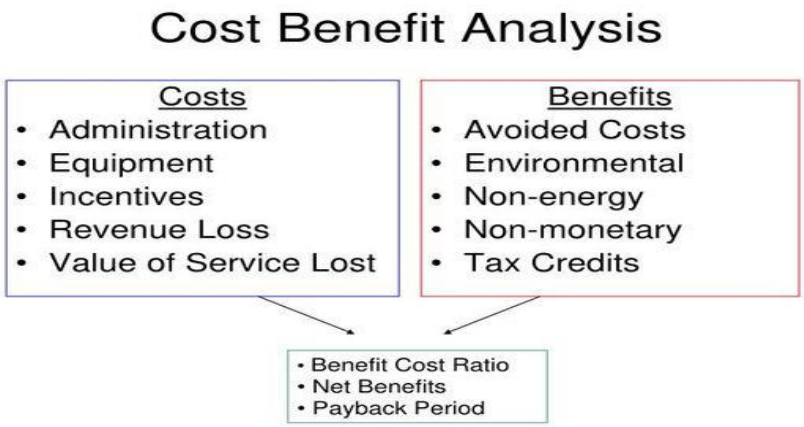


Figure 2. 4: Cost benefit Analysis.

The Cost-Benefit Analysis (CBA) assesses a project's worth to society on the basis of its costs and benefits in terms of money and is commonly utilized in transport project appraisal, while giving a new overview of CBA in Transport Policy and Planning, its origins, foundation upon welfare economics, and debate for contemporary developments and challenges. Considering the high economic costs of meeting Kuwait's increasing electricity demand and the environmental effects of fossil fuels [84]. The prevalence of solar radiation in Kuwait renders solar system implementation significantly more viable. With a current price of $5/W and 15% efficiency, the Cost of Electricity for a 1 MW station is projected to be approximately $0.20/kWh. This becomes economically feasible when oil is about $100 per barrel. The Cost-Benefit Analysis revealed that if the value of conserved energy resources utilized in generating conventional electricity and the expense of curtailing CO2 emissions are factored in, the actual economic cost of electricity in a PV system would be greatly reduced. The initial economic evaluation advised the introduction of PV technology in Kuwait [85]. Electricity supplier decisions about investments in low-carbon power technologies like PV (photovoltaics) and CCS (carbon capture and storage) hinged on projected profitability or surpluses. Judging PV investment profitability, it is needed to account for additional expenditures owing to changes in PV power plant productivity levels and the requirements of backup capacities. Modification in the balance of the power plant fleet, impacting the merit-order curve, also affected the rate of return. The rival investments in CCS and PV with respect to potential merit-order effects and profitability, employed investments in Germany [86].

2.8. Life Cycle Assessment

Businesses and industries started analyzing how their processes impacted the environment as environmental awareness increased. Fears of the exhaustion of natural resources and the degradation of the environment compelled businesses to provide more eco-friendly products and operations. Environmental performance became a priority, prompting some businesses to seek pollution prevention approaches and environmental management systems to go beyond regulatory compliance. Life cycle assessment started to become an instrument. Considering the entire life cycle of a product, from material extraction to disposal. Life cycle assessment quantified a product's life cycle, providing extensive

knowledge about environmental aspects and better trade-offs while making a decision regarding products and processes [87].

2.8.1. Life Cycle Assessment with Environmental Sustainability

Fig. 2.5 describes how every project can become a success along with environmental implications and sustainability methodologies. Right at the start of the project each parameter should value for its lasting repercussions. Any material used for projects could be worked out up to its end application so that its total life cycle will be computed and appropriate last time disposal will be implemented.

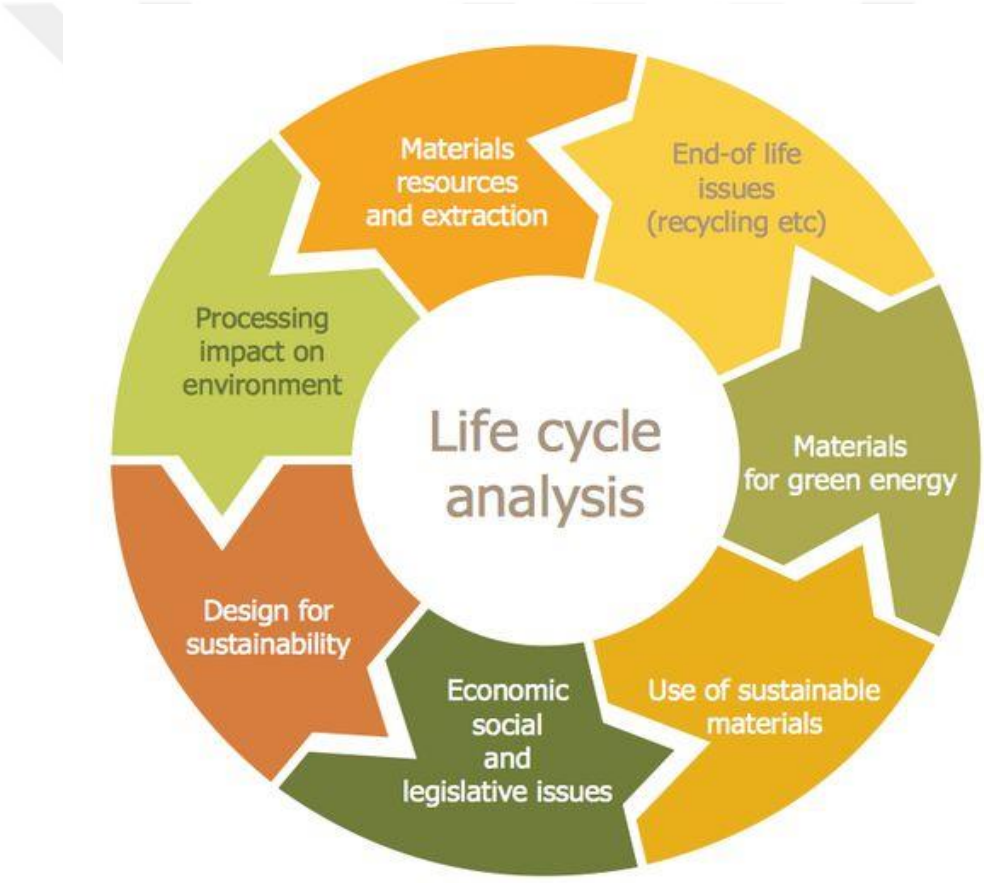


Figure 2. 5: Life cycle assessment with environmental sustainability.

2.9. Challenges And Limitations in Current Approaches

Limitations and challenges in the existing methods for carbon capture are high energy intensity and corresponding costs, and further research and development required to increase capture efficiency and scalability.

2.9.1. Challenges faced by existing solar-assisted post-carbon capture approaches

Although it is not possible to predict the future with complete accuracy, it is extremely probable that in a hundred years, our main sources of energy will no longer be fossil fuels Soeder [88]. The replacements could be sophisticated, renewable technologies such as nuclear energy and engineered geothermal systems as additional sources to supplement wind and solar power. At the opposite end there are those, particularly among the youth, who are despondent about the future, viewing the climate crisis as an unmanageable problem, and thus losing hope. At the same time, there are others who just go on with their lives, not caring about climate matters, believing strongly that science will easily come up with solutions. Both extremes, with their delusional and perilous perspectives, have one thing in common: a failure to take meaningful action. By contrast, a pragmatic approach accepts the fact of the crisis without falling into hopelessness, understanding that there are solutions available, even if not readily available. This pragmatic approach is essential for successful action. Industrialized countries need to shift from fossil fuels to carbon-free or zero-carbon fuels and scale up these technologies for application in less developed nations. Although they contribute very little to greenhouse gas emissions, the less developed world must endure extreme impacts of climate change. The industrialized world, which has contributed most to the climate crisis, has a responsibility to set things right and help less developed countries avoid similar mistakes.

Aside from its use to describe the capacity to rapidly adapt to troublesome challenges, the word "resilience," first coined in recent times, also referred to a durable potential for ecological restoration throughout an organism's entire life span. Because the energy system is a crucial aspect of interactions between human society and the natural environment, the concept of "resilience" might be utilized to quantify the extent to which existing energy technologies optimize trade-offs in various energy systems. However, no technique existed with which to estimate the resilience attribute of any energy system quantitatively and

extensively. [89] introduced the energy system resilience analysis, a conceptual framework of preliminary resilience analysis for energy systems. A case study was performed for the recently developed solar-assisted post-carbon capture and storage process with primary energy consumptions (PED), life cycle cost (LCC), and life cycle greenhouse gas (GHG) potential reductions as parameters. For integrated analysis, methods such as gray relational analysis (GRA), life cycle assessment (LCA), and LCC analysis were employed.

The application of solar power for high-pressure feed-water pre-heating was revealed to have better performance in both multi-criteria gray relational degree (0.72) and life cycle greenhouse gas reduction (73.1%).

2.9.2. Technical challenges

In the long term, solar radiation has become an important source of clean, renewable power that can potentially provide sufficient power to serve the world's growing population. The past energy crisis is exacerbated by increasing concerns over the quality of the water, especially in developing countries. The application of solar energy using solar photovoltaic systems for electricity generation and water and wastewater treatment has significant potential on a worldwide level. Developments in this area have opened up opportunities to improve the standard of living of people in general. The primary objectives of the review paper are to provide the reader with a background of solar photovoltaic systems' short history, the numerous types of solar photovoltaic materials present, and the solar cell efficiencies achievable with the available sun. This study conducted by [90].

In India, where about 70% of the population lived in rural villages, it is necessary to electrify these villages to ensure inclusive economic growth. The problem, however, was the transmission and distribution of electricity to sparsely populated regions far from power generation stations, hindering the country from reaching 100% electrification. To overcome this, there is a necessity to investigate decentralized sources of energy for these hamlets. Given how abundant solar energy in India is the micro-grid system using solar photovoltaic panels seemed like a positive sign. Using the photovoltaic effect, this device converted light energy into direct current power. Additional power generated during the daytime is used to charge batteries to be utilized during the night. The alternate current, which is fed to the load through a power distribution network formed from direct current power by inverters and

power conditioning equipment. This process took up more land and cost more to start than other renewable energy systems. Due to its low operating and maintenance costs, the solar photovoltaic microgrid system is chosen. Although it took up more land and cost more to initiate. The system was also scalable, allowing modules to be added when power demands increased. The paper examines the solar photovoltaic micro-grid technologies that were traditionally employed to electrify rural regions in India and the challenges that successfully encountered along the way. This survey is studied by [91].

2.9.3. Economic constraints

Small and medium-sized businesses (SMEs) play a crucial role in most projects and contribute significantly to the economies of emerging countries, including Iraq. With issues confronting the public and private sectors, SME growth is critical to addressing the increasing rate of unemployment. Iraqi SMEs face numerous issues that vary by sector and location. These issues are exacerbated by internal factors such as inexperienced project owners and the lack of feasibility valuations. The project is subject to external variables, and although the project has the potential to work, shortages of funds are often seen as an obstacle. The current study focuses on the role of accounting information provided by small and medium-sized business owners in reducing financial shortages. Addressing these problems, particularly in the hospitality and travel industries, can contribute to those preventing small hotels and tourism businesses in Iraq from shutting down [92]. With the in-built complexity of Iraqi construction projects, effective management of these calls for pinpoint understanding. This research needed to find and describe deterrents in building investment projects in Iraq through the examination of their importance and influence on operation.

Interviews with consultants, engineers, and project managers identified 47 problems such as administrative, legal, financial, economic, technical, infrastructure, documentary credit, and other constraints. A questionnaire examined the impact of these issues, identifying 18 primary reasons for delays in projects. Among the major challenges were sluggish government administrative processes, delays in budget approvals, poor coordination between ministries and the provincial governments, land buying pauses,

hesitance among foreign companies to invest, and a low level of knowledge among employees regarding relevant laws and guidelines [93].

2.9.4. Environmental concerns

Price [94] carry out an environmental risk study in Iraq. With so many challenges in Iraq, it is imperative to carry out a study on environmental hazards. These challenges are brought about by population growth, the impact of three wars, climate change, inadequate land use planning, and encroachment of sensitive ecosystems (World Bank, 2017). The implications manifest themselves in many ways, ranging from deteriorated water quality, soil salination, air contamination, and war-related contamination, degradation of key ecosystems, effects of climate change, and the very real specter of water scarcity.

The authors [95] did a case study to analyze the concerns and perceptions of environmental issues by the public in Kurdistan Region-Iraq. 450 participants were selected randomly from a variety of populations and were asked questions about gender, age, and education affecting attitudes towards the environment, with females, age groups between 20-30 years, and those who have a Ph.D. showing increased environmental awareness. Geographically, Sulaimani contributed most with 28.48%, followed by Erbil (21.95%), Duhok (17.61%), Halabja (16.69%), and Kirkuk (15.00%). The different participation rates indicated the environmental consciousness, facilities, culture, and stability of each location. Surprisingly, the study revealed that COVID-19 was beneficial to the environment.

2.9.5. Project feasibility evaluation

In Table 2.4, the various project studies are carried out based on environmental economy, geological factors and their final cost benefit analysis. The table illustrates how sustainable methods were implemented in various parts of the globe. Most of the world regions are continuously marching towards renewables sources due to the majority of factor life cycle of the project. Today every project to be considered for a long period of time to be utilized without or less damaging the environment.

Table 2. 4: Project feasibility evaluation

Sr. #	Methods/Techniques	Useful applications	Ref.
1	Preference Evaluation OR Econometrics, Quantitative Analysis	Energy demand progress in China	[96]
2	cost-Benefit Analysis, Environmental Impact Assessment	Cost-benefit-analysis on various domestic energy use options	[97]
3	Cost-Benefit Analysis, Sensitivity Analysis	Quantification of the economic problem associated with the reduction of direct CO2 emissions	Vellini, Bellocchi [98]
4	Multiple Criteria Decision Analysis	Estimation of the ranges of different stakeholders on various energy transition scenarios	[99]
5	Life Cycle Cost	Cost efficiency assessment and sustainable technology solutions in the residential sector	[100]
6	Environmental Impact Assessment	Analysis of the benefits of photovoltaic systems in a German region	[101]
7	Multiple Criteria Decision Analysis	Assessment of urban sustainability performance through indicators of 57 cities around the world	[102]
8	Project feasibility	Calculation of the social profitability of the photovoltaic system in Germany	[103]
9	Assessment of solar radiation	methodology for assessing solar radiation and energy production on building roofs and vertical fronts in the city	[104]
10	Multi-policy analysis of sustainable choices in Jordan	analysis of sustainable choices in Jordan	[105]
11	Quantitative Analysis simulation technique	Assessment of China's energy sector transition strategy built on a dynamic simulation model	[106]
12	Cost-Benefit Analysis	Analysis of renewable energy costs in the United Arab Emirates	[106]
13	Cost-Benefit Analysis of environmental project	Strengths and disadvantages of an approach to the environmental economy	Bachmann [107]

2.10. Research Gaps and Opportunities

Despite advances in carbon capture technologies and the integration of renewables in power generation, there exists a perceptible gap in the current literature. Individual research works have examined some features of post-combustion capture or solar integration, but a thorough techno-economic comparison of different solar-assisted post-carbon capture methods for natural gas combustion cycle units is glaringly absent. The lack of such a comparative evaluation holds back the formulation of well-grounded strategies for the large-scale deployment of such technologies. To bridge this knowledge gap, this research study intends to have a wide-ranging and systematic review of various solar-assisted post-carbon capture strategies. Through evaluating both technical viability and financial feasibility, the research endeavors to provide an in-depth insight into the possible advantages and drawbacks of such integrated technologies.

2.10.1. The gaps in existing literature linked with research aims of current study

To date literature has not seen an inclusive techno-economic evaluation of solar-augmented post-carbon capture methods exclusively developed for natural gas combustion cycle unit's There is limited research focusing on how to integrate renewable energy, notably solar electricity, into carbon capture technology. No site-specific investigations, especially in Iraq, hinder us from having insights into how such methods have performed in other situations. There are knowledge gaps in the long-term performance, policy implications, and socio-economic impacts of solar-assisted post-carbon capture technology. Conducting a thorough review of technological and economic capability through our research will bridge gaps. This will provide useful material to support effective integrated system implementation and inform decision-making.

2.10.2. Potential opportunities for future research in this area

There are many opportunities that will arise for future research in this area. To maximize the productivity and efficiency of solar-assisted post-carbon capture systems, researchers need to explore improved optimization methods. The primary interest in researching is how such technologies will integrate into national energy grids, which maximize the distribution and utilization of energy. The more in-depth examination of the socioeconomic impacts,

such as employment and community building, will help to provide a better understanding of the wider advantages of solar-assisted post-carbon capture systems. Additionally, it is important to conduct research with the aim of enhancing the existing legal and policy frameworks to enhance broader use of these technologies. Lastly, a comprehensive life cycle assessment may provide an overall picture of the whole environmental influence, guiding the application of solar-assisted post-carbon capture in an eco-friendly manner.

2.10.3. Key terms and concepts relevant to this study

Understanding the terminologies and concepts employed in post-carbon capture studies of solar-assisted natural gas combustion cycle units is very important for grasping the study focus. Solar technology, i.e., photovoltaic and solar thermal technology, can enhance the sustainability and efficiency of the combustion cycle. Post-carbon capture is used to describe strategically collecting CO2 emissions following the combustion of natural gas. Solvents or membranes separate and capture CO2. Natural gas combustion cycle units describe the whole process of generating electricity from natural gas. Estimating the technological feasibility and economic viability and analyzing the total efficiency and cost-effectiveness of the integration of solar-assisted post-carbon capture systems are pivotal techno-economic issues for this research.

2.11. Summary Of the Literature Review

The literature review reflects the existing knowledge gaps and issues in knowledge about solar-assisted post-carbon capture methods for natural gas combustion cycle units. Of particular note is the absence of an elaborate techno-economic comparison. Meager research on the integration of renewable energy, and an absence of site-specific assessments, leading to massive information gaps. Areas of research gaps are the absence of long-term performance analysis, policy issues, and socioeconomic effects associated with these technologies. This review emphasizes the essential requirement for further research to fully bridge these gaps. Subsequent research needs to be organized in state-of-the-art optimization techniques, explore grid integration options, perform in-depth socioeconomic evaluations, and enhance knowledge of policy frameworks and regulatory aspects. Bridging these gaps will assist in verifying a more informed and sustainable deployment of solar-assisted post-carbon capture technologies in the energy industry.

2.11.1. Summarized key findings from the reviewed literature

Key information regarding solar-assisted post-carbon capture techniques for natural gas combustion cycle units is provided by the literature review. The key fact that emphasizes the necessity of a systematic calculation of these units' feasibility and economic viability is the apparent lack of a modified and detailed techno-economic comparison. The absence of site-specific evaluations and the minimal focus on the integration of renewable energy. Most especially solar power, the knowledge gaps get highlighted even more, particularly in regions like Iraq where such methods would be feasible. Secondly, the research also fails to investigate the socio-economic impacts, policy implications, or long-term efficiency of solar-assisted post-carbon capture technology. These findings point to the importance of filling these knowledge gaps in the future so that essential information for sound decision-making and efficient use of integrated systems in the energy sector can be given.

2.11.2. Relevance of literature to current research topics.

The literature review is relevant to some extent to our specific field of research. That is the techno-economic considerations of solar-assisted post-carbon capture methods in the case of Iraqi natural gas combustion cycle plants. The aims of our study are directly influenced by the deficiencies that have been identified. Ranging from inadequate comparative details to scanty analysis of renewable energy integration and location-specific estimates. With a clearer understanding of these gaps, it can design a study that is precisely tailored to the special needs of Iraq. This study will provide useful insights into the technical and economic viability and possible socio-economic benefits of incorporating solar-assisted post-carbon capture technologies into natural gas combustion cycle units. By correlating our work with these disparities in the literature, it will be a valuable addition to the reservoir of facts that will enable Iraq to hold sustainable energy solutions and make well-informed choices.

Chapter 3

Research Methodology

3.1. Overview Of Methodology

The current research aims to substantially promote the integration of Solar Thermal Energy into the Besmaya NGCC power plant in Baghdad, Iraq. This paper combines these factors in a unique way through thorough process simulation and modelling via Aspen Plus software. The central goal of current research is not only to simulate the power plant in its current state but also to perform a rigorous preliminary analysis. Previous research is extended in this work by modeling and incorporating a solar-assisted PCC plant into the existing power system, offering a new method of increasing energy efficiency and sustainability. Notably, the whole process is analyzed in depth, offering a thorough technical analysis. Furthermore, this research adds new knowledge by estimating the solar thermal power potential specifically for the Baghdad coordinates, taking advantage of the capabilities of SAM. With these developments, it is intended to bridge some gaps in current literature and provide useful inputs for future studies and real-world applications in the context of integrating renewable energy into traditional power plants.

3.2. Development Of the Combined Cycle Power Plant (CCPP) Model

The Besmaya Natural Gas Combined Cycle (NGCC) power plant is Iraq's largest power generation facility with an installed capacity of a whopping 3 GW. Located just 25 km east of Baghdad, beyond the Kurdistan region, this critical energy infrastructure plays an important role in fulfilling the country's power needs. To understand its operational dynamics, a detailed simulation of the Besmaya NGCC was carried out with the well-known Aspen Plus modelling tool. The research methodology is depicted in Fig. 3.1. For purposes of this study, key design information was borrowed from a comprehensive report issued by General Electric (GE) on Steam Turbine Operations Mass Global Investment, with a focus on the Besmaya Combined Cycle Power Plant (CCPP) in Baghdad, Iraq [108]. The Aspen Plus simulation software was utilized to create the model for the NGCC plant following the plant configuration and performance parameters specified in the GE report.

Slicing the NGCC plant into four major sections, each of these sections has a unique function in the overall operational effectiveness. The Plant Combined Cycle (PCC) configuration, as detailed by the GE report, formed the template for the development of the Aspen Plus simulation model. The following sections discuss an in-depth discussion of each of these constituent elements, highlighting their functionalities in the overall NGCC plant scheme. This method enables the minutest analysis of the inner mechanisms of the plant and helps to achieve a comprehensive understanding of the intricate system dynamics.

The Peng-Robinson equation of state (Eq.3.1) was employed, which is the accepted thermodynamic property package for hydrocarbon systems and power plants [109]. Multiple unit operations contained in the software were employed to construct the model. All operations that were used are explained in Table 3.1.

$$P = \frac{RT}{V-b} - \frac{a}{V^2-2bV-b^2} \tag{3.1}$$

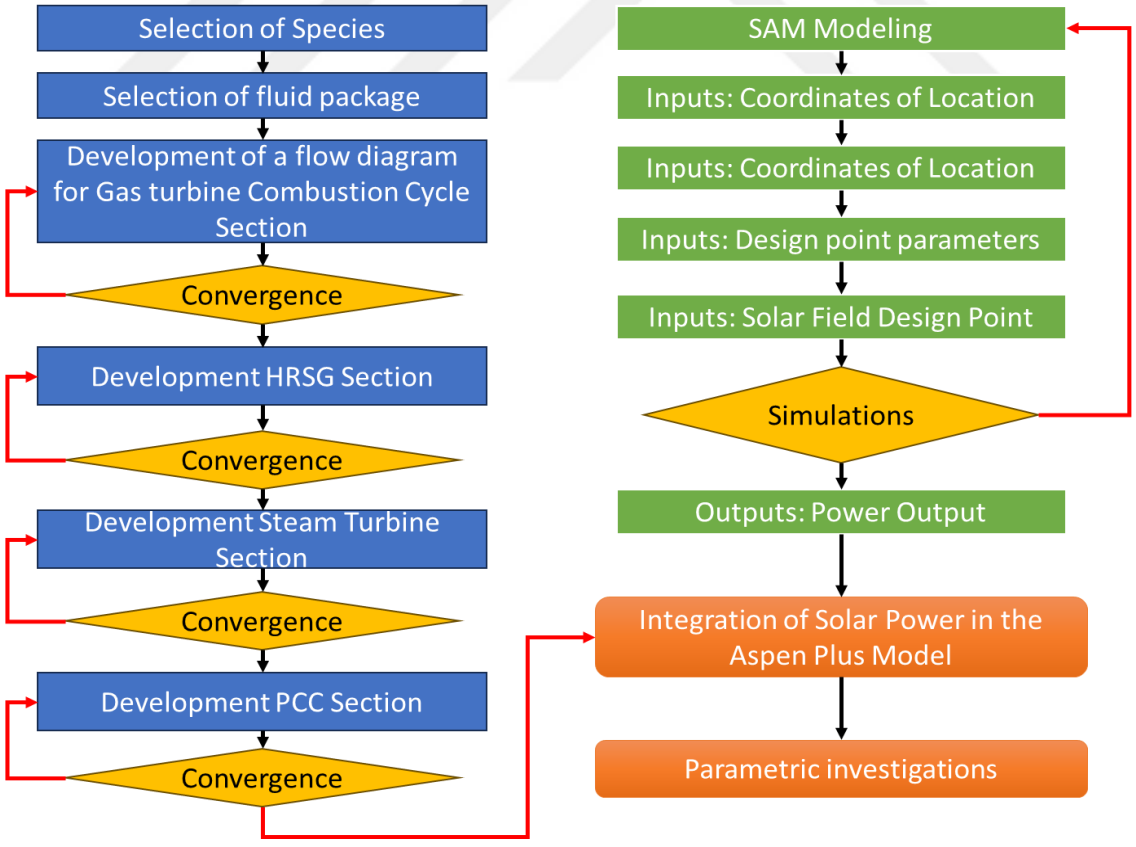


Figure 3. 1: Power generation through natural gas combustion (gas turbine section) [117].

Table 3. 1: The installed operations in the developed model with their short description.

Sr. #	Name of Operation	Type of operation	Short description
Gas Turbine Section			
1	AIRCOMP1, AIRCOMP2	Compressors	Isentropic compressor Outlet specification: discharge pressure: 31 bar. Efficiencies: Isentropic 0.784, Mechanical 0.985
2	COMB-1, COMB-2	RGibbs Reactors	Calculation option: Calculate phase equilibrium and chemical equilibrium. Operating conditions: Heat duty 0 kW. Included vapor phase.
3	GAS-T-1, GAS-T-2	Turbines	Isentropic turbines Outlet specification: Discharge pressure is set at 1.048 bar. Efficiencies: Isentropic 0.89, Mechanical 0.98
Heat Recovery Steam Generator (HRSG) Section			
4	HP-SUPER	Heat exchanger	Shortcut countercurrent heat exchanger with design mode of calculation. Cold stream outlet temperature: 530° C
5	HP-EVAPO	Heat exchanger	Shortcut countercurrent heat exchanger with design mode of calculation. Cold stream outlet vapor fraction: 0.5
6	HP-ECONO	Heat exchanger	Shortcut countercurrent heat exchanger with design mode of calculation. Cold stream outlet vapor fraction: 0
7	LP-ECONO	Heat exchanger	Shortcut countercurrent heat exchanger with design mode of calculation. Cold stream outlet temperature: 217.6° C.
8	LP-EVAPO	Heat exchanger	Shortcut countercurrent heat exchanger with design mode of calculation. Cold stream outlet vapor fraction: 0.2
9	LP-SUPER	Heat exchanger	Shortcut countercurrent heat exchanger with design mode of calculation. Cold stream outlet temperature: 140° C.
10	PREHEATE	Heat exchanger	Shortcut countercurrent heat exchanger with design mode of calculation. Cold stream outlet vapor fraction: 0
11	P101	Pump	Discharge pressure was set at 73.5 bar
12	P103	Pump	Discharge pressure was set at 6 bar
13	COOLER	Heater/Cooler	Flash type: Temperature and Pressure with 80° C and 2 bar.
14	HPTURBIN	Turbine	Isentropic turbine Outlet specification: Discharge pressure: 6 bar Efficiencies: Isentropic 0.95, Mechanical 0.98
15	LPTURBIN		Isentropic turbine Outlet specification: Discharge pressure: 1 bar. Efficiencies: Isentropic 0.95, Mechanical 0.98
CO_2 capture system			
16	ABSORBER	Rad/Frac	Calculation type: Equilibrium Number of stages: 10 Condenser and Reboiler: None Convergence: Standard Top stage pressure: 1.08 bar Stage pressure drop: 0 bar
17	STRIPPER	Rad/Frac	Calculation type: Equilibrium Number of stages: 20 Feed plate location: 10 Condenser: Partial vapor; Reboiler: None Valid phase: Vapor-liquid Convergence: Standard Operating specification Distillation rate: 350 kg/s Top stage pressure: 1.05bar Stage pressure drop: 0 bar
18	P-AMINE	Pump	Discharge pressure was set at 3 bar
19	REBOILER	Heat Exchanger	Shortcut countercurrent heat exchanger with design mode of calculation. Cold stream outlet temperature:170° C.
20	CSP	Heater	Flash type: Pressure and Duty with 1 bar and 35000 kW.

As per usual practices, modelling requires assumptions. For the current studies, the following assumptions were made to develop a comprehensive and representative model.

- It was assumed that the physical properties of materials and fluids within Aspen Plus are accurately represented. Moreover, Aspen Plus library components and models that were utilized for simulating NGCC plant components are estimating the real parameters.
- Custom models or Aspen Plus extensions were implemented for simulating solar thermal energy integration.
- The steady-state operating conditions were maintained for NGCC and solar components.
- The climate data specific to the Baghdad region was used for solar resource assessment using SAM.
- The model validation is conducted through comparison with available plant data or experimental results.
- It was assumed that sensitivity analysis is performed to assess uncertainties and identify key parameters affecting system performance.

3.2.1. Gas turbines section

NGCC plant design is of the natural gas combustion system (Fig. 3.2). It includes two gas turbines with a capacity of 260 MW, each turbine with 98 % mechanical efficiency. Excess air is compressed to 20 bar pressure, 20 % excess air, before input into the combustion chamber. For the combustion chamber, R-Gibbs reactor model was applied in Aspen Plus simulation software that follows the principle of Gibbs free energy minimization. It consists of solving equations describing system behavior to minimize the system free energy subject to certain constraints like temperature, pressure, and composition. The conditions available in the plant are summarized in Table 3.2 that were taken from the plant manual [108].

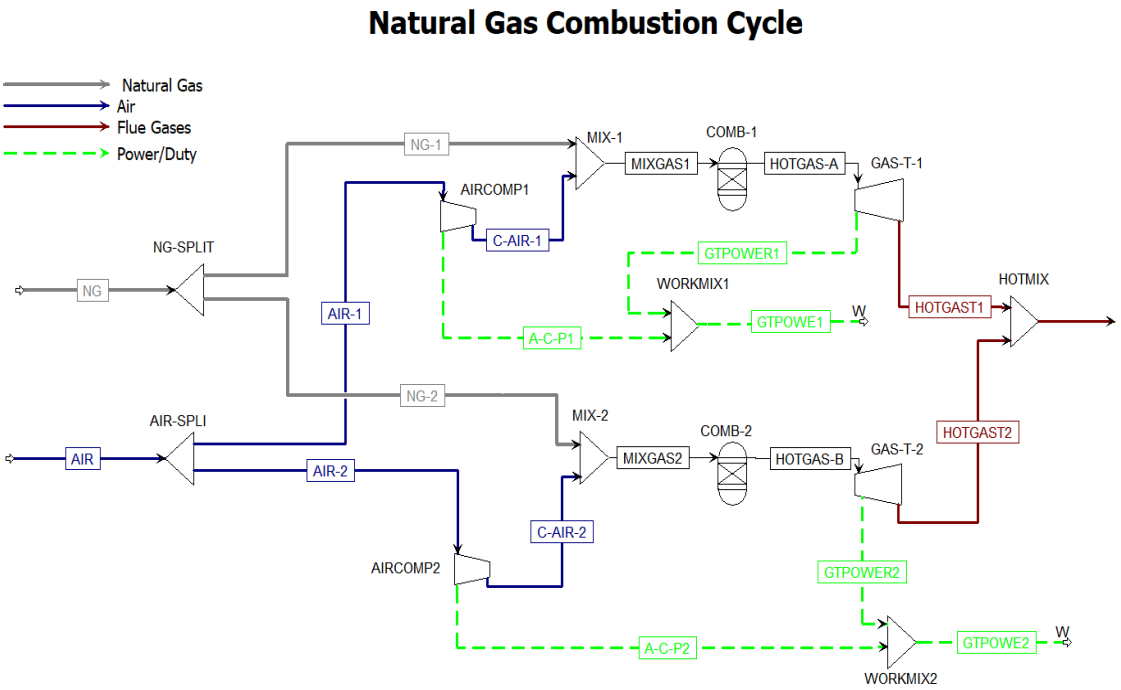


Figure 3. 2: Power generation through natural gas combustion (gas turbine section) [129].

Table 3. 2: Plant operating and design conditions for base case development.

Parameter		Unit	Value
Natural Gas Flow		kg/s	30
Airflow		kg/s	860
Temperature of High-pressure steam		°C	535
Pressure of High-pressure steam		bar	72
Temperature of Low-pressure steam		°C	210
Pressure of Low-pressure steam		bar	6
Temperature of exhaust flue gases at the inlet of (Heat recovery steam generator) HRSG		°C	>600
Temperature of leaving flue gases from HRSG		°C	100~110
Natural Gas composition (mol %)			
	Methane		92.7
	Ethane		3.15
	Propane		0.45
	Isobutane		0.029
	C6+		0.006
	N_2		3.0
	CO_2		0.65

3.2.2. Waste Heat recovery and steam generation section

Following the combustion of natural gas in the gas turbine system, the hot gases in the temperature range of 600~650 °C are passed to the heat recovery steam generator (HRSG) system. Two distinct HRSGs exist in the plant. Nevertheless, for simplicity, the two distinct streams of hot flue gases are combined into a single stream and supplied to the HRSG system. The HRSG heats a single steam turbine generator (STG) cycle as illustrated in Fig. 3.3. The HRSG consists of high-pressure (HP) and low-pressure (LP) sections with individual economizer, evaporator, and superheater heat exchangers for each pressure section. Water is supplied into the HRSG system through two water streams. One water stream is led from the LP-superheater and HP-economizer cooled down to become saturated steam and pumped into the HP-tank. The flow of HP steam from the HP-evaporator is kept in circulation from an 85 % efficient pump. HP steam from the HP tank is ultimately sent from the HP-super heater to achieve the temperature of 530° C and at pressure 73 bar is ready to produce energy from the HP-steam turbine (Fig. 3.4). LP steam is produced from LP-economizer at the pressure of 6 bar and the temperature of 156° C and combined with the LP steam from HP-steam turbine and supplied to the LP-steam turbine. The two turbines together generate 230 MW of power. In such a manner, the overall power generation of the entire plant falls in the range of 750 MW.

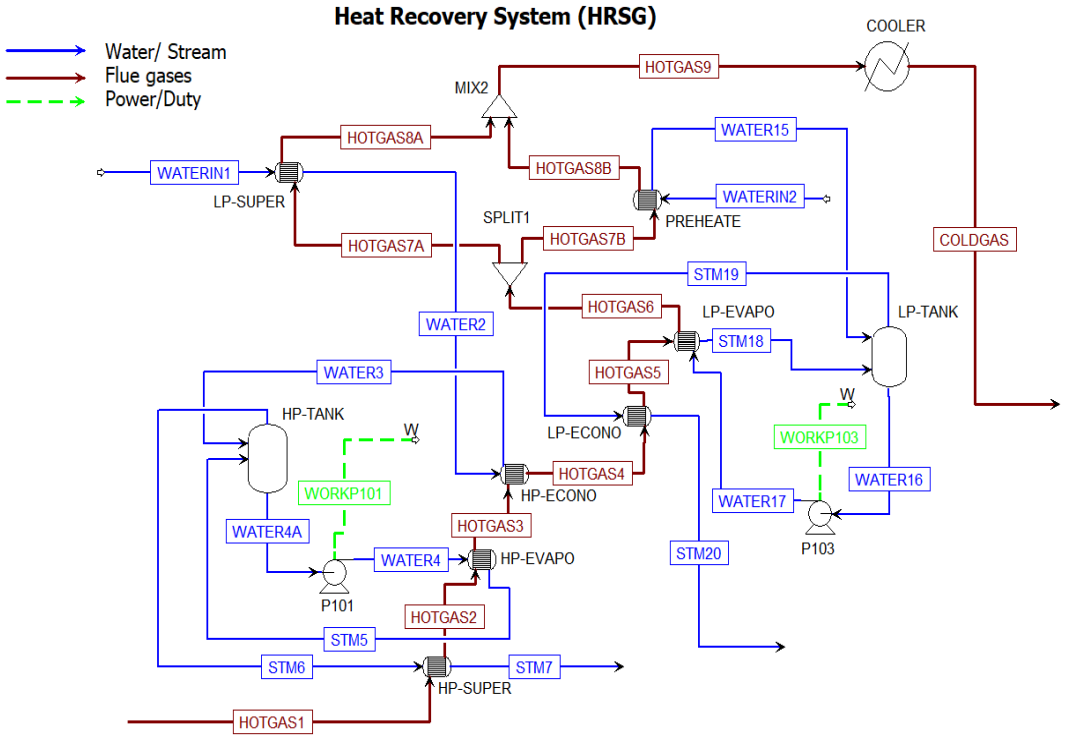


Figure 3. 3: Heat recovery steam generator system [129].

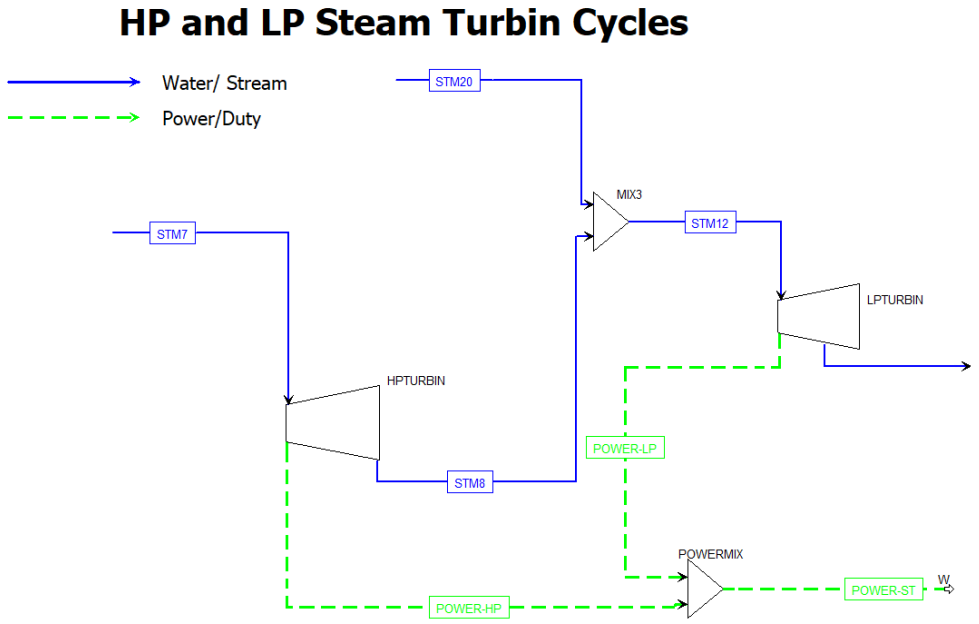


Figure 3. 4: Power generation from HP and LP steam [129].

3.2.3. CO_2 capture plant

During the following phase, incorporating a post-carbon capture (PCC) process based on monoethanolamine (MEA) absorbent was evaluated to attain CO2 capture from the flue gases emerging from the HRSG section. MEA is viewed as an economical and effective absorbent to capture CO2 from exhaust gases [110]. The PCC process using MEA consists of a low-temperature absorber column (see Fig. 3.5), in which carbon dioxide is absorbed effectively and efficiently from flue gas by CO2-lean MEA. After partial heating in a heat exchanger (crossflow) by high-temperature CO2-lean MEA leaving the stripper, the CO2-rich MEA moves to a stripper column, in which thermal stripping of carbon dioxide from the amine occurs. The heat for the stripper is supplied by the reboiler via LP-steam, and the separate CO2 from the MEA is vented at the top part of the stripper. The production of the LP steam (Hot In stream) is achieved with the help of concentrated solar power (CSP).

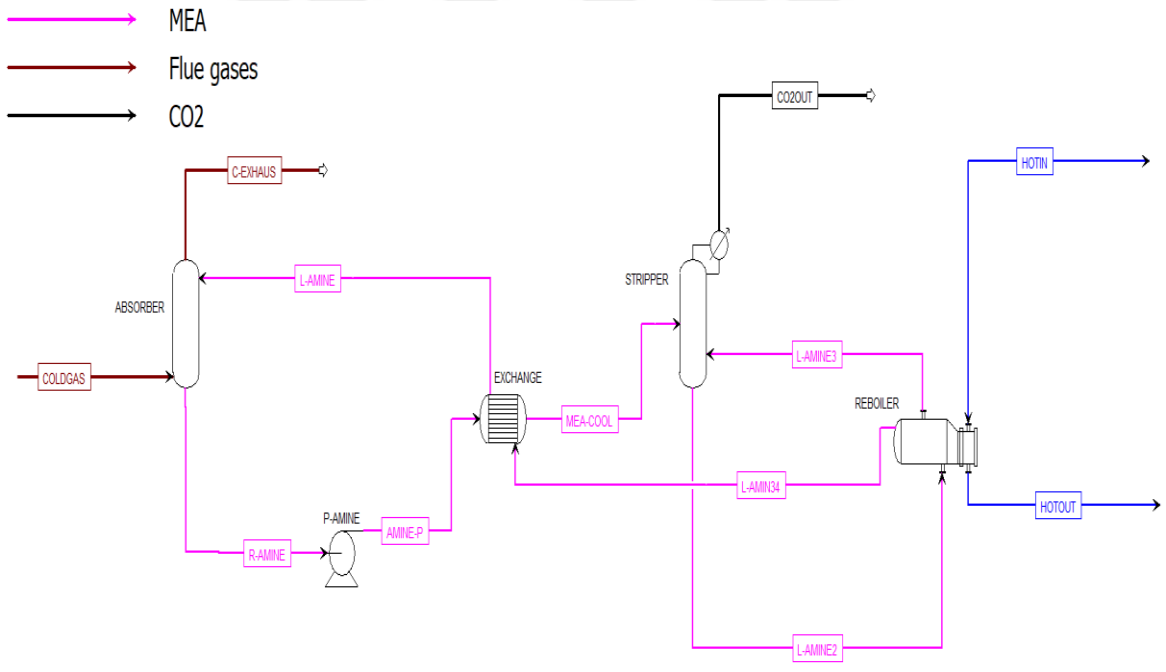


Figure 3. 5: MEA-based post-carbon capture from flue gases [129].

3.2.4. Integration of solar heat for PCC

PCC needs heat in the reboiler (Fig.3.5) to stripping the CO2 from the rich amine for its recirculation. This energy demand for the heating process can decrease the overall economy of the PCC process. Use of solar energy for heating the reboiler using heat transfer fluid (HTF) is an option already explored by researchers [25, 111, 112]. To this end, an HTF circulation loop for reboiler heat adjustment was incorporated in the constructed model of NGCC+PCC model. The initiation of the evaluation of Solar-Assisted Combined Cycle (SACC) began with careful simulation to measure the effects of the addition of a solar thermal source to the existing NGCC+PCC model.

The first major application of solar thermal energy was identified as being directed toward heating the PCC stripper reboiler. This application is highly compatible with solar thermal energy integration, mainly because of the relatively moderate steam temperatures for the stripper range around 170 °C. The enhancement of solar energy provides a direct route to increasing the net power output of the plant.

This improvement is realized through reducing the dependency on Low-Pressure (LP) steam extraction for the reboiler. The solar assisted reboiler heating arrangement is explained in Fig. 3.6, providing a visual explanation of the innovative arrangement. In this system, a High-Temperature Fluid (HTF), in this case water, having a temperature of 150 °C from the solar field is also heated to 300° C by "ADDHEAT" heater (Fig. 3.6) and thus also effectively increases the temperature of LP steam fed to the stripper reboiler to 170 °C, carefully placed at 0.9 °C above the saturation temperature. After transferring thermal energy to the LP steam, the HTF experiences a controlled process of heat rejection, then comes back to the solar field at a temperature of 130 °C.

The conditioned 170 °C steam is supplied to the reboiler, releasing heat throughout the critical stages of condensation and cooling, finally reaching 130 °C. Such a complex dance of solar thermal energy integration not just maximizes the NGCC+PCC model's efficiency but also highlights the ability to tap renewable resources to complement traditional power generation processes. The schematic diagram in Fig. 3.6 is a useful visual tool in understanding the complex details of this solar assisted reboiler heating system within the overall operation of the power plant.

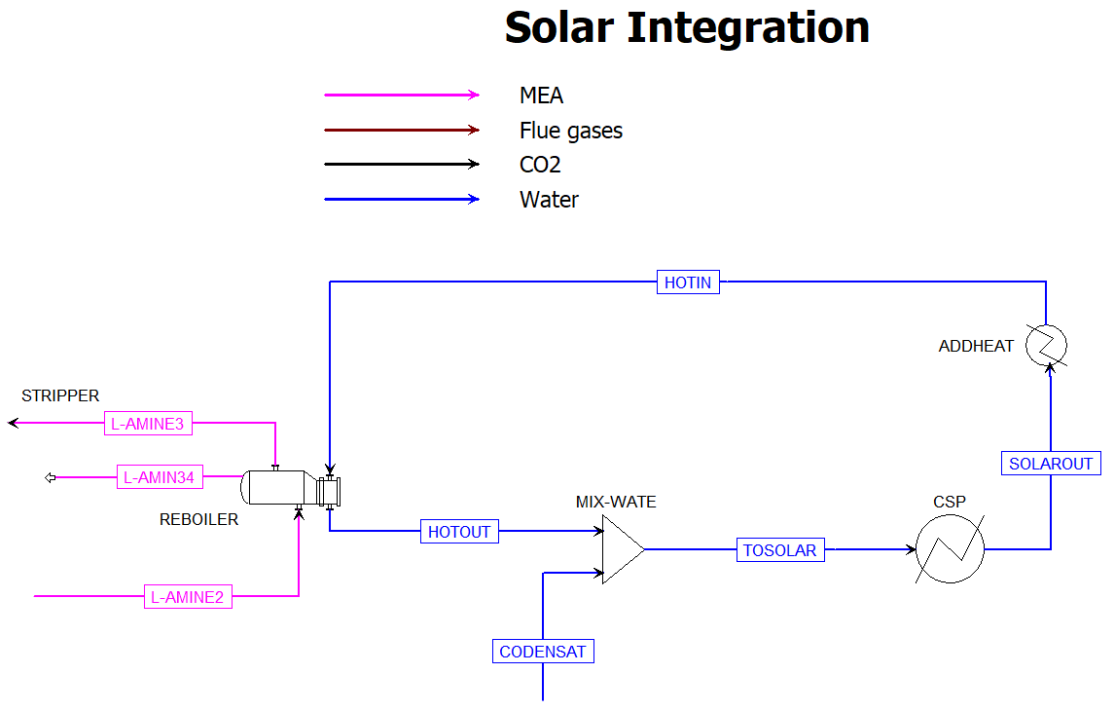


Figure 3. 6: Solar heat integration with PCC [129].

3.3. Modeling Of Catalytic Conversion of Co_2 into Methanol

Another method of carbon capture from the flue gases of power plant was tested. One such study has been converting CO2 catalytically into methanol. Catalytic conversion of CO2 with the assistance of H2 is researched by various researchers [113, 114]. The CO2 conversion to methanol described in this work is an adaptation of the work done by Van-Dal et al., [115] and Pérez-Fortes et al [116]; and subsequently also applied by Meunier et al., [114]. The main difference is that in earlier works, the CO2 was initially captured through amine absorption or other methods and then it was used for conversion to methanol. But in our suggested carbon capture plan, it was intended to convert CO2 available in flue gases (>8%) directly into methanol with the assistance of H2 gas. The modeling plan is explained in two sections. In the first section the mechanism of catalytic reactors and separation of methanol from product gases is described. In the latter section, the generation of H2 gas is explained by solar water splitter.

3.3.1. Conversion of CO_2 into methanol and product separation

The flue gas composition received from power plant is presented in Table 3.3. Proposed conversion process has been illustrated by Fig. 3.7. The gas is compressed by increasing the pressure up to 78 bars. The temperature of the gas by compression increased higher than 800°C which in the cooler it is cooled down and kept under the range 150 ~ 155 °C. Then the flue gas is supplied in the plug flow reactor with the H2 gas. H2 gas is produced with the assistance of solar water splitter, the procedure for that explained in the following section. For the same purpose the solar energy calculated in our previous study [117] is used as an energy to split the molecule of water into H2 and O2. The condensate discharged from the steam turbine system is used as a feedstock in the solar water splitter. In the reactor three kinetic reactions are solved to catalytic convert CO2 to methanol using H2. The reactions are specified in Eq. (3.2) to (3.4).

$$\text{R1:} \quad CO + 2H_2 \rightarrow CH_3OH \tag{3.2}$$

$$\text{R2:} \quad CO_2 + H_2 \rightarrow CO + H_2O \tag{3.3}$$

$$\text{R3:} \quad CO_2 + 3H_2 \rightarrow CH_3OH + H_2O \tag{3.4}$$

The kinetics of the reactions mentioned above were characterized by Langmuir-Hinshelwood-Hougen-Watson (LHHW) expression and the kinetic parameters were borrowed from earlier work [118]. The LHHW kinetic expression is a widely applied model in chemical kinetics, especially in heterogeneous catalysis. It is used to describe the rate of a reaction that takes place on a catalyst surface, normally involving adsorption of reactant molecules onto the surface and subsequent surface reaction steps. The overall structure of LHHW kinetic expression as given by Aspen Plus software is explained via Eq. (3.5).

$$r = k.\frac{k_{ads} \cdot p_{CO2} \cdot p_{H2}}{1 + k_{ads} \cdot p_{CO2} + k_{ads} \cdot p_{H2}} \tag{3.5}$$

Where:

- r represents the reaction rate
- k is the rate constant
- K_{ads} is the adsorption equilibrium constant

- p_{CO2} is the partial pressure of carbon dioxide
- p_{H2} is the partial pressure of hydrogen

Table 3. 3: The composition of flue gas used as feedstock for conversion process

Specie	Mass fraction
Nitrogen	0.742
Oxygen	0.102
CO_2	0.088
Water	0.068

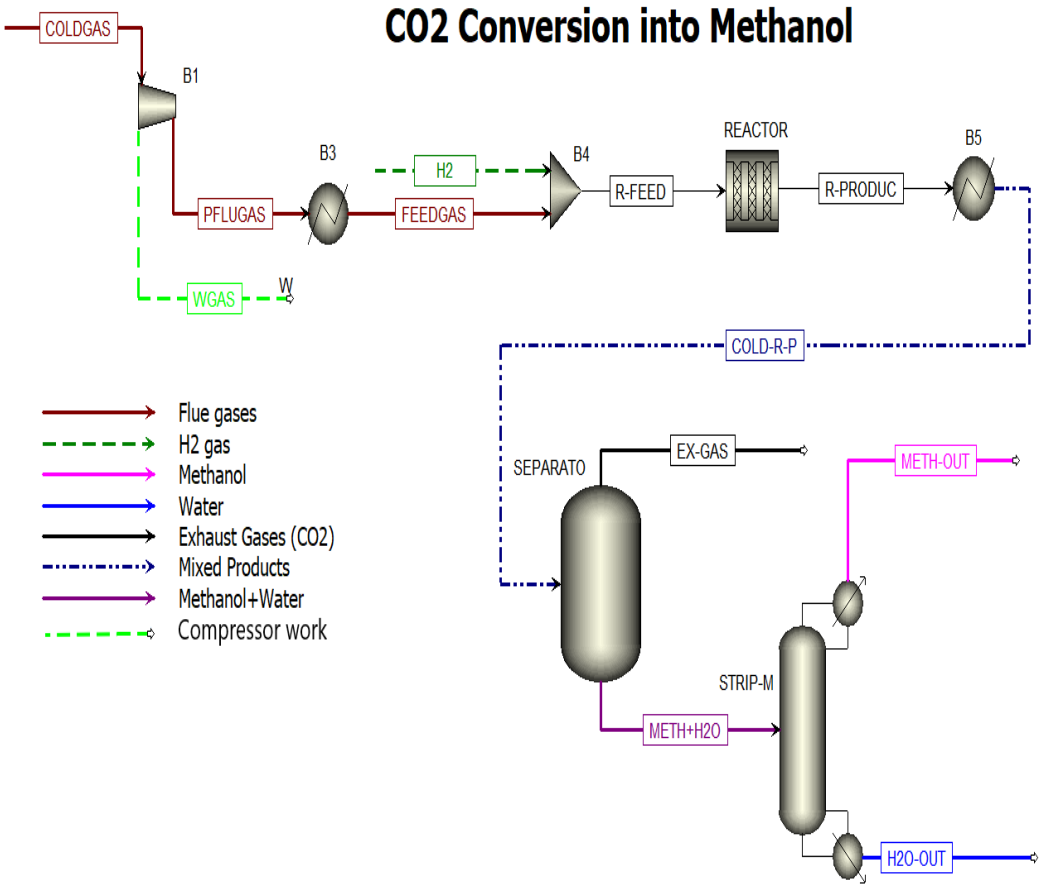


Figure 3. 7: The process flow diagram for conversion of CO_2 into methanol [130].

3.3.2. Modeling of solar water splitter

The hydrogen gas is needed for the catalytic conversion of CO2 to methanol. This is fuel, and the major success of this suggested idea is the free hydrogen availability. For this, water splitting concept is used in this study as suggested by Ulleberg (2003) [119]. By passing an electric current (DC) through two electrodes with a separation of aqueous electrolyte of high ionic conductivity, water may be dissociated into hydrogen and oxygen [120]. The reaction of water splitting may be described as follows:

$$H_2O(liq) + energy(electricty) \rightarrow H_2(gas) + \frac{1}{2}O_2(gas) \quad (3.6)$$

A minimum electric voltage needs to be provided to the two electrodes for this reaction to happen. The Gibbs energy for water splitting (explained below) can be used to calculate this minimum voltage, also known as the reversible voltage. The electrolyte in an alkaline electrolyze is typically aqueous potassium hydroxide (KOH), with the hydroxide ion OH− and potassium ion K+ handling ionic transport. Here, anodic and cathodic reactions are occurring that:

Anode: $$2OH^-(aq) \rightarrow \frac{1}{2}O_2(gas) + H_2O(liq) + 2e^- \quad (3.7)$$

Cathode: $$2H_2O(liq) + 2e^- \rightarrow H_2(gas) + 2OH^-(aq) \quad (3.8)$$

The electricity required for splitting water is being provided by solar parabolic trough collectors for which the power is estimated. The process flow diagram for solar water splitting unit is shown in Fig. 3.8, following the similar strategy as explained in earlier research [121]. According to this, the condensate coming out from the steam turbines is utilized in the process. The electrolyze consists of a stack in which water is dissociated into H_2 and O_2 gases in the presence of KOH electrolyte. The operating pressure for the splitter is set at 7 bar. The split streams of H_2 and O_2 contain the water so these water molecules are later separated through flash separators at 25°C and 6.7 bar.

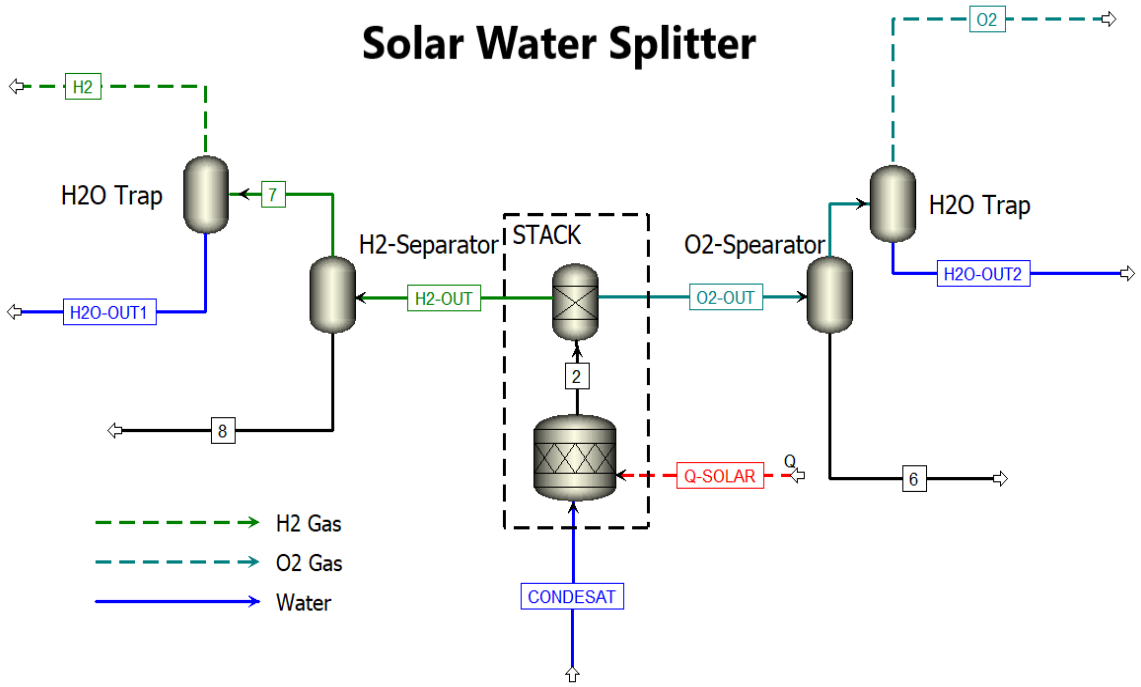


Figure 3. 8: Process of Solar Water Splitter [130]

3.4. Estimating The Solar Potential At Baghdad Coordinates with Parabolic Trough Collectors

Bravo et al. (2020) [111] used a strategy of solar energy used in this study to simulate a parabolic trough collector in Iraq, Baghdad, with NREL's SAM software. The first step in configuring the SAM model is to procure solar and meteorological data for the location of interest, that is, Baghdad at coordinates 33°18'46.0980"N and 44°21'41.3568"E. SAM determined average daily direct normal irradiance (DNI) for the area to be about 5 kW hr/m2/day, with July experiencing maximum DNIs of about 773 W/m2. Hourly DNI-cosine product irradiance is shown in Fig. 3.9 with peak values above 900 W/m2 during peak sunlight hours and informing design of the parabolic trough solar collector field. Table 3.4 summarizes key design parameters for building and simulating the solar field in Baghdad based on available solar irradiation data.

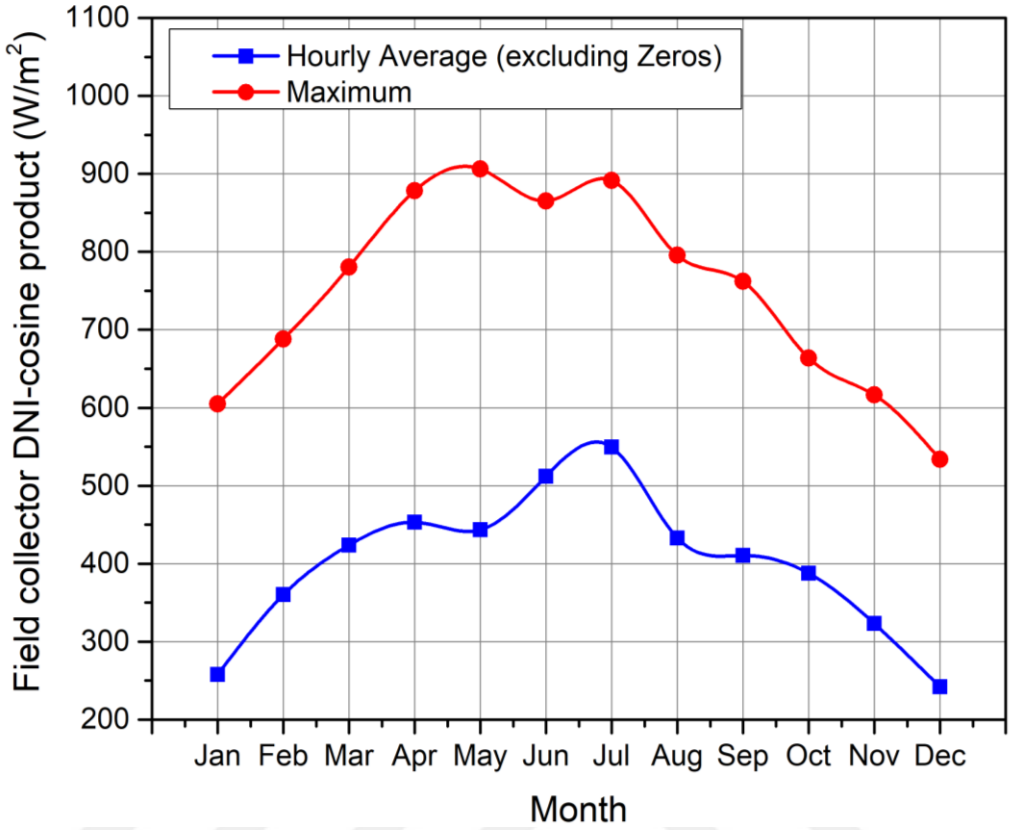


Figure 3. 9: Hourly DNI-Cosine Product Irradiance for Parabolic Trough Collector at Baghdad, Iraq.

The solar thermal power component design parameters were carefully developed to achieve a specified capacity of 350 MWth and solar multiple of 1.8 to deliver heat to the thermal heat sink by the High-Temperature Fluid (HTF). The stripper reboilers thermal duty required power input to the HTF at the receiver to be 630 MWth, with specific focus on the strategic distribution of resources. A key feature in this design was the setting of a defined outlet temperature of 260 °C for the HTF above the temperature of the thermal sink indicated by the steam in the reboiler at 170 °C, improving overall efficiency and performance.

Furthermore, careful temperature control measures were adopted, having a return temperature of 160 °C for the HTF back to the solar field in concurrence with introducing cold condensate around 150°C into the HTF-to-reboiler steam heat exchanger. This considered strategy guarantees optimal thermal conditions and smooth operation of the solar assisted reboiler heating mechanism. The design also took into account the best number of

parabolic trough assemblies in series per loop, with parallel arrangements designed to produce the intended thermal power at the design point Direct Normal Irradiance (DNI), reflecting a well-rounded and forward-looking design philosophy for integrating sustainable energy into the NGCC+PCC plant configuration.

Table 3. 4: The input parameters for SAM to design solar field collectors.

	Units	Value
DNI for the Design	[W/m^2]	900
High-temperature fluid (HTF)		Pressurized water
The maximum Operating Temp of HTF	[°C]	360
Target Solar Multiple		1.8
Target Receiver Thermal Power	[MW]	630
Heat Sink Thermal Power	[MW]	350
HTF Field Inlet Temp.	[°C]	140
HTF Field Outlet Temp.	[°C]	260
Reflective Aperture Area	[m^2]	650
Number of Troughs Per Loop		6
Length of Collector Assembly	[m]	115
Number of Modules per Assembly		8
Aperture Width	[m]	6
Average Surface-to-Focus Path Length	[m]	2.15
Piping Distance Between Assemblies	[m]	1

Chapter 4

Results and Discussion

4.1. Overview

The NGCC power plant was modeled based on actual conditions (labeled as the NGCC(Base) case) of the Besmaya NGCC power plant in Baghdad, Iraq. Aspen Plus software was employed to model the process. Subsequently, two strategies were employed to capture carbon. In the first approach, a PCC was also modeled based on MEA absorption and stripping cycle to the base model. Lastly, a solar model was also incorporated with PCC and was termed as NGCC+PCC(Solar). Solar thermal energy was used to heat the fluid in the reboiler. In second strategy, the CO2, available in flue gases, was catalytically converted into methanol in the presence of H2, which was generated using solar water splitter based on condensate water from turbine system. This scenario is also known as NGCC+METH(Solar). Solar thermal energy played a key role in the heating of water splitter heater. For the estimation of solar thermal energy at the plant site, the SAM model simulated the parabolic trough solar power plant. The results for the Base case mode, NGCC+PCC(Solar) and NGCC+METH(Solar) model and solar energy integration are explained in following sub-sections.

4.2. Simulation Results

The simulation results are discussed in sub-sections starting with model validation results.

4.2.1. Model validation

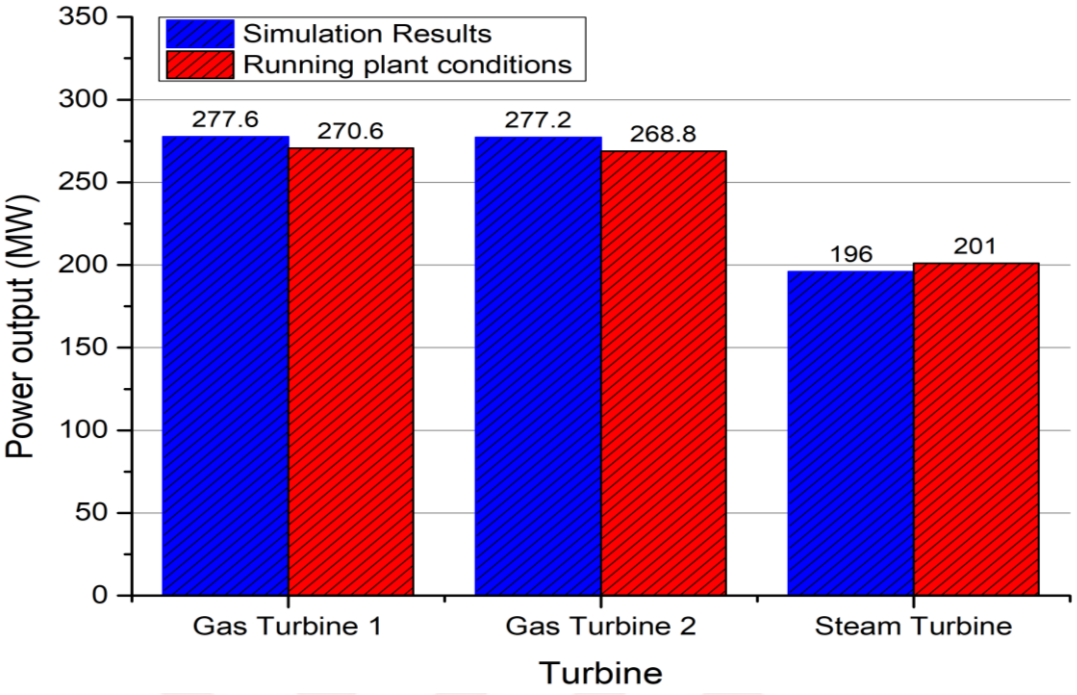
The NGCC power plant was subjected to careful simulation, carefully designed to replicate prevailing operational and design conditions carefully listed in Table 3.2 (previous chapter). After this rigorous simulation procedure, a thorough validation phase followed, where the simulated results were seriously examined against prevailing plant running conditions. This examination was mainly focused on the complex dynamics of turbine power outputs and the complex intricacies of the major process stream conditions. The comparative study, graphically depicted in Fig. 4.1, highlights the striking similarity between modeled

power outputs and their empirical counterparts when implemented in the field during actual plant performance. Such a critical study brings to the fore a high degree of congruence, with deviations lying admirably within a narrow margin of less than 2% throughout the board of estimates. Furthermore, the keen eye moves on to Fig. 4.2, in which the temperature profiles of different key operating conditions are carefully placed against simulation results and thus reveal a striking similarity between the simulated and real plant data. The margin of error, carefully measured in the 1 to 5% range, is a physical proof of the unshakeable fidelity and solidity of the simulated estimates compared to their real-life counterparts. Therefore, it is clearly seen that the NGCC base model, carefully simulated and verified, is an unshakable beacon of trust, steadfastly plotting the trajectory of future predictions with unmatched accuracy and certainty. The standard deviation is calculated by following equation.

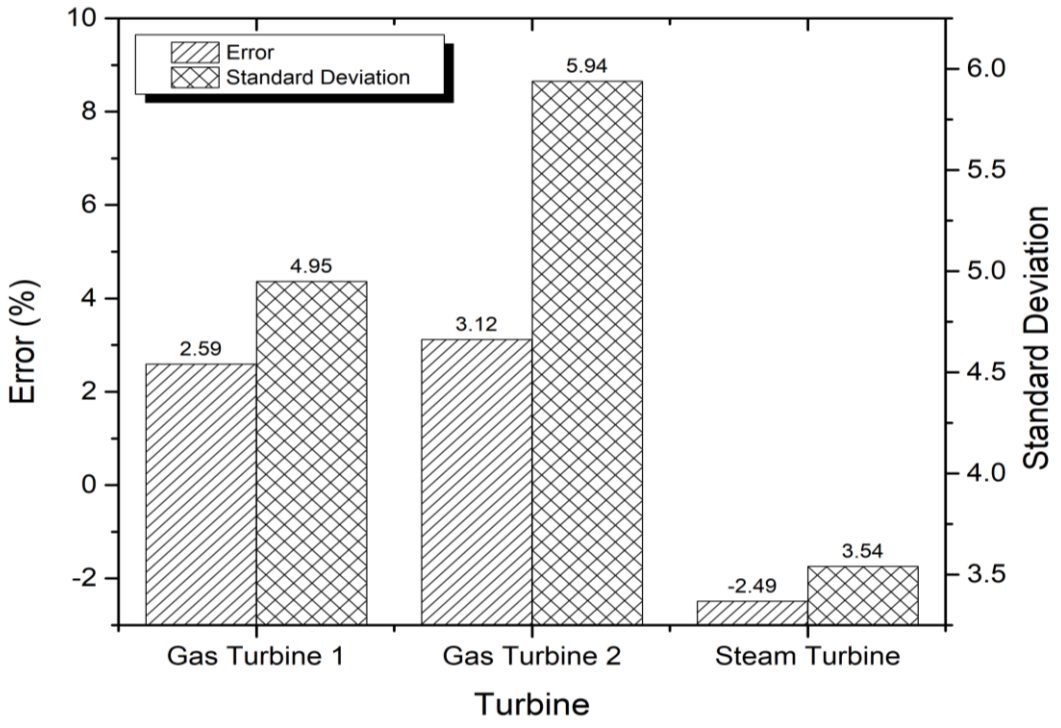
$$SD = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

Where:

- SD = Standard Deviation
- n = number of data points in the sample
- x_i = each data point
- $\bar{x}$= sample mean

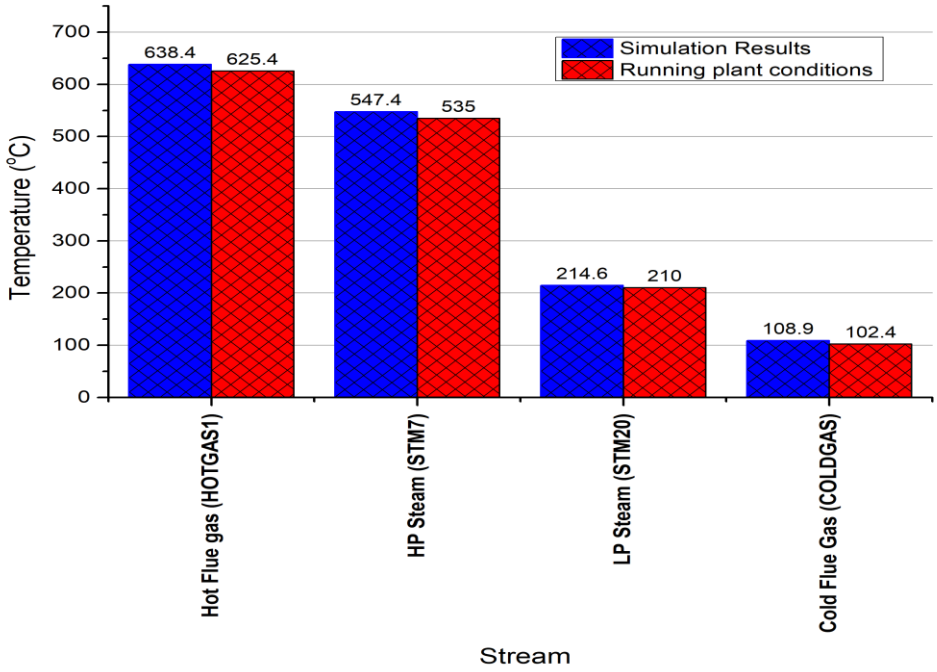


(a)

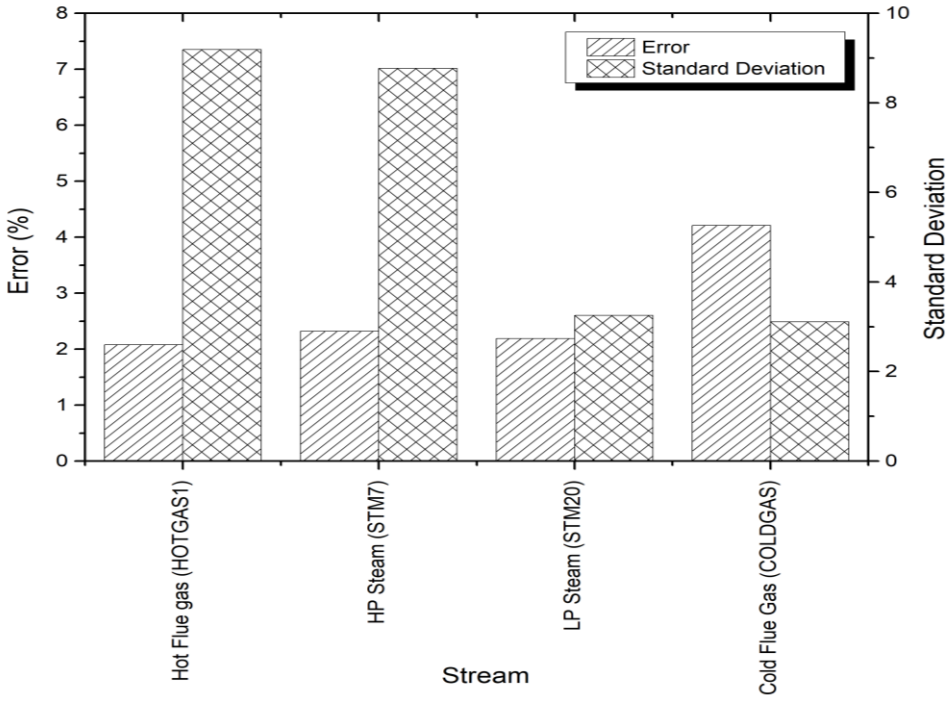


(b)

Figure 4. 1: (a)The comparison of simulation and plant running conditions in terms of power output from all turbines. (b) Error and standard deviation.



(a)



(b)

Figure 4. 2: (a) The comparison of simulation and plant running conditions in terms of temperatures of important operating conditions (b) Error and standard deviation.

4.2.2. Simulation results for Base Case (NGCC) and Base+PCC(Solar) model

The simulation outputs of the NGCC (base) case and NGCC with solar assisted PCC (NGCC+PCC+Solar) are presented in Table 4.1. It was noted that the net NGCC plant capacity was approximately 750 MW prior to the installation of PCC which decreased up to 6.7 % and went down to the range of 699 MW. The CO2 emissions from the current NGCC plant were evaluated as 2,119,318 tons/year by considering 85 % plant efficiency while after the PCC instalment it decreased to 18,064 tons/year after the installation of PCC with MEA circulation. The removal is estimated at approximately 99 % which is the highest achievable efficiency by using any PCC configuration.

Table 4. 1: Simulation results for NGCC (Base) and solar-assisted NGCC+PCC(Solar).

Parameter	NGCC (Base)	NGCC+PCC(Solar)	% Difference
Power [kWe]			
Gas Turbine 1 power	277,606	277,606	0
Gas Turbine 2 power	277,606	277,606	0
HP Steam Turbine Power	132,188	132,188	0
LP Steam Turbine Power	63,490	63,490	0
Total Gross Power	751,340	751,340	0
Auxiliary loads [kW_e]			
Condensate pump 1	34	34	0
Condensate pump 2	1	1	0
Rich Amine Circulation Pump	-	43,549	
Hot gas cooler	-	8,825	
Total Auxiliaries	35	52,409	52,374
Net Power	751,305	698,931	-6.97
Energy Balance (Thermal)			
HHV of Natural Gas [kJ/kg]	51,107	51,107	0
Thermal Input HHV [kW_{th}]	1,533,210	1,533,210	0
Net Plant Efficiency (HHV) [%]	49.8	48.0	-3.6
Flue gas cooling Duty [kW_{th}]	63,926	63,926	0
Reboiler Duty [kWh]	-	43,217,000	
Stream Balance			
Natural Gas Feed Flow [kg/s]	30	30	0
Air Feed Flow [kg/s]	860	860	0
Flue Gas Flow [kg/s]	890	769.523	-13.54%
Stack CO_2 [kg/s]	79	0.60	-99
CO_2 Emissions [tons/year]*	2,119,318	18,064	-99

*Calculated using the 85 % efficiency factor of the plant.

4.2.3. Simulation results for NGCC process integrated with CO_2 conversion into methanol (NGCC+METH(Solar))

The detailed analysis of the simulation output results for the NGCC (base) and (NGCC+METH) configurations is carefully outlined in Table 4.2, providing a treasure trove of information regarding the complex dynamics of plant performance under different operating conditions. One notable observation arising from the tabulated data is the noticeable effect of Methanol recovery on the net NGCC plant capacity. Starting at a solid 750 MW, the capacity of the plant undergoes significant decreases of up to 9.06% after the process of Methanol synthesis, with the final ranging from 682 MW. Such tangible decrease signifies the intricate process interaction between alterations and total plant production, giving insight into the subtle trade-offs involved in experimenting with alternative formats designed to bring about greater working efficiency.

A key factor in determining the environmental impact of the NGCC plant is in estimating CO2 emissions, an essential factor with regard to our present-day emphasis on sustainability. CO2 emissions from the NGCC plant prior to the Methanol recovery integration were estimated at a whopping 2,119,318 tons/year, based on an assumed efficiency of the plant at 85%. However, with the advent of the Methanol recovery process, a revolution occurs, with CO2 emissions decreasing phenomenally to as low as 16,069 tons/year. Interestingly, even this decrease surpasses the emissions in the case of PCC with the MEA circulation system, where CO2 emissions were calculated at about 18,064 tons/year. This significant reduction of emissions highlights Methanol recovery as having a major transformational effect on reducing NGCC operations' environmental footprint and bringing about an era of changed, more benign energy production principles.

Of utmost importance is the high efficiency attained in CO2 removal, a performance metric that signifies the effectiveness of PCC setups in arresting greenhouse gas emissions. Interestingly, both the NGCC+METH setup and the PCC with MEA circulation system share a high removal efficiency of around 99%, a peak in the pursuit of maximum CO2 capture effectiveness. This record level of efficiency highlights the effectiveness of PCC technologies in reducing carbon emissions, emphasizing their central role in creating a sustainable energy future.

Essentially, the conclusions drawn from the simulation outcomes emphasize the revolutionizing potential of Methanol recovery in enhancing the operating efficiency and eco-friendliness of NGCC plants. Additionally, the extraordinary efficiency of CO2 removal emphasizes the key contribution of advanced PCC configurations to reducing greenhouse gas emissions, the way to a cleaner energy future.

Table 4. 2: Simulation results for NGCC (Base) and NGCC with Catalytic conversion of CO_2 into Methanol

Parameter	NGCC (Base)	NGCC+METH	Difference
Power [kWe]			
Gas Turbine 1 power	277,606	277,606	0
Gas Turbine 2 power	277,606	277,606	0
HP Steam Turbine Power	132,188	132,188	0
LP Steam Turbine Power	63,490	63,490	0
Total Gross Power	751,340	751,340	0
Auxiliary loads [kW]			
Condensate pump 1	34	34	0
Condensate pump 2	1	1	0
Rich Amine Circulation Pump	-	-	-
Hot gas cooler	-	153	-
Hot gas compressor	-	69,446	-
Total Auxiliaries	35	69,634	-
Net Power	751,305	681,706	-9.26%
Energy Balance (Thermal)			
HHV of Natural Gas [kJ/kg]	51,107	51,107	0
Thermal Input HHV [kW_{th}]	1,533,210	1,533,210	0
Net Plant Efficiency (HHV) [%]	49.8	44.46	-10.72%
Flue gas cooling Duty [kW_{th}]	63,926	63,926	0
Reboiler Duty [kWh]	-	139,691	-
Stream Balance			
Natural Gas Feed Flow [kg/s]	30	30	0
Air Feed Flow [kg/s]	860	860	0
Flue Gas Flow [kg/s]	890	769.523	-13.54%
Stack CO_2 [kg/s]	79	0.60	99%
CO_2 Emissions [tons/year] *	2,119,318	16,069	99.2%

*Calculated using 85% efficiency factor of the plant.

4.3. Parametric Investigations

Parametric studies performed on models are a pillar in comprehending the subtle interaction between different input parameters and the resulting system behavior. Such studies entail varying model parameters systematically over defined ranges to thoroughly investigate their influence on major performance indicators. Through careful examination of the resulting data, researchers acquire precious knowledge about the underlying mechanisms controlling system dynamics, allowing for well-informed decision-making and optimization procedures. Such studies empower stakeholders to determine the best operating conditions, reveal potential weaknesses, and spur innovation by extending the limits of traditional knowledge. Finally, parametric studies constitute an invaluable tool in the toolkit of engineers and researchers, enabling the ongoing improvement and evolution of model-based analysis in a wide variety of fields from engineering and physics to economics and more. Parametric studies were carried out on both the models and elaborated in the following paragraphs.

4.3.1. Parametric investigations on NGCC+PCC(Solar) model

Sensitivity analysis of various crucial parameters such as natural gas flow and MEA flow rate was performed to test the model stability and its overall performance based on earlier studies [122, 123]. The effect of the rate of natural gas flow was seen on the total power generation from the gas turbines and steam turbines with the CO2 emission as indicated in Fig. 4.3. The flow rate of natural gas ranged from 14 to 30 kg/s. The natural gas feed flow rate was linearly related to power outputs from the turbine. The linear relationship between the natural gas feed flow rate and power outputs from the turbine can be explained on the grounds of the basic laws of thermodynamics and the functioning of gas turbines.

With the increase of natural gas flow rate within the given range (14 to 30 kg/s), additional fuel is fed to the gas turbine's combustion chamber. This increases the rate of combustion and production of high-temperature, high-pressure gases in a corresponding manner. The high-temperature, high-pressure gases expand quickly when flowing through the turbine blades and cause the turbine rotor to spin, eventually creating mechanical work. This linear trend comes from the fact that, in this range, an increase in the fuel flow rate proportionally increases the mass flow rate of the hot gases through the turbine. Due to this

consistent increase in mass flow rate, there is a linear increase in the turbine's power output. It should be mentioned that this linear relationship applies under the given operating conditions and range of natural gas flow rates. Outside of this range, nonlinear effects like turbine efficiency variations or constraints in combustion dynamics can impact the relationship between fuel flow rate and power output.

At 14 kg/s, the gas turbine generated 209 MW of total power while the maximum power of 556 MW generated through the turbine was received at 30 kg/s natural gas flow rate. Steam turbines, on the other hand, generated power ranging from 54 to 240 MW. It was observed that the slope of the power rise of the gas turbine was slightly greater compared to the power output from steam turbines. The greater slope of power rise of the gas turbine over the steam turbine is due to the natural differences of their thermodynamic processes. Gas turbines have the general property of being quicker in their response to variation in the fuel flow rate as they are started and controlled with lower difficulty levels in contrast to steam turbines. Further, gas turbines operate under increased pressures and temperature conditions, causing an increased prompt response towards fluctuation in input fuels. On the other hand, steam turbines, though efficient and dependable, tend to be slower in response because they take time to heat water to produce steam and become optimized to operate. Therefore, the capability of the gas turbine to respond rapidly to variation in fuel flow rate also assists in its comparatively steeper power increase slope over observed ranges compared to steam turbines.

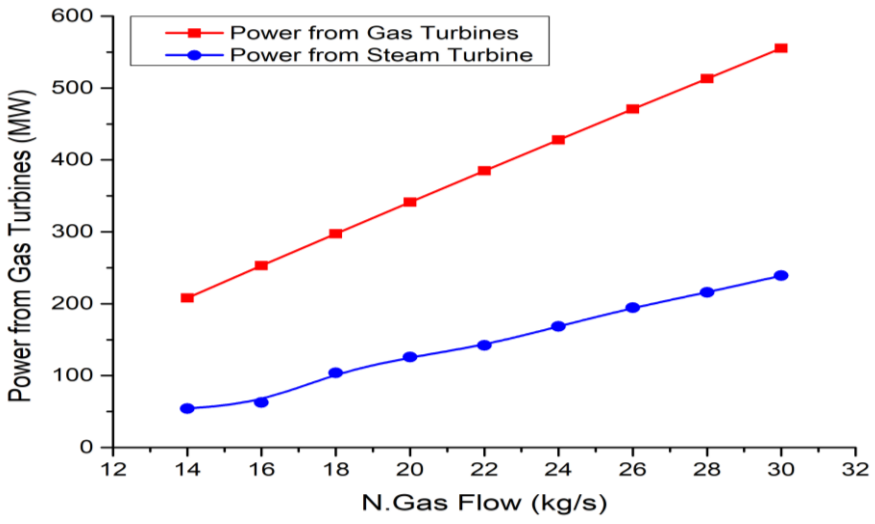


Figure 4. 3: Effect of natural gas feed flow rate on power generation.

CO2 production is also linearly raised from 36 kg/s to 79 kg/s (1135296 to 2491344 tones/year) on the rising natural gas flow without PCC (Fig.4.4). But it can be seen that after the commissioning of PCC, CO2 is highly regulated, and the maximum limit is only 0.672 kg/s (21192 tons/year). This is nearly 98 % removal of CO2 from the flue gases.

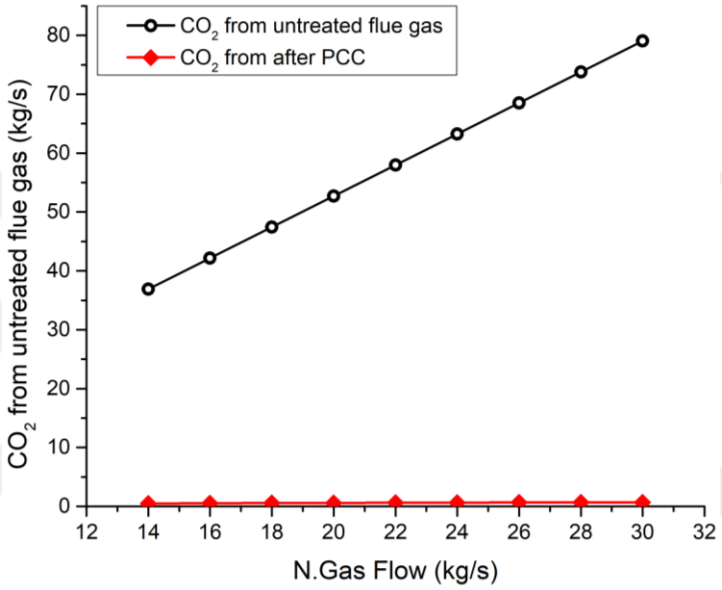


Figure 4. 4: Effect of natural gas on CO_2 production with and without PCC.

Table: The date for Figure 4.4

Power from Steam Turbine	CO_2 from untreated flue gas	CO_2 after captured from MEA Process	CO_2 after capture from Methanol Process
MW	kg/s	kg/s	kg/s
54.21807	36.89588	0.48523	0.31256
62.62816	42.16672	0.52664	0.39079
103.69439	47.43756	0.56242	0.44603
125.89397	52.7084	0.59266	0.51676
141.99981	57.97924	0.61769	0.5484
168.27998	63.25008	0.63783	0.57965
194.36064	68.52092	0.65342	0.58255
215.78606	73.79176	0.66476	0.59392
239.11023	79.06261	0.67218	0.60976

The impact of MEA flowrate in the PCC area on flue gas CO2 fraction and MEA pump duty is depicted in Fig. 4.5. The MEA flowrate was boosted from 150000 kg/s to 300,000 kg/s in the absorption column. At 150,000 kg/s the mass fraction of CO2 in stack gas was brought down to below 1 % (0.7 %). The additional increase in MEA flow to 300,000 kg/s, CO2 fraction was achieved in an almost zero range. In contrast, because of the high flow rate, the MEA recirculation pumping duty is linearly raised from 33 MW to 67 MW. From this, it has been understood that the most optimized feeding rate of 150000 kg/s MEA is required to achieve less than 1 % CO2 in the stack gas.

The finding that an MEA flow rate to obtain less than 1 % CO2 in the stack gas can be understood by looking at the absorption kinetics and equilibrium behavior in the absorption tower. At lower flow rates, the MEA solution has enough time of contact with the flue gas to capture CO2 molecules effectively, leading to a drop of CO2 mass fraction in the stack gas to below 1 %. But when the MEA flow rate is increased beyond this optimized level, the extra volume of solvent might not further enhance CO2 capture efficiency because of mass transfer and absorption kinetic limitations. In addition, raising the MEA flow rate above the optimized level necessitates higher pumping duties for MEA recirculation. This rise in pumping duty reflects that the system is utilizing more energy to drive the solvent around, without gaining much improvement in CO2 capture efficiency. Hence, the trend observed here emphasizes the need to balance absorption efficiency against energy consumption in maximizing CO2 capture processes.

The effect of solar power on total duty on reboiler is also analyzed and a linear decreasing trend is exhibited in Fig.4.6. For 5000 kW of the solar plant, the reboiler duty in excess is estimated at around 88137 kW to heat rich MEA in stripping column. At the highest available solar power i.e. 50000 kW, the reboiler duty was brought down till 88092 kW.

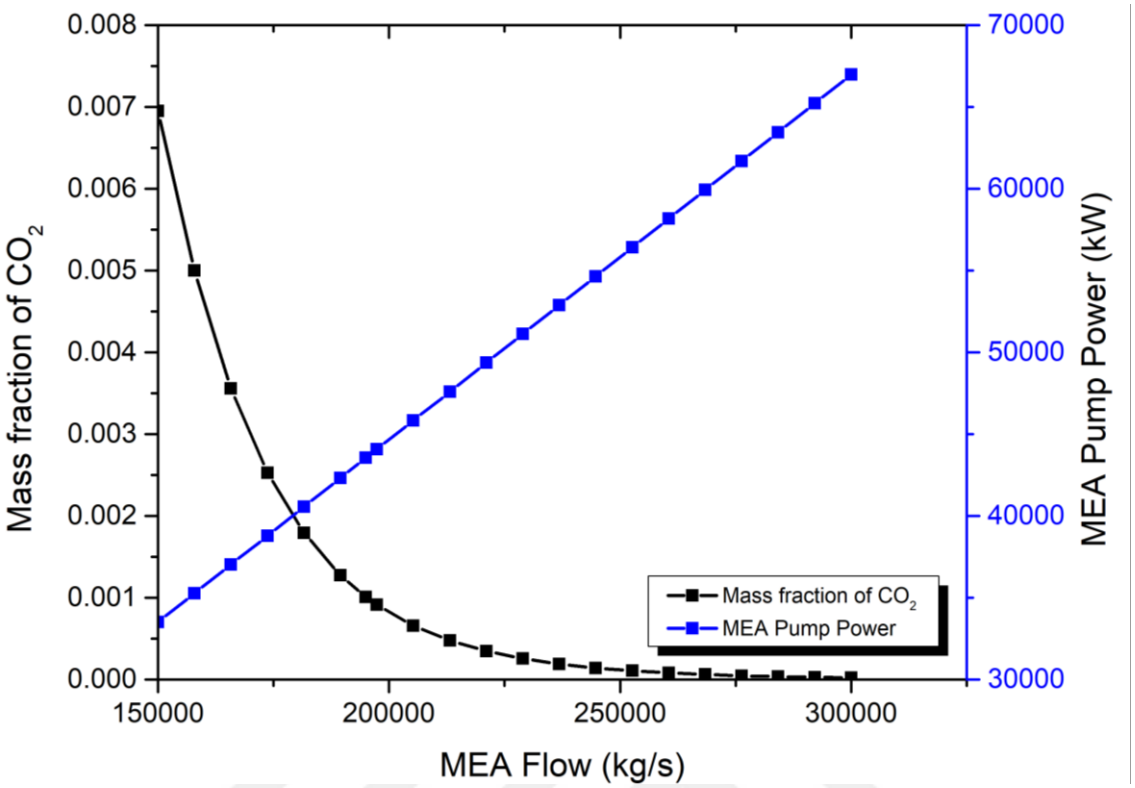


Figure 4. 5: The effect of MEA flow rate on the mass fraction of CO_2 in stack gas and MEA pump duty.

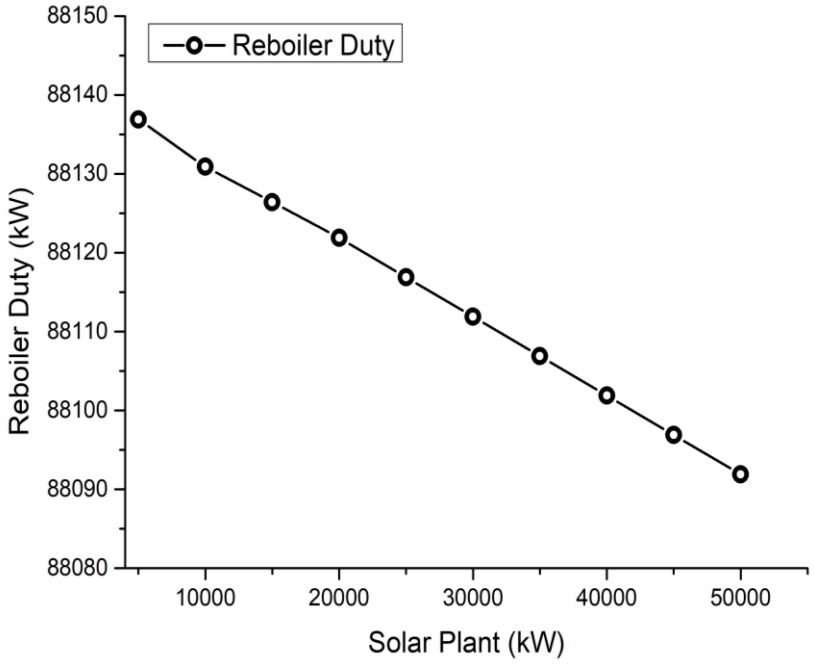


Figure 4. 6: Effect of Solar power on reboiler duty for stripping columns.

4.3.2. Parametric investigations on NGCC+METH(Solar) model

The parametric studies carried out provided insight into the complex dynamics of carbon dioxide (CO2) production in the NGCC+METH model, highlighting the significant effect of different operating parameters on system performance. Of particular interest is the demonstration of a linear rise in CO2 production, from 36 kg/s to 79 kg/s (or 1,135,296 to 2,491,344 tonnes/year), with increasing natural gas flow rates for untreated flue gas, as illustrated in Fig. 4.7. Yet, a key observation is made upon the installation of either carbon capture technology: a significant reduction in CO2 emissions is attained, actually dampening the ceiling to just 0.672 kg/s (21,192 tonnes/year) for CO2 absorption using MEA absorbent, and 0.60976 kg/s (19,229 tonnes/year) for producing Methanol. Such a significant decrease highlights the effectiveness of both technologies in realizing an impressive CO2 removal efficiency of about 98%, significantly offsetting the environmental footprint of NGCC operations.

In addition, a comparative analysis of the two carbon capture processes shows interesting results. More precisely, it is observed that the efficiency of CO2 captures in Methanol production is higher than that of absorption using MEA solution, though by a small margin. This finding points to the inherent advantages of catalytic conversion processes, emphasizing the increased efficiency and flexibility provided by Methanol production as a carbon capture process within the NGCC system.

In conclusion, the parametric studies conducted in the NGCC+METH model not only clarify the effectiveness of carbon capture technologies in reducing CO2 emissions but also highlight the subtle nuances in performance among various capture methods. These findings have far-reaching implications for the design and optimization of carbon capture systems, which will lead to more sustainable and environmentally friendly energy production practices in the quest for a greener future.

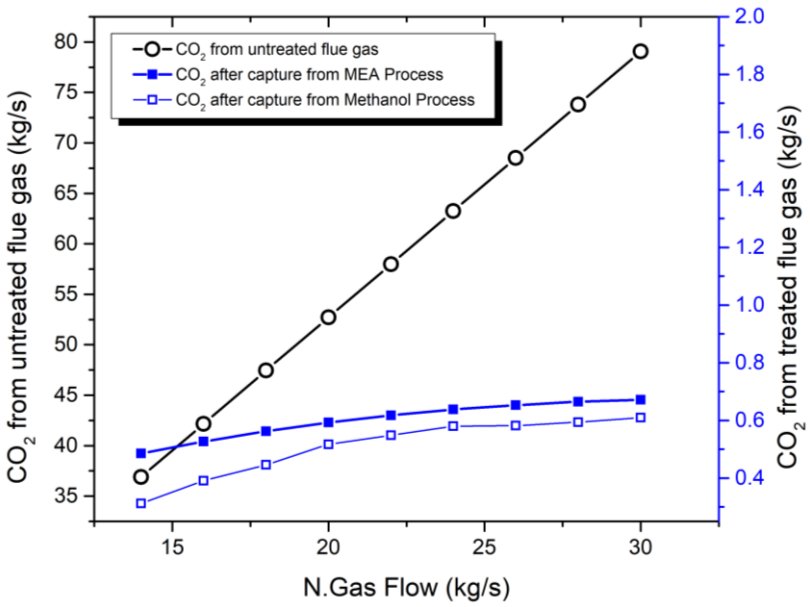


Figure 4. 7: Effect of natural gas on CO_2 production with and without carbon capture

The influence of flue gas feed rate (raw exhaust gases emitted from power plant) on the yield of methanol and CO2 mass fraction in final exhaust gases (treated gas) is indicated in Fig. 4.8. It was realized that the rate of production of methanol is increased almost linearly by raising the rate of untreated flue gas feed from 500 to 1500 kg/s. The highest methanol production was obtained at 56.86 kg/s at the highest untreated flue gas feed rate i.e., 1500 kg/s. The cause of this trend is self-evident because the higher feed rate of untreated flue gas carries higher composition of CO2 which maximizes the productivity of methanol by maximizing the rate of conversion of CO2. The primary aim of the study is the recovery of maximum CO2 and reducing CO2 emissions.

For this the increased production of methanol was correlated with CO2 mass fraction in the flue gases (treated flue gases). It was observed from Fig. 4.7 that CO2 mass fraction is not affected by the production of higher quantity of methanol on increasing the feed rate of untreated flue gases. The highest CO2 fraction in the treated exhaust gases were in the range of <0.0077 which is considerably lower than CO2 fraction in the untreated flue gases (>0.08). Therefore, finally it can be stated that the process is sufficient to accommodate the large variety of flue gases feed rate with higher rate of value able product i.e., methanol and regulated rate of CO2 mass fraction in exhaust gases.

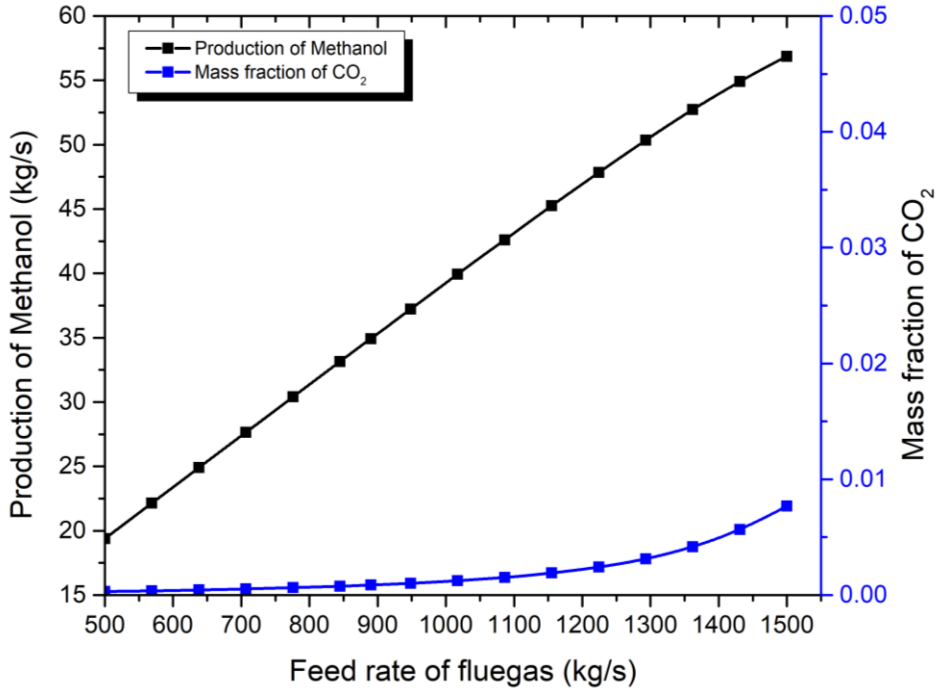


Figure 4. 8: The effect of MEA flowrate on mass fraction of CO_2 in stack gas and MEA pump duty

The overall efficiency of the process strongly depends on the adequate production of H2 gas required in the process of methanol conversion. For this the effect of current density was explored on the H2 gas production along with new power requirements that would be met from solar power generation. The effect is given on Fig. 4.9. From the graph it has been seen that H2 gas production is linearly raised on raising current density from 1000 to 10,000 A/m2¬. The maximum H2 gas was estimated 8059.3 kg/s at 10,000 A/m2. On the other hand, the power input to the stack is also nearly linearly raised. The highest power demand for the stack was approximate to be around 145.8 kW which would easily be supported from the approximated solar power generation for a year.

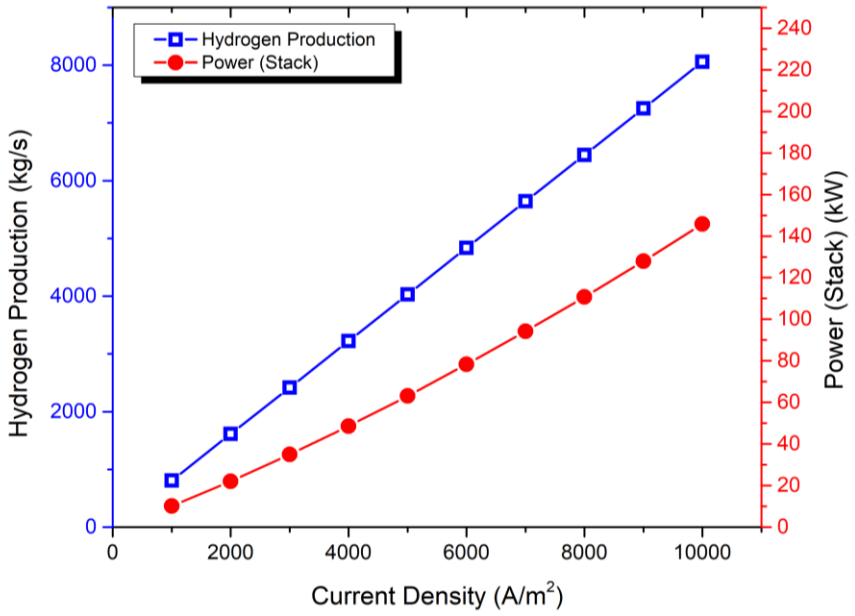


Figure 4. 9: Hydrogen production and Power to stack requirement against current density

4.4. Results And Analysis of Solar Power Plant

The parabolic trough solar collector field was simulated by NREL's SAM for the NGCC power plant in Baghdad, Iraq. Table 4.3 presents the general statistics about the annual energy production. From this, around 984,018,688 kWhth annual energy potential is waiting at the chosen coordinates (Baghdad, Iraq) as per the strategy of earlier studies [112]. The solar energy potential can also be seen from Fig. 4.10 which demonstrates yearly AC energy in a year. The highest 336300 kW solar energy can be utilized at the chosen coordinates of Baghdad, Iraq.

The SAM has also calculated the power output on a monthly basis which is depicted in Fig 4.11. The maximum power reaches the level of 350000 kW during almost all the months, especially the summer season months (April to September). This can be further ascertained from Fig.4.12 representing day-wise system power generation and receiver thermal absorption. The greater curves during the summer period for the majority of the days are illustrated that ensures sufficient solar potential can propel the reboiler duty to recover CO2 from the flue gases.

Table 4. 3: Summary of SAM simulations

Metric	Value
Annual energy	984,018,688 kWh_{th}
Annual gross energy	984,071,552 kWh_{th}
Annual thermal freeze protection	52,833 kWh_{th}
Capacity factor	32.1 %
Annual electricity load	4,970,618 kWh_{e}

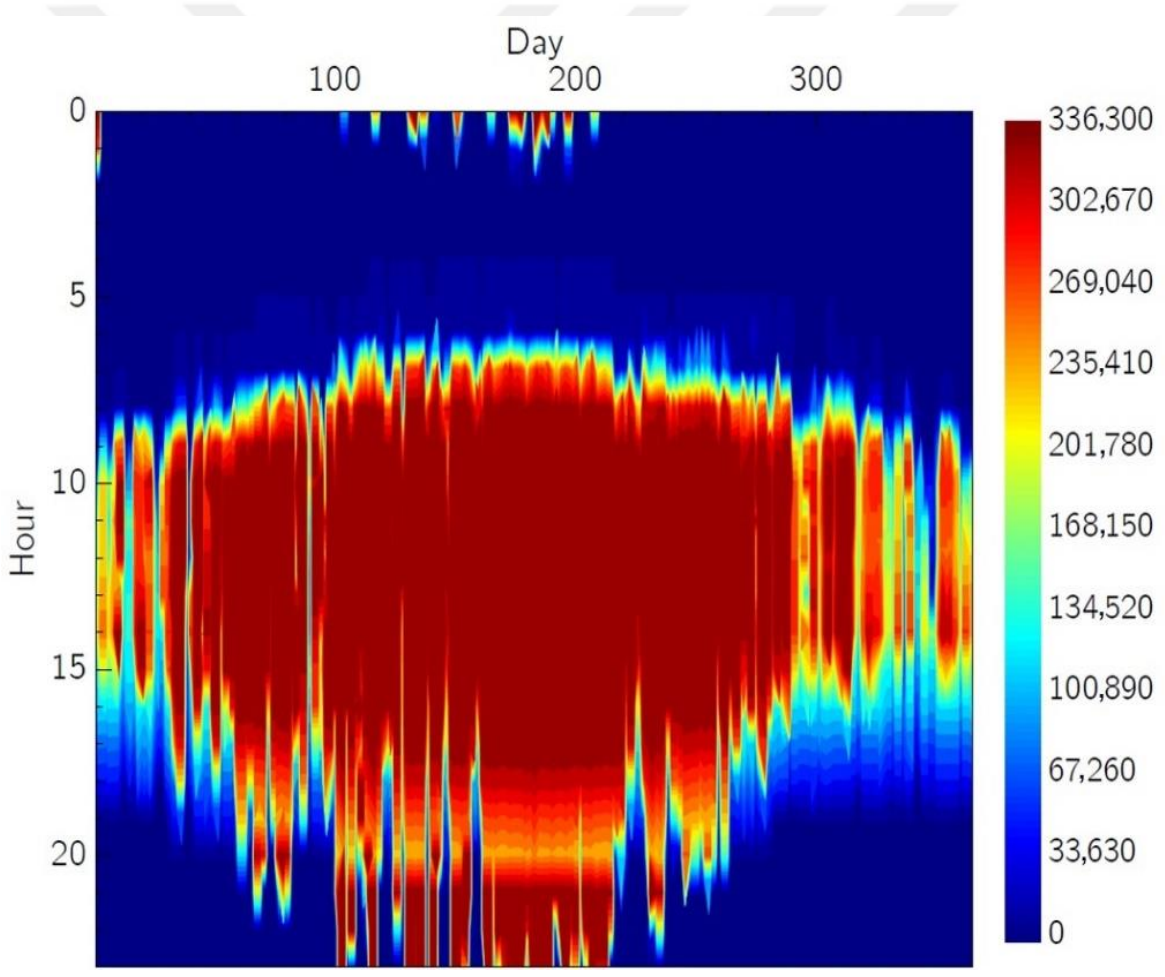


Figure 4. 10: Annual AC Energy in Year 1 (kW).

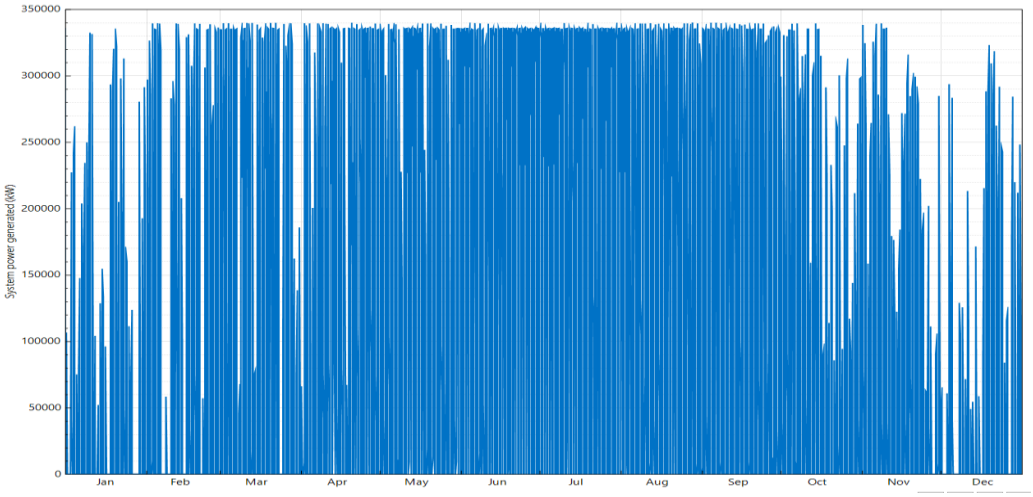


Figure 4. 11: Monthly system generated power estimated by SAM.

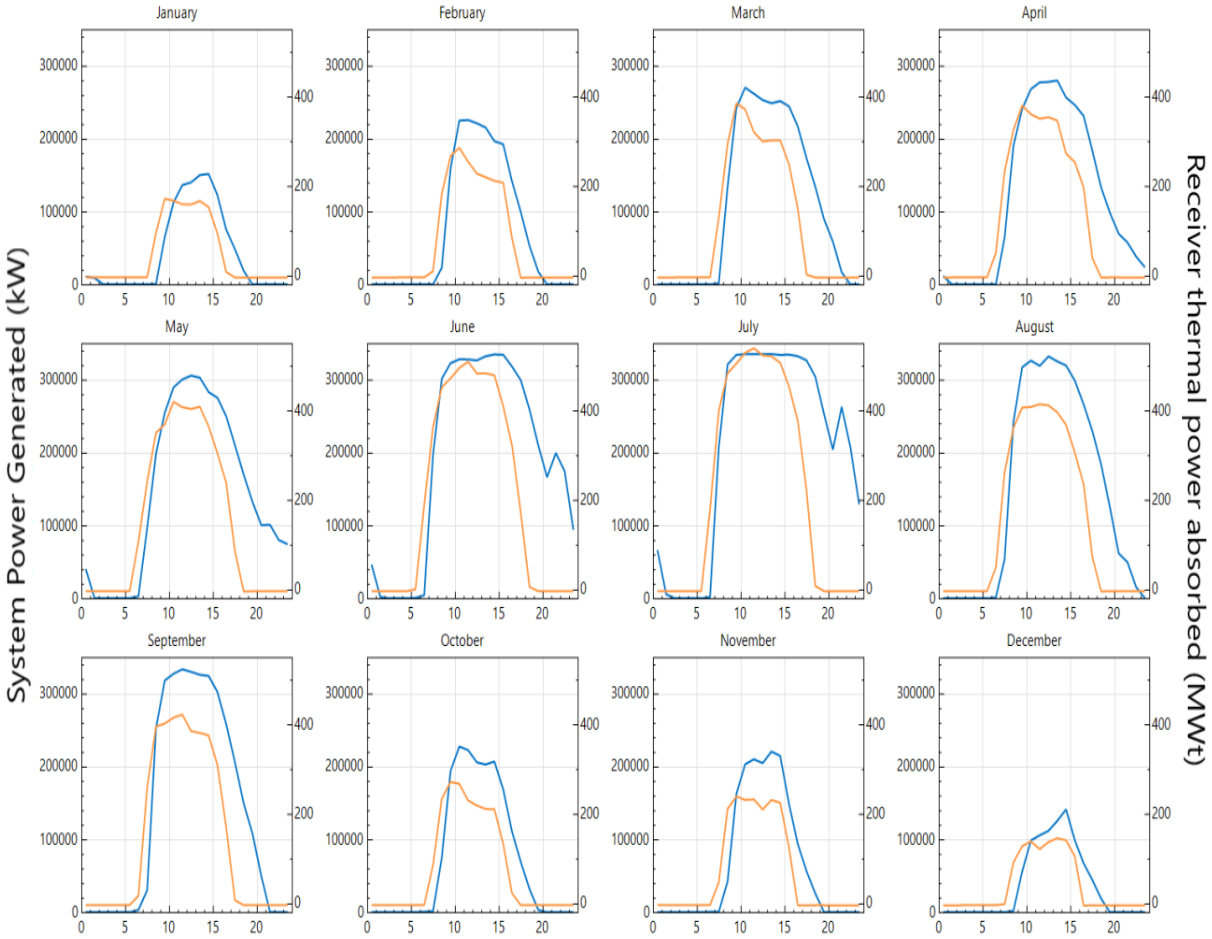


Figure 4. 12: Month-wise system power is generated, and receiver thermal power is absorbed.

Average system power produced, and receiver thermal power measured is depicted in Fig. 4.13. From the figure, it has been estimated that best time to utilize solar energy is between 10 to 16 hours on every day of the year. The system can produce over 200,000 kW electricity during the year along with the heat taken by HTF is between 340 MWth.

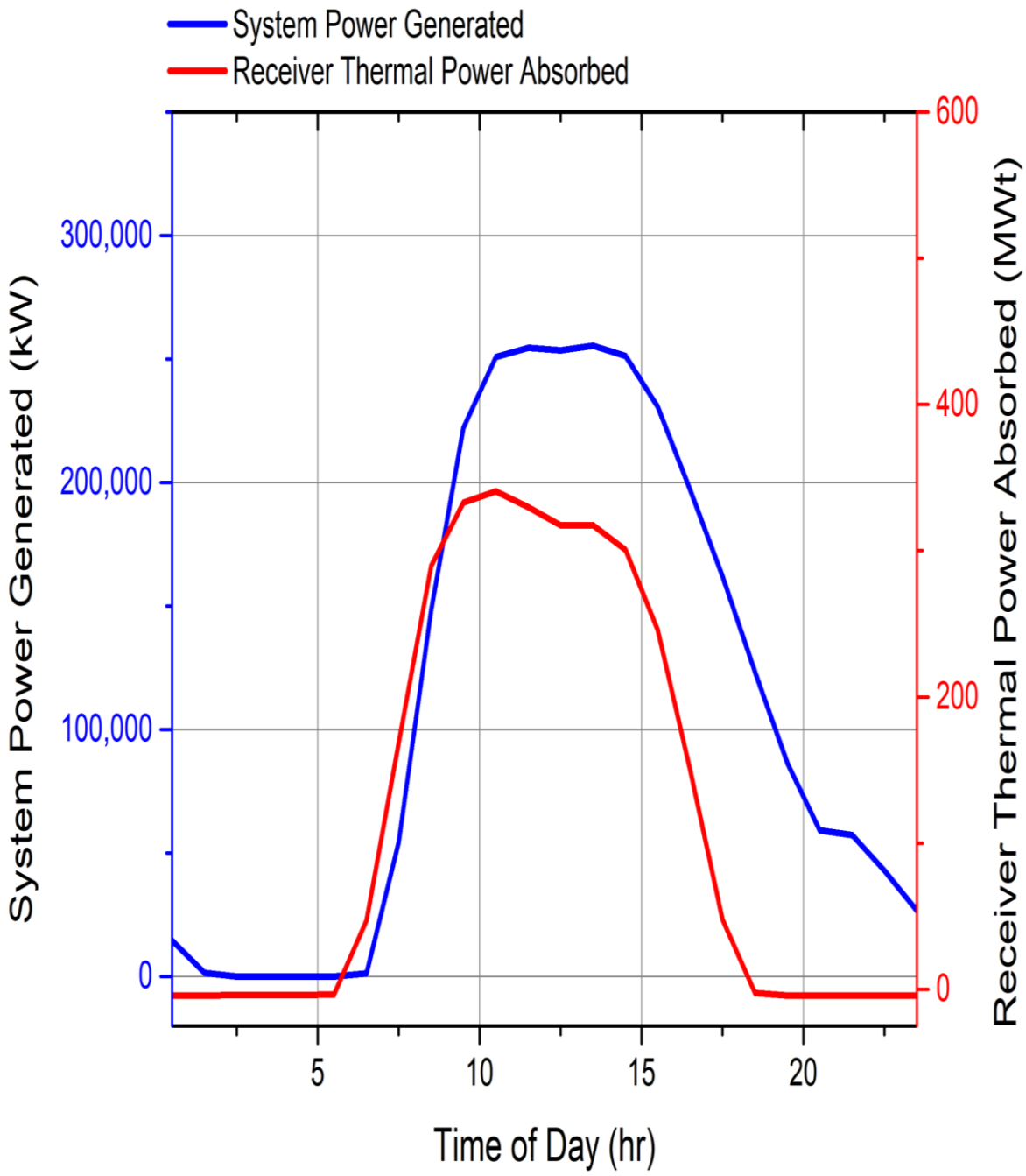


Figure 4. 13: Annual system power generated, and receiver thermal power absorbed

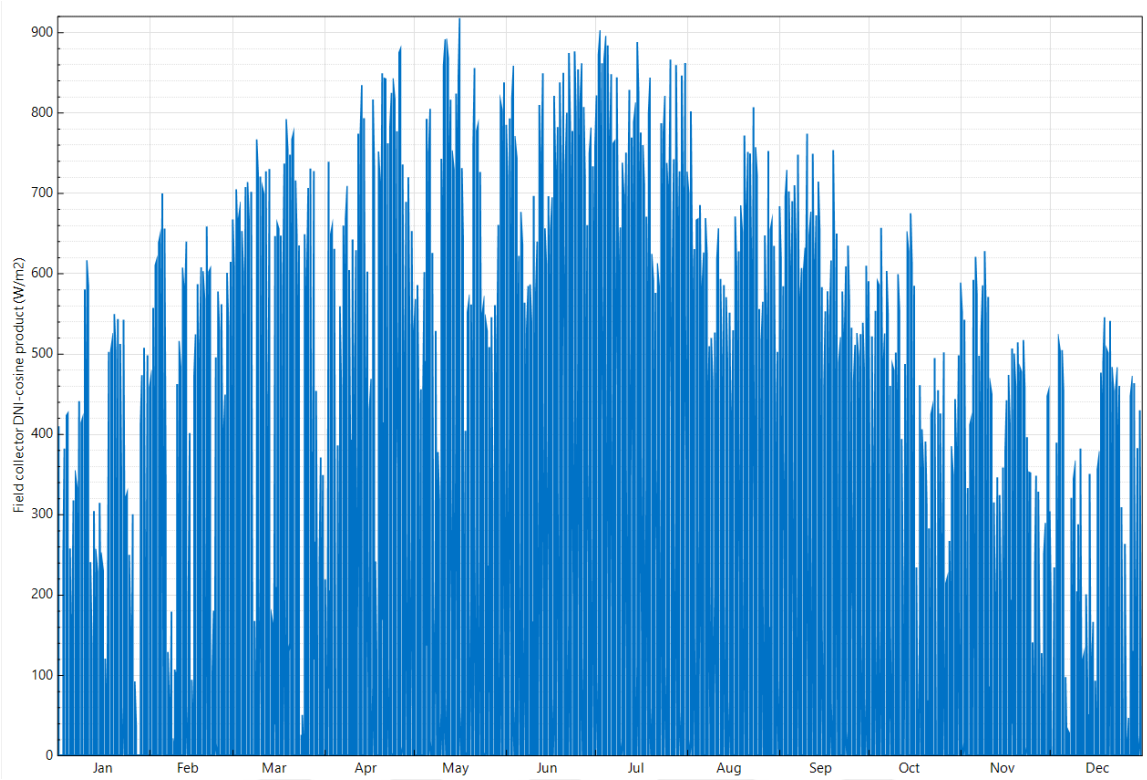


Figure 4. 14: Field collector DNI-Cosine product (W/m^2)

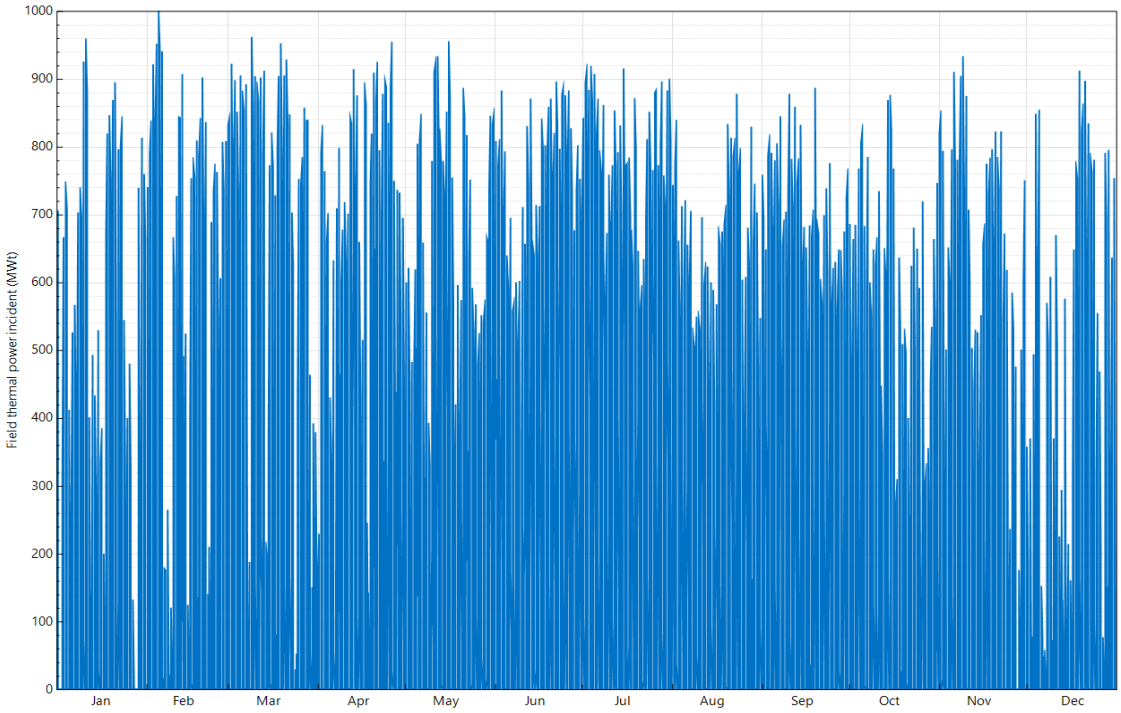


Figure 4. 15: Field thermal power incident (MWth)

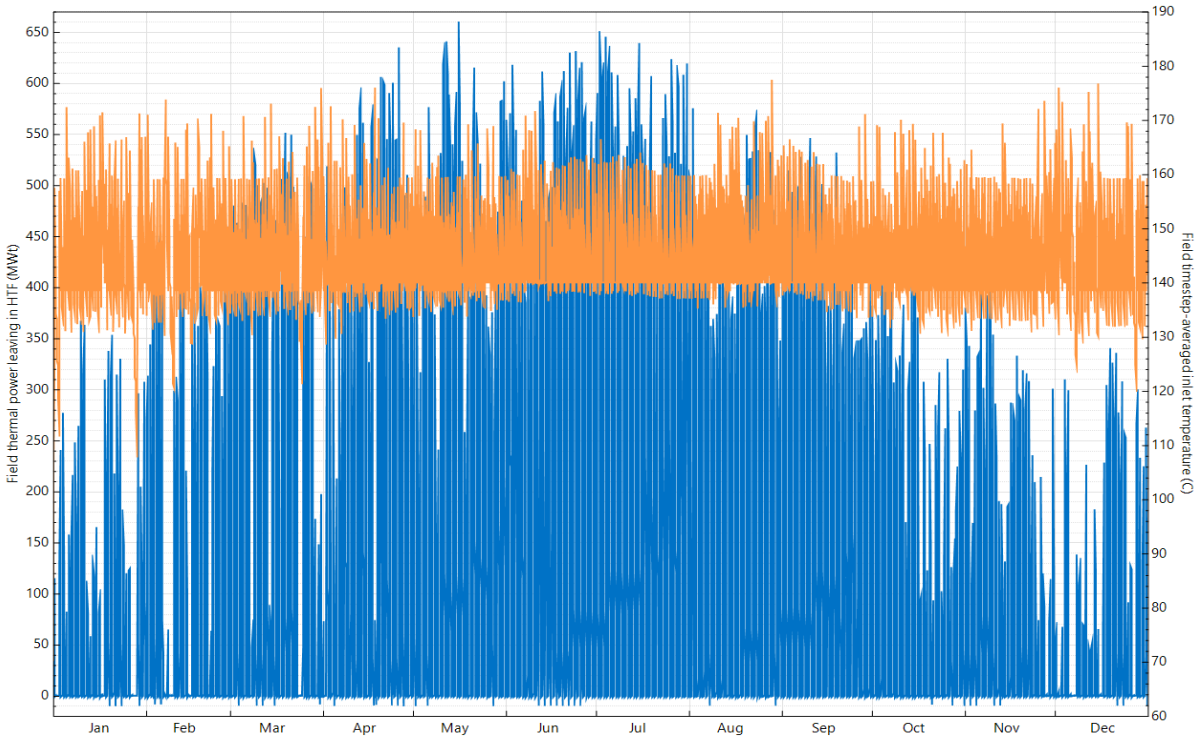


Figure 4. 16: Field thermal power leaving HTF versus field timestep-averaged inlet temperature

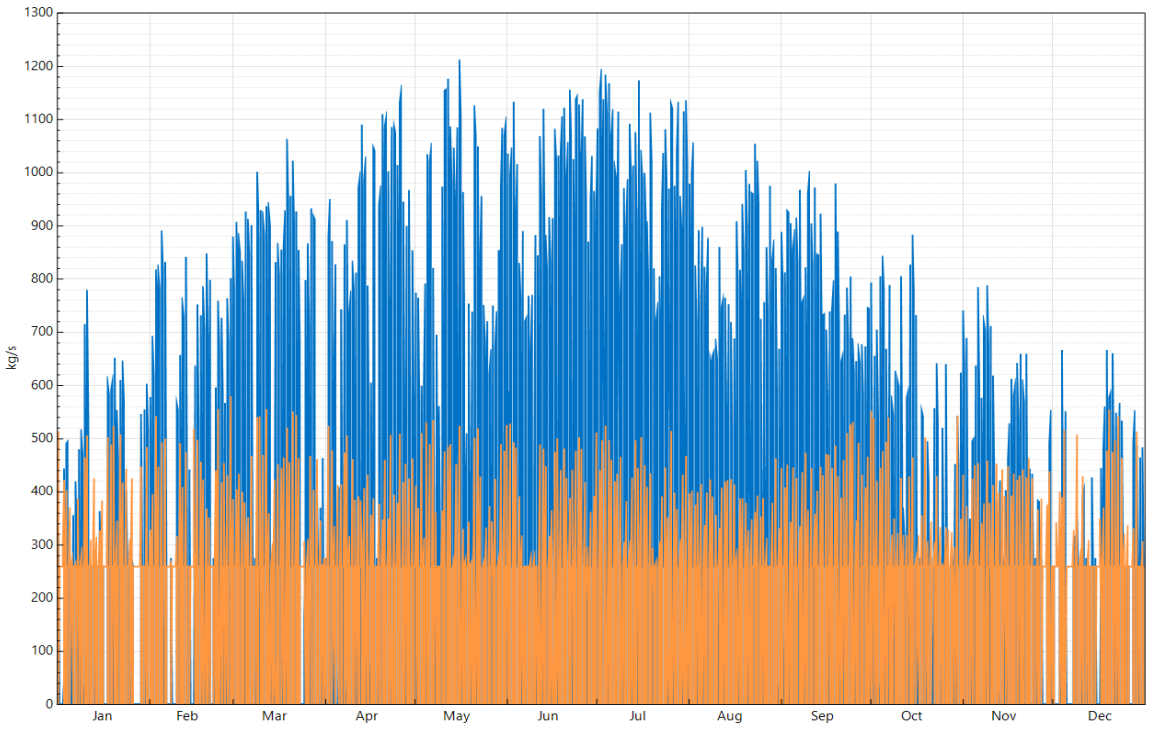


Figure 4. 17: Field total mass flowrate delivered versus field total mass flowrate recirculated

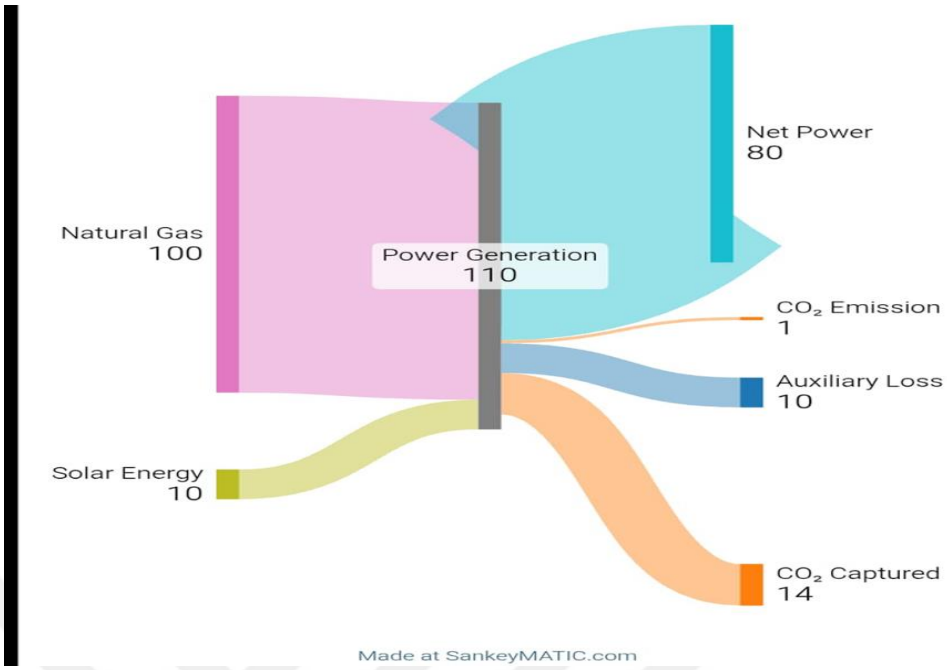


Figure 4. 18: Sankey diagram of the NGCC with solar-assisted post-combustion carbon capture, showing significant CO_2 reduction due to capture and solar input.

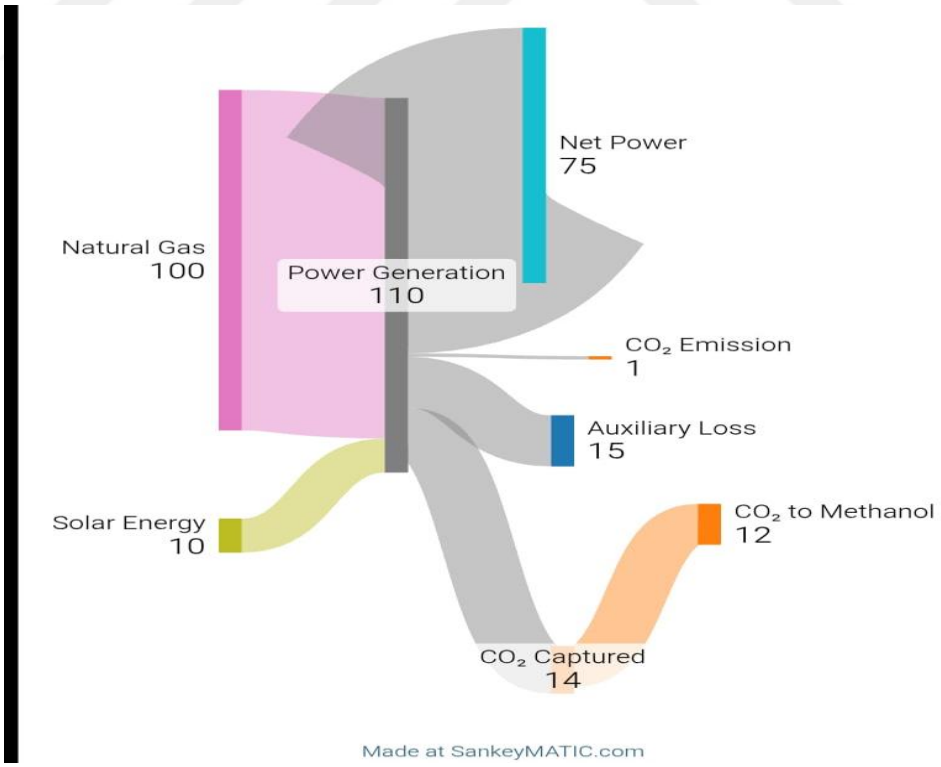


Figure 4. 19: Sankey diagram of the NGCC with solar-assisted post-combustion carbon capture, showing significant CO_2 reduction due to capture and solar input.

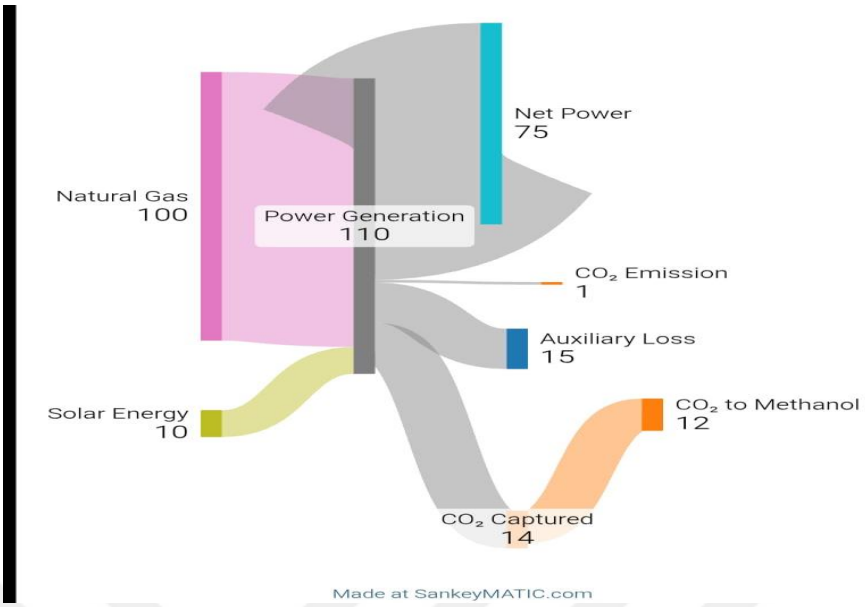


Figure 4. 20: Sankey diagram of the NGCC with solar-assisted PCC and CO_2 conversion to methanol, showing effective resource utilization and minimal emissions.

Figure 4.18 illustrates how integrating solar energy and PCC reduces CO_2 emissions by capturing nearly all the produced CO_2, albeit with some auxiliary energy loss. Figure 4.19 illustrates how integrating solar energy and PCC reduces CO_2 emissions by capturing nearly all the produced CO_2, albeit with some auxiliary energy loss. Figure 4.20 shows the final scenario where the captured CO_2 is converted to methanol, minimizing emissions and adding value by producing a useful chemical feedstock.

4.5. Economic Evaluation

The financial analysis of any process entails a detailed examination of its financials to ascertain its feasibility and return on investment. This analysis generally encompasses evaluating both capital and operating expenses, revenue streams, and financial indicators like net present value (NPV), internal rate of return (IRR), and payback period. Moreover, factors like market demand, regulatory requirements, risk analysis, and sustainability considerations are part of the analysis. Through a thorough economic appraisal, stakeholders can make informed choices on resource allocation, investment prospects, and strategic planning, ensuring optimal resource utilization and maximum economic gains. In this section both the process were economically evaluated and discussed in subsequent sub-sections.

4.5.1. Economic evaluation for process of carbon capture with MEA absorption system

The economic analysis of the Besmaya Natural Gas Combined Cycle (NGCC) power plant, integrated with the MEA absorption method for carbon sequestration, involves a careful examination of many cost elements and financial indicators in order to check the economic viability of the project. First of all, the overall capital price for setting up the NGCC power plant and integrating the MEA absorption method is estimated at USD 1,426,020,000 as presented in Table 4.4. This includes costs associated with equipment purchases, construction, and setup, among other capital expenditures required for the initiation of the project. Once established, the estimated total operating expense of the process totals USD 1,753,880,000 annually. The operating expenses include costs associated with maintenance, labor, utilities, and other recurring operational expenses required for maintaining the plant's operation and carbon capture activity.

Table 4. 4: Summary of the economic evaluation for the process of CO2 capture using solar assisted MEA absorption system

Head	Value
Total Capital Cost [USD]	1,426,020,000
Total Operating Cost [USD/Year]	1,753,880,000
Total Raw Materials Cost [USD/Year]	0
Total Product Sales [USD/Year]	0
Total Utilities Cost [USD/Year]	1,494,770,000
Desired Rate of Return [Percent/'Year]	20
P.O. Period [Year]	0
Equipment Cost [USD]	758,298,500
Total Installed Cost [USD]	829,764,284

In economic feasibility evaluation, lack of raw material cost at USD 0 annually implies that the process might draw largely from accessible inputs like natural gas to be used for generating power and MEA solution to be used for capturing carbon and avoiding direct raw material costs.

According to Table 4.5, the utility cost analysis indicates very high costs that come with the process operation. Electricity is one of the main utilities, consumed at a rate of 48,604.238 KW and costing 3,766.828445 USD per hour. Cooling water, which is used at a rate of 1,371.646 MMGAL/H, is a main contributor to operating costs, at a cost of 164,597.52 USD per hour. In addition, steam, produced at 1,077,426,000 BTU/H, is another vital utility that costs 2,154.852 USD per hour. These utility expenses, required for maintaining process operations and optimal conditions, reflect the necessity of effective resource planning and optimization techniques to reduce operational costs and improve overall economic efficiency.

Table 4. 5: The cost of utilities for the process of CO_2 capture using solar assisted MEA absorption system

Name	Fluid	Rate	Rate Units	Cost per Hour	Cost Units
Electricity		48604.238	KW	3,766.828	USD/H
Cooling Water	Water	1371.646	MMGAL/H	164,597.52	USD/H
AP-UTIL-U-1	Steam	1077426000	BTU/H	2,154.852	USD/H

Additionally, with no data provided on overall product sales, it suggests that the project is not likely to create direct income from sales of products. Therefore, the economic assessment would be based mostly on cost benefit and financial analysis to determine profitability and return on investment. Reflecting on the annual total cost of utilities of USD 1,494,770,000, it highlights the importance of energy use and utility costs during the operational stage. This includes the use of electricity, water, gas, and other utilities essential to plant operations and carbon capture.

A target rate of return of 20% annually has been specified to ensure that the project earns enough returns to meet the expectations of investors and offset the connected risks and capital investment. With a payback period of 20 years, the economic analysis ensures that the project earns enough returns in its lifetime to satisfy investors' expectations as well as compensate for risks and capital investment.

Considering an approximate estimate of annual revenue from carbon credit or government grants and presumed operating expense savings through optimization, the financial analysis can reveal possible profitability, risk management strategy, and decision to invest.

4.5.2. Economic evaluation for CO_2 conversion into Methanol process

In analyzing the economic feasibility of the second model for the Besmaya NGCC power plant, which incorporates CO2 conversion to methanol through hydrogenation and hydrogen synthesis through a solar water splitter, a detailed comparison with the economic parameters of the earlier model is justified, based on a predetermined payback period of 20 years.

The summarized economic assessment information is given in Table 4.6. The sum of capital expenditures for the second model is evaluated at USD 206,144,000 representing investments in procuring equipment, construction, and installation required in process implementation. This amount compared to the original model's capital expenditure of USD 1,426,020,000 translates to a noticeable decrease, possibly reflecting cost savings or variations in project size and scope.

Operating costs for the second model stand at USD 157,302,000 a year, including maintenance, labor, utility, and other operations-related expenses. This is compared to the earlier model’s operating expense of USD 1,753,880,000 and reflects a significant reduction, perhaps pointing towards more efficient operation or resource allocation processes.

Table 4. 6: Summary of the economic evaluation for the process of CO_2 conversion into methanol.

Head	Value
Total Capital Cost [USD]	206,144,000
Total Operating Cost [USD/Year]	157,302,000
Total Raw Materials Cost [USD/Year]	0
Total Product Sales [USD/Year]	0
Total Utilities Cost [USD/Year]	135,010,000
Desired Rate of Return [Percent/'Year]	20
P.O. Period [Year]	0
Equipment Cost [USD]	146,748,200
Total Installed Cost [USD]	173,877,200

Similarly, the utilities cost for the second model is USD 135,010,000 annually, showing costs related to electricity, water, gas, and other utility costs necessary for process operations. This amount is significantly lower compared to the previous model's utilities cost of USD 1,494,770,000, perhaps showing efficiency in energy and resource utilization tactics.

Utility cost analysis identifies substantial costs incurred in running the process according to Table 4.7. Electricity is identified as a leading utility, with a consumption rate of 41,567.219 KW, costing an hour 3,221.459472 USD. Cooling water, used at a rate of 27.68348 MMGAL/H, adds to operational costs at a cost of 3,322.0176 USD per hour. Further, steam is consumed at two different rates: 438.9341 KLB/H at 100 PSI, which costs an hour of 3,572.923574 USD, and 2,642,580,000 BTU/H, which costs an hour of 5,285.16 USD. These utility expenditures, important for the upkeep of process operations and ideal conditions, play a key role in emphasizing the importance of efficient resource optimization techniques and resource management to reduce operational costs and improve overall economic performance.

With a target rate of return at 20% annually, the two models should provide returns sufficient to satisfy investors' expectations and cover risks and capital investment in the 20-year payback period. Nonetheless, whereas the payback period is given, additional analysis

will be needed to ascertain if the second model provides this target and how it contrasts with the prior model regarding return on investment.

Table 4. 7: The cost of utilities for the process of CO_2 conversion into methanol

Name	Fluid	Rate	Rate Units	Cost per Hour	Cost Units
Electricity		41567.219	KW	3,221.459472	USD/H
Cooling Water	Water	27.68348	MMGAL/H	3,322.0176	USD/H
Steam @100PSI	Steam	438.9341	KLB/H	3,572.923574	USD/H
AP-UTIL-U-1	Steam	2642580000	BTU/H	5,285.16	USD/H

4.6. Comparative Analysis with Literature

The findings were compared with chosen literature for the benchmarking of the two technologies. Table 4.8 outlines a concise comparison of findings from the present study to some other similar research work. From the comparison, it has been seen that primarily MEA solvent is utilized to strip CO2 effectively from the combustion flue gases. The solar power is generally utilized to decrease the cost of PCC energy and enhance the overall economy of the process. The efficiency of removal in current study was found 99 % which is nearly in top range. Thus, the present study indicated a notable contribution to the large capacity power plants with high capturing CO2.

Table 4. 8: Comparison of results with literature

Capacity of Power Plant	Fuel utilized	CO_2 removal technology	Energy Management	CO_2 reduction	Brief description of salient results	Ref.
699 MW power plant	Natural gas	Absorption of CO_2 using MEA	Solar integration	99 %	18,064 t/year CO_2 emissions after PCC	This study
682 MW power plant	Natural Gas	Catalytic Conversion of CO_2 into Methanol in presence of H_2	Solar integration	99.2%	16,069 t/year CO_2 emissions after CO_2 conversion	This study
55 MWth	MSW	(MEA) based post-combustion CO_2 Capture (PCC).	MSW direct combustion	99.72 %	Flue gas flow rate was 30.7 kg/s	Su et al., (2023) [123]
Not mentioned	CH_4 combustion	Tetra ethylene pentamine-impregnated mesoporous silica (TEPA/SBA-15) and blended chemical aqueous absorbent (MEA + PZ)	-	74.4	CO_2 reduction capacity was in the range of 0.819 tCO_2/MWh →0.210 tCO_2/MWh	Kim et al., (2023) [124]
330 MW power plant	Coal	MEA based PCC	Solar integration	51.6 %	CO_2 emissions 0.874 tonnes/MWh	Kev et al., (2023) [125]
547.8 MW	Natural gas	MEA based PCC	Solar assisted PCC	90 %	CO_2 emissions 145,262 tonnes/year	Bravo et al., (2020) [111]
200 kW	Natural gas	MEA based PCC	Solar assisted PCC	90	CO_2 emissions: 0.0882 kg CO_2/kW	Jordan et al., (2019) [126]

On the whole, the suggested system has many benefits because this suggested solar-assisted system is capable of minimizing the CO2 from flue gases using maximum solar energy. Combining solar thermal power with PCC technology can lower the CO2 emissions from fossil fuel-based electricity generation, which can be used in the fight against climate change. Solar thermal energy can be used to supplement the heat input needed for PCC capture processes, enhancing overall energy efficiency and lowering fuel usage. Through the utilization of solar energy, the suggested system encourages the incorporation of renewable energy sources into traditional power plants, diversifying the energy mix and improving energy security. Additionally, based on local solar resource availability and energy market conditions, the application of solar thermal energy can result in cost savings through the reduction of fuel consumption and operational costs. Implementation of solar-augmented PCC technology is in line with sustainable development objectives through the encouragement of the shift towards cleaner sources of energy and less harm to the environment from power production.

Besides the aforementioned benefits, some challenges or disadvantages may also be encountered. Of these the major problem is the cost of the system. Initial capital expenditures

that are involved with the installation of solar thermal collectors and their incorporation into PCC systems can be high, perhaps creating financial challenges for project developers. Furthermore, combining solar thermal energy with PCC processes presents extra technical complexities, such as system design, control optimization, and equipment compatibility, that may need special skills and resources.

4.7. Challenges And Barriers to Implementing and Scaling Up The Solar-Assisted PCC System Iraq and Middle East Region

Installation and upscaling of a solar-assisted Post-Combustion Capture (PCC) system in the case of Iraq and the broader Middle East also poses a set of challenges and obstacles that should be taken into account with consideration [127]. Within the implementation and large-scale deployment of solar-assisted Post-Combustion Capture (PCC) systems in markets such as Iraq and the broader Middle East, the barriers and challenges noted cross over into the intricacies inherent in CO2 to Methanol Conversion Technology. This technology, as much as it holds the promise of carbon capture and use, brings an added layer of complexity that has to be navigated.

One major challenge is that CO2 to Methanol Conversion Technology must be integrated into current energy infrastructures, which are largely based on traditional fossil fuel-powered power generation. Like solar-assisted PCC systems, the implementation of CO2 to Methanol Conversion Technology involves enormous changes and investment in established infrastructures. Rebuilding current facilities or building new ones to implement the conversion process involves huge capital investment and technical know-how, creating obstacles for large-scale deployment.

Furthermore, the intermittent of solar energy resources, which poses challenges for ensuring reliable and consistent power generation in regions with variable weather patterns, also impacts CO2 to Methanol Conversion Technology. The reliance on solar energy as a primary input for the conversion process necessitates robust strategies for managing fluctuations in solar irradiance to maintain consistent methanol production rates. This necessitates advanced control systems and storage technology to buffer changes in the availability of sun and provide uninterrupted operation of the conversion process.

Another relevant barrier is in the availability of adequate lands for installing solar collectors and methanol production plants at the sizes necessary to fulfill energy needs. Just as with solar-assisted PCC systems, the challenge of finding sufficient space for solar installations also extends to CO2 to Methanol Conversion Technology. In densely populated or urbanized areas, identifying suitable sites for both solar arrays and methanol production plants may be constrained by land availability and regulatory constraints, further complicating the deployment of this technology.

Additionally, technical complexity in merging solar thermal energy with CO2 to Methanol Conversion Technology brings operational issues identical to those for solar-assisted PCC systems. It is critical to maximize coordination between solar collectors, methanol synthesis reactors, and other elements of the conversion process in order to maintain smooth operation and optimal efficiency. Further, making sure that solar units and methanol manufacturing equipment are reliable and durable in extreme desert conditions common in the Middle East requires aggressive engineering solutions as well as regular maintenance procedures.

Regulatory and policy environments also have a significant role in promoting or hindering the installation of CO2 to Methanol Conversion Technology. Ambiguity in energy policies, carbon pricing schemes, and renewable energy targets can lead to investment risks and discourage stakeholders from investing in long-term projects. Clear and steady regulatory environments that promote the installation of renewable energy and utilization of carbon are necessary for avoiding such barriers.

Conclusion In conclusion, the challenges and barriers associated with implementing solar-assisted PCC systems in the Middle East region are compounded by the complexities that characterize CO2 to Methanol Conversion Technology. These challenges and barriers will take concerted efforts where collaboration between government, industry stakeholder, institutions of research and international organizations set the pace to implement these in practice. Through proactive efforts to remove technical, economic, regulatory, and social impediments, the deployment and up-scaling of solar-assisted PCC systems, along with CO2 to Methanol Conversion Technology, can help the Middle East, including Iraq, advance towards a cleaner, more resilient energy future.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

Finally, this study sheds light on the change-making capabilities of hybridizing solar thermal power and post-combustion carbon capture in the Besmaya Natural Gas Combined Cycle (NGCC) power plant in Baghdad, Iraq. The base simulation without carbon capture presented a strong overall power generation capacity of 751 MW with a net plant efficiency of 49.8 %. Yet, by incorporating post-combustion capture (PCC), the overall power capacity dipped slightly to 698 MW, alongside a small drop in efficiency to 48 %. With a net plant efficiency of 49.8%, the carbon capture-free baseline simulation recorded a robust overall power generating capacity of 751 MW. Integration of post-combustion capture (PCC), however, led to a decline in efficiency to 44 % and a moderate decrease in overall power capacity to 682 MW.

Most importantly, the environmental impact assessment demonstrated an impressive CO2 emissions reduction achievement. In the absence of solar-assisted PCC, the NGCC plant produced 2,119,318 tonnes of CO2 per year. With integration through solar assistance, emissions were reduced by a staggering 99 %, to a mere 18,064 tonnes/year. In the absence of solar-assisted CO2-to-Methanol conversion process, the NGCC plant produced 2,119,318 tonnes of CO2 per year. With integration with solar support, CO2-to-methoanol conversion process, the emissions were reduced by a whopping 99%, to a mere 16,069 tonnes/year. The solar potential study for Baghdad showed an annual solar energy availability of around 984,018,688 kWhth. The solar power system designed proved its effectiveness by producing 350,000 kW during summer, showing the viability and seasonal flexibility of solar integration. In addition, the simulation results sketched out the energy distribution within the solar-supported system, having a flue gas cooling duty of 63,926 kWhth and reboiler duty of 43,217 MWth.

The application of solar energy to split hydrogen from condensate water is a breakthrough technology in sustainable energy. With sunlight power, we are able to split water molecules into hydrogen and oxygen, which provides a renewable and clean fuel

source. This process not only reduces the environmental footprint involved with traditional methods of hydrogen production but also uses an abundant yet often underappreciated resource—water condensate—that exists in many industrial environments. By using emerging solar water splitting technologies, we are able to make decentralized hydrogen production a possibility, allowing communities to move toward a cleaner, more independent energy infrastructure.

In conclusion, a detailed economic analysis of the Besmaya NGCC power plant with MEA absorption for carbon capture is essential to evaluate its economic viability and long-term viability. Based on different cost factors, revenue sources, and financial indicators, stakeholders are able to make effective investment and implement decisions in a manner aligned with economic goals and environmental sustainability.

This study not only offers useful information on the technicalities of incorporating solar thermal energy into NGCC plants but also highlights its central role in realizing significant carbon emission reductions. As countries across the globe struggle with the need to shift to cleaner energy systems, the information here adds to the body of knowledge seeking to promote sustainable and environmentally friendly energy solutions. The findings of this research hold important implications for policymakers, energy analysts, and industry players, shaping future efforts toward a more sustainable and efficient energy future.

5.2. Recommendations

Based on the research, the following were the recommendations.

- Additional Research on Integration Techniques: With the potential for transformation shown by integrating solar thermal energy and post-combustion carbon capture into NGCC plants, additional research should be conducted to examine other integration techniques and technologies. Researching new methods for maximizing the coordination between solar thermal systems, carbon capture processes, and power plant operations could maximize overall efficiency and performance.
- Techno-Economic Analysis of Solar Integration: A thorough techno-economic analysis of solar integration into NGCC facilities would offer pertinent information

regarding the cost-effectiveness and financial prudence of the same. Examining the requirement of capital investments, operating expenditure, and income streams from the use of solar-powered carbon capture could assist decision-making for policy-makers and the industry.

- Long-Term Monitoring Performance: Having long-term monitoring performance programs for solar-assisted NGCC facilities is necessary for assessing the sustainability and reliability of such systems in the long run. Long-term tracking of essential performance metrics, including the capacity for power generation, efficiency, and reduction in carbon emissions, would allow scientists to spot trends, rectify operational issues, and enhance system functioning.
- Policy Support and Incentives: Encouragement of supporting policy structures and incentives at international and national levels is essential in the process of accelerating the installation of solar-assisted carbon capture technologies. Collaborating with policymakers to encourage targets for renewable energy, carbon price schemes, and solar integration projects financial incentives can ensure large-scale deployment and expansion of these ventures.
- Collaborative Research and Knowledge Sharing: Facilitating coordination among academia, industry, and governmental institutions is critical for the promotion of research and innovation in solar-assisted carbon capture. Institutionalizing collaborative research programs, knowledge-exchange platforms, and inter-disciplinary partnerships would promote synergies, speed up technological advancement, and better solve complex problems.
- Public Awareness and Education: Public education and awareness concerning the advantages of solar-assisted carbon capture technology is paramount to securing support and gaining societal acceptance. Introducing outreach programs, educational resources, and public relation campaigns to express the environmental, economic, and social advantages of such technologies could promote wider acceptance and adoption.

By following these recommendations, scientists can help ensure the ongoing development and utilization of solar-assisted carbon capture technologies, ultimately leading to a cleaner and more efficient energy paradigm.

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Selected Publications:

1. Yasser Abbas Hammady Al-Elanjawy, Mustafa Yilmaz. (Issue 3, 2025). Revolutionizing energy: converting CO2 into methanol using flue gases from natural gas combined cycle power plants. Sustainable Energy Fuels, 2025,9, 833-846, https://doi.org/10.1039/D4SE01183J.

2. Yasser Abbas Hammady Al-Elanjawy, Mustafa Yilmaz. (20 Mar 2024). Solar-Assisted Carbon Capture Process Integrated with a Natural Gas Combined Cycle (NGCC) Power Plant—A Simulation-Based Study, Processes 2024, 12, 613. https://doi.org/10.3390/pr12030613.

3. Yasser Abbas Hammady Al-Elanjawy, Mustafa Yilmaz. (2 Mar 2024). Integrated Systems of a Solar Thermal Energy Driven Power Plant, Appl. Sci. 2024, 14, 2088.https://doi.org/10.3390/ app14052088.

Appendix A: Economic Evaluation and Design Tables

Model 1: CO2 capture via MEA Absorption

Model 2: CO2 conversion into Methanol

Table A1: Cost of Equipment installed in Model 1

Name	Equipment Cost [USD]	Installed Cost [USD]	Equipment Weight [LBS]	Installed Weight [LBS]
COOLER	172,500	355,300	50,400	88,942
P-AMINE	0	0	0	11,696,752
LP-EVAPO	377,400	669,100	105,400	177,016
MIX2	0	0	0	0
MIX3	0	0	0	0
GAS-T-2	0	0	0	0
HP-ECONO	1,622,100	2,880,100	445,400	573,153
LPTURBIN	0	0	0	0
STRIPPER-cond	0	0	0	0
STRIPPER-cond acc	506,700	1,270,700	196,500	369,737
STRIPPER-overhead split	0	0	0	0
STRIPPER-reflux pump	5,600	36500	270	3,514
STRIPPER-tower	728,760,000	785,769,984	345,370,016	352,309,056
P103	17,700	128,800	1,300	24,494
LP-TANK-flash vessel	104,400	359,000	40,300	89,160
NG-SPLIT	0	0	0	0
HP-SUPER	0	0	0	0
REBOILER	25,300	136,900	5,500	30,573
MIX-2	0	0	0	0
MEACOOL	743,500	1,221,300	224,000	340,374
ABSORBER-tower	22,308,600	30,103,800	10,267,600	11,858,466
P101	52,700	731,600	4,100	145,357
MIX-WATE	0	0	0	0
HP-TANK-flash vessel	1,379,100	2,105,400	718,800	855,607
WORKMIX1	0	0	0	0
AIR-SPLI	0	0	0	0
WORKMIX2	0	0	0	0

CSP	181,000	374,500	54,500	98,850
AIRCOMP1	0	0	0	0
PREHEATE	149,100	345,100	42,200	88,178
HPTURBIN	0	0	0	0
LP-ECONO	26,000	139,600	5,800	31,568
COMB-1	0	0	0	0
AIRCOMP2	0	0	0	0
POWERMIX	0	0	0	0
COMB-2	0	0	0	0
MIX-1	0	0	0	0
GAS-T-1	0	0	0	0
ADDHEAT	0	0	0	0
HOTMIX	0	0	0	0
SPLIT1	0	0	0	0
LP-SUPER	1,866,800	3,136,600	529,200	841,916
HP-EVAPO	0	0	0	0

Table A2: TEMA Standards for Heat Exchangers for Model 1

TEMA HEX

User tag number	COOLER	LP-EVAPO	HP-ECONO	STRIPPER-cond	HP-SUPER	REBOILER	MEACOOL	CSP	PREHEATE	LP-ECONO	ADDHEAT	LP-SUPER	HP-EVAPO
Remarks 1	Equipment mapped from 'COOLER'.	Equipment mapped from 'LP-EVAPO'.	Equipment mapped from 'HP-ECONO'.	Equipment mapped from 'STRIPPER'.	Equipment mapped from 'HP-SUPER'.	Equipment mapped from 'REBOILER'.	Equipment mapped from 'MEACOOL'.	Equipment mapped from 'CSP'.	Equipment mapped from 'PREHEATE'.	Equipment mapped from 'LP-ECONO'.	Equipment mapped from 'ADDHEAT'.	Equipment mapped from 'LP-SUPER'.	Equipment mapped from 'HP-EVAPO'.
Number of identical items	1	1	1	1	1	1	1	1	1	1	1	1	1
Heat transfer area [sqm]	1181.969229	2440.907028	1896.95757	1060770.977	348.78727	90.45300101	5335.960804	1286.888952	934.689637	100.345862	6027619.556	5158.456171	1341.702096
Front end TEMA symbol	B	B	B	B	B	B	B	B	B	B	B	B	B
Shell TEMA symbol	E	E	E	E	E	E	E	E	E	E	E	E	E
Rear end TEMA symbol	M	M	M	M	M	M	M	M	M	M	M	M	M
Tube design gauge pressure	415796.08	671046.0772	7878671.079	415796.08	7563671.081	243421.08	243421.08	243421.08	771046.0825	621046.0815	243421.08	7878671.079	7616171.079
Tube design temperature [C]	121.1111111	264.6377017	460.5169756	121.1111111	824.9163889	327.7777778	152.7777778	152.7777778	195.1034467	268.6496406	343.3333333	195.1034467	734.9030089
Tube operating temperature	35	155.5571389	290.95632	35	530	170	125	125	162.0712661	217.6	315.5555556	140	288.6947439
Tube outside diameter	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254
Shell material													
Shell design gauge pressure	243421.08	413587.7494	5218671.08	243421.08	5008671.078	128594.411	243421.08	128594.411	480254.415	380254.4166	128504.411	5218671.08	5043671.077
Shell design temperature [C]	121.1111111	264.6377017	460.5169756	121.1111111	824.9163889	327.7777778	121.1111111	127.4268867	195.1034467	268.6496406	327.7777778	195.1034467	734.9030089
Shell operating temperature	89.21651222	236.8599239	432.7391978	81.45984389	797.1386111	300	41	99.649108889	167.3256689	240.8718628	300	167.3256689	707.1252311
Tube length extended [meter]	6.096	6.096	6.096	6.096	6.096	6.096	6.096	6.096	6.096	6.096	6.096	6.096	6.096
Tube gauge													
Tube pitch [meter]	0.03175	0.03175	0.03175	0.03175	0.03175	0.03175	0.03175	0.03175	0.03175	0.03175	0.03175	0.03175	0.03175
Number of tube passes	1	1	1	1	1	1	1	1	1	1	1	1	1
Number of shell passes	1	1	1	1	1	1	1	1	1	1	1	1	1

Table A3: Centrifugal Pumps installed in Model 1

Centrifugal pump				
User tag number	P-AMINE	STRIPPER-reflux pump	P103	P101
Remarks 1	Equipment mapped from 'P-AMINE'.	Equipment mapped from 'STRIPPER'.	Equipment mapped from 'P103'.	Equipment mapped from 'P101'.
Liquid flow rate [cum/sec]	214.416	0.0022	0.2084	0.646
Fluid head [meter]	19.579		5.960	7.609
Fluid specific gravity	1.001	0.96561	0.856	0.671
Design gauge pressure [N/sqm-gauge]	243,421.08	243,421.08	671,046.077	7,616,171.079
Design temperature [C]	121.111	121.111	183.334	316.442
Fluid viscosity [N-sec/sqm]	0.0005	0.0005	0.0005	0.0005
Pump efficiency [fraction]	0.8593	0.7	0.83796	0.8593

Table A4: Turboexpander in Model 1

Turboexpander				
User tag number	GAS-T-2	LPTURBIN	HPTURBIN	GAS-T-1
Remarks 1	Equipment mapped from 'GAS-T-2'.	Equipment mapped from 'LPTURBIN'.	Equipment mapped from 'HPTURBIN'.	Equipment mapped from 'GAS-T-1'.
Actual gas flow rate Inlet [cum/sec]	93.949	112.490	11.170	93.949
Design gauge pressure Inlet [N/sqm-gauge]	2,998,671.078	398,671.078	7,198,671.079	2,998,671.078
Design temperature Inlet [C]	1,745.662	202.348	530	1745.662
Design gauge pressure Outlet [N/sqm-gauge]	3,471.080	-1,328.921	498,671.0772	3471.0809
Power output [Watt]	552,158,905.5	63,490,166.5	132,187,588.9	55,215,8905.5
Molecular weight	28.210	18.015	18.015	28.210
Specific heat ratio	1.270	1.312	1.273	1.270
Compressibility factor Inlet	1	1	1	1
Isentropic efficiency [fraction]	0.89	0.95	0.95	0.89

Table A5: Multi-diameter towers in Model 1

Multi-diameter tower		
User tag number	STRIPPER-tower	ABSORBER-tower
Remarks 1	Equipment mapped from 'STRIPPER'.	Equipment mapped from 'ABSORBER'.
Diameter Bottom section [meter]	182.88	47.396
Bottom tangent to tangent height [meter]	20.7264	12.8016
Design gauge pressure Bottom [N/sqm-gauge]	24,3421.08	24,3421.08
Design temperature Bottom [C]	198.3115667	121.111
Operating temperature Bottom [C]	170.5337889	40.377
Number of trays Bottom section	28	15
Bottom Tray type	SIEVE	SIEVE
Bottom Tray material		
Bottom Tray spacing [meter]	0.6096	0.609
Molecular Wt Overhead Prod.	34.87	28.489

Table A6: Vertical vessels in Model 1

Vertical vessel		
User tag number	LP-TANK-flash vessel	HP-TANK-flash vessel
Remarks 1	Equipment mapped from 'LP-TANK'.	Equipment mapped from 'HP-TANK'.
Liquid volume [cum]	78.463	233.432
Vessel diameter [meter]	3.2004	4.8768
Vessel tangent to tangent height [meter]	9.7536	12.4968
Design gauge pressure [N/sqm-gauge]	721,046.0798	7,826,171.081
Design temperature [C]	189.849	318.736
Operating temperature [C]	162.071	290.958

Table A7: Centrifugal gas compressors in Model 1

Centrifugal gas compressors		
User tag number	AIRCOMP1	AIRCOMP2
Remarks 1	Equipment mapped from 'AIRCOMP1'.	Equipment mapped from 'AIRCOMP2'.
Actual gas flow rate Inlet [cum/sec]	400.805	400.805
Design gauge pressure Inlet [N/sqm-gauge]	71.080	71.080
Design temperature Inlet [C]	25	25
Design temperature Outlet [C]	617.929	617.929
Design gauge pressure Outlet [N/sqm-gauge]	2,998,671.078	2,998,671.078
Compressor speed [rpm]		
Driver power [Watt]	274,552,767.2	274,552,767.2
Molecular weight	28.850	28.850
Specific heat ratio	1.399	1.399
Compressibility factor Inlet	1	1
Compressibility factory Outlet	1	1
Driver type	MOTOR	MOTOR

Table A8: Cost of Equipment installed in Model 2

Unit operation					
Name	Equipment Cost [USD]	Installed Cost [USD]	Equipment Weight [LBS]	Installed Weight [LBS]	Utility Cost [USD/HR]
COOLER	311,700	544,800	90,600	139,213	344.199
B1	11,966,500	15,284,500	261,900	913,198	2,890.75
B5	703,200	1,201,400	202,400	324,977	1,255.972
LP-EVAPO	795,800	1,317,800	224,000	359,061	0
SEPARATO	1,536,700	1,997,000	662,400	747,673	0
MIX2	0	0	0	0	0
MIX3	0	0	0	0	0
GAS-T-2	0	0	0	0	0
HP-ECONO	783,100	1,684,100	229,000	328,955	0
LPTURBIN	0	0	0	0	0
P103	99,872,000	102,500,000	6,619,400	7,085,345	231.26
LP-TANK	7,551,900	12,125,000	3,681,900	4,759,902	0
H2SEPARA	226,500	48,1200	73,300	114,235	0
NG-SPLIT	0	0	0	0	0
HP-SUPER	0	0	0	0	0
MIX-2	0	0	0	0	0
STRIP-M	15,632,800	23,577,400	3,821,200	5,358,542	7,064.819
P101	47,400	725,900	3,600	144,815	2.890
HP-TANK	1,245,200	1,955,200	647,100	780,922	0
WORKMIX1	0	0	0	0	0
AIR-SPLI	0	0	0	0	0
WORKMIX2	0	0	0	0	0
AIRCOMP1	0	0	0	0	0
PREHEATE	203,400	400,900	56,600	103,092	0
B4	0	0	0	0	0
H2OSPLIT	463,000	709,700	104,700	143,500	0
HPTURBIN	0	0	0	0	0
LP-ECONO	27,600	141,500	6,300	32,143	0
COMB-1	0	0	0	0	0
AIRCOMP2	0	0	0	0	0
POWERMIX	0	0	0	0	0
COMB-2	0	0	0	0	0
MIX-1	0	0	0	0	0
B3	2,414,400	4,160,500	755,000	1,173,621	3572.923778
REACTOR	31,400	1,490,00	4,600	23,290	0
GAS-T-1	0	0	0	0	0
HOTMIX	0	0	0	0	0
SPLIT1	0	0	0	0	0
LP-SUPER	2,935,600	4,921,300	830,400	1,297,974	0
HP-EVAPO	0	0	0	0	0

Table A9: TEMA Standards for Heat Exchangers for Model 2

TEMA HEX												
User tag number	COOLER	B5	LP-EVAPO	HP-ECONO	HP-SUPER	STRIP-M-cond	PREHEATE	LP-ECONO	B3	LP-SUPER	HP-EVAPO
Remarks 1	Equipment mapped from 'COOLER'.	Equipment mapped from 'B5'.	Equipment mapped from 'LP-EVAPO'.	Equipment mapped from 'HP-ECONO'.	Equipment mapped from 'HP-SUPER'.	Equipment mapped from 'STRIP-M'.	Equipment mapped from 'PREHEATE'.	Equipment mapped from 'LP-ECONO'.	Equipment mapped from 'B3'.	Equipment mapped from 'LP-SUPER'.	Equipment mapped from 'HP-EVAPO'.
Number of identical items	1	1	1	1	1	1	1	1	1	1	1
Heat transfer area [sqm]	2077.624316	4710.671485	5147.803901	1641.879822	414.26406	24373.39231	1290.084752	112.506389	5976.68255	8214.159341	1774.295869
Front end TEMA symbol	B	B	B	B	B	B	B	B	B	B	B
Shell TEMA symbol	E	E	E	E	E	E	E	E	E	E	E
Rear end TEMA symbol	M	M	M	M	M	M	M	M	M	M	M
Tube design gauge pressure [N/sqm-gauge]	415796.08	415796.08	671046.0772	7878671.079	7563671.081	415796.08	771046.0825	621046.0815	5358671.083	7878671.079	7616171.079
Tube design temperature [C]	121.1111111	311.7777778	269.059265	413.4563667	821.0644206	121.1111111	184.3122867	274.102365	192.1111111	184.3122867	717.0988706
Tube operating temperature [C]	35	35	155.5345089	290.8955661	530	35	155.5345089	217.6	164.3333333	140	288.6133222
Tube outside diameter [meter]	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254
Shell design gauge pressure	243421.08	243421.08	413587.7494	5218671.08	5008671.078	243421.08	480254.415	380254.4166	8088671.081	5218671.08	5043671.077
Shell design temperature [C]	121.1111111	311.7777778	269.059265	413.4563667	821.0644206	121.1111111	184.3122867	274.102365	180.7777778	184.3122867	717.0988706
Shell operating temperature [C]	86.686486	284	241.2814872	385.6785889	793.2866428	65.54822611	156.5345089	246.3245872	153	156.5345089	689.3210928
Tube length extended [meter]	6.096	6.096	6.096	6.096	6.096	6.096	6.096	6.096	6.096	6.096	6.096
Tube pitch [meter]	0.03175	0.03175	0.03175	0.03175	0.03175	0.03175	0.03175	0.03175	0.03175	0.03175	0.03175
Number of tube passes	1	1	1	1	1	1	1	1	1	1	1
Number of shell passes	1	1	1	1	1	1	1	1	1	1	1

Table A10: Centrifugal Pumps installed in Model 2

Centrifugal pump			
User tag number	P103	STRIP-M-reflux pump	P101
Remarks 1	Equipment mapped from 'P103'.	Equipment mapped from 'STRIP-M'.	Equipment mapped from 'P101'.
Liquid flow rate [cum/sec]	45.616	0.950	0.594
Fluid head [meter]	5.601		6.949
Fluid specific gravity	0.911	0.737	0.734
Design gauge pressure [N/sqm-gauge]	671,046.077	103,425	7,616,171.079
Design temperature [C]	183.312	121.111	316.391
Fluid viscosity [N-sec/sqm]	0.0005	0.0005	0.0005
Pump efficiency [fraction]	0.859	0.7	0.859

Table A11: Turboexpander in Model 2

Turboexpander				
User tag number	GAS-T-2	LPTURBIN	HPTURBIN	GAS-T-1
Remarks 1	Equipment mapped from 'GAS-T-2'.	Equipment mapped from 'LPTURBIN'.	Equipment mapped from 'HPTURBIN'.	Equipment mapped from 'GAS-T-1'.
Actual gas flow rate Inlet [cum/sec]	95.642	111.416	10.494	95.642
Design gauge pressure Inlet [N/sqm-gauge]	2,998,671.078	398,671.078	7,198,671.079	2,998,671.078
Design temperature Inlet [C]	1,773.589	192.838	530	1,773.589
Design gauge pressure Outlet [N/sqm-gauge]	3,471.080	-1328.921	498,671.077	3,471.080
Power output [Watt]	554,266,138.2	63,036,537.02	125,037,551.8	554,266,138.2
Molecular weight	28.210	18.015	18.015	28.210
Specific heat ratio	1.287	1.333	1.347	1.287
Compressibility factor Inlet	1.004	0.980	0.939	1.004
Isentropic efficiency [fraction]	0.89	0.95	0.95	0.89

Table A12: Multi-diameter towers in Model 2

Multi-diameter tower	
User tag number	STRIP-M-tower
Remarks 1	Equipment mapped from 'STRIP-M'.
Diameter Bottom section [meter]	21.031
Bottom tangent to tangent height [meter]	19.507
Design gauge pressure Bottom [N/sqm-gauge]	24,3421.08
Design temperature Bottom [C]	135.9161
Operating temperature Bottom [C]	108.1383
Number of trays Bottom section	26
Bottom Tray type	SIEVE
Bottom Tray spacing [meter]	0.6096
Molecular Wt Overhead Prod.	32.038

Table A13: Vertical Vessels in Model 2

Vertical vessel				
User tag number	SEPARATO-flash vessel	LP-TANK-flash vessel	H2SEPARA	HP-TANK-flash vessel
Remarks 1	Equipment mapped from 'SEPARATO'.	Equipment mapped from 'LP-TANK'.	Equipment mapped from 'H2SEPARA'.	Equipment mapped from 'HP-TANK'.
Liquid volume [cum]	375.302	12,970.437	137.310	210.1691
Vessel diameter [meter]	11.43	13.716	6.4008	4.572
Vessel tangent to tangent height [meter]	3.657	87.782	4.2672	12.801
Design gauge pressure [N/sqm-gauge]	1,571,046.083	721,046.079	243,421.08	7,826,171.081
Design temperature [C]	121.111	183.312	121.111	318.673
Operating temperature [C]	50	155.534	45.499	290.895

Table A14: Centrifugal gas compressors installed in Model 2

Centrifugal gas compressor			
User tag number	B1	AIRCOMP1	AIRCOMP2
Remarks 1	Equipment mapped from 'B1'.	Equipment mapped from 'AIRCOMP1'.	Equipment mapped from 'AIRCOMP2'.
Actual gas flow rate Inlet [cum/sec]	18.269	400.618	400.618
Design gauge pressure Inlet [N/sqm-gauge]	4,898,671.082	71.080	71.080
Design temperature Inlet [C]	80	25	25
Design temperature Outlet [C]	49.641	617.704	617.704
Design gauge pressure Outlet [N/sqm-gauge]	7,698,671.078	2,998,671.078	2,998,671.078
Driver power [Watt]	79,446,451.51	275,242,023.8	275,242,023.8
Molecular weight	28.210	28.850	28.850
Specific heat ratio	1.442	1.3999	1.3999
Compressibility factor Inlet	0.899	0.999	0.9995
Compressibility factor Outlet	0.935	1.0078	1.0078
Driver type	MOTOR	MOTOR	MOTOR

Table A15: U-tube reboiler installed in Model 2

U-tube reboiler	
User tag number	STRIP-M-reb
Remarks 1	Equipment mapped from 'STRIP-M'.
Number of identical items	1
Heat transfer area [sqm]	32,117.542
Tube design gauge pressure [N/sqm-gauge]	243,421.08
Tube design temperature [C]	152.777
Tube operating temperature [C]	125
Tube outside diameter [meter]	0.0254
Shell design gauge pressure [N/sqm-gauge]	24,3421.08
Shell design temperature [C]	135.916
Shell operating temperature [C]	108.13837
Tube length extended [meter]	6.096
Tube pitch [meter]	0.03175
Tube pitch symbol	TRIANGULAR
Number of tube passes	2
Duty [kW]	774,540.198
TEMA type	BKU

Table A16: Packed SD Tower in Model 2

Packed SD tower	
User tag number	REACTOR
Remarks 1	Equipment mapped from 'REACTOR'.
Vessel diameter [meter]	1.066
Vessel tangent to tangent height [meter]	2.133
Design gauge pressure [N/sqm-gauge]	243,421.08
Design temperature [C]	311.777
Operating temperature [C]	284
Total packing height [meter]	1.828
Molecular weight Overhead prod	24.353

Appendix B: System Advisory Model (SAM) Modeling Snapshot

Table B1: Solar Resource Library

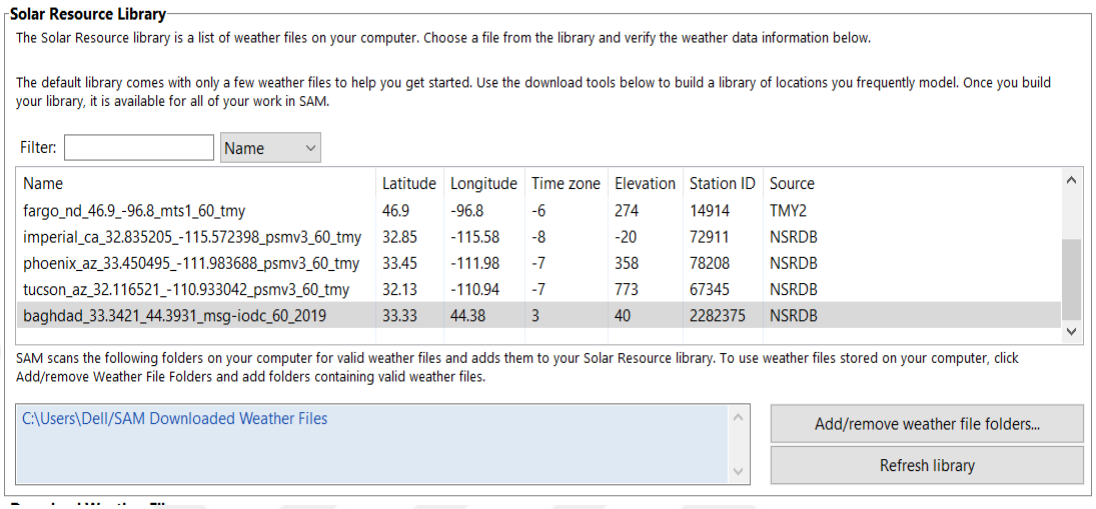


Table B2: Weather Data Information

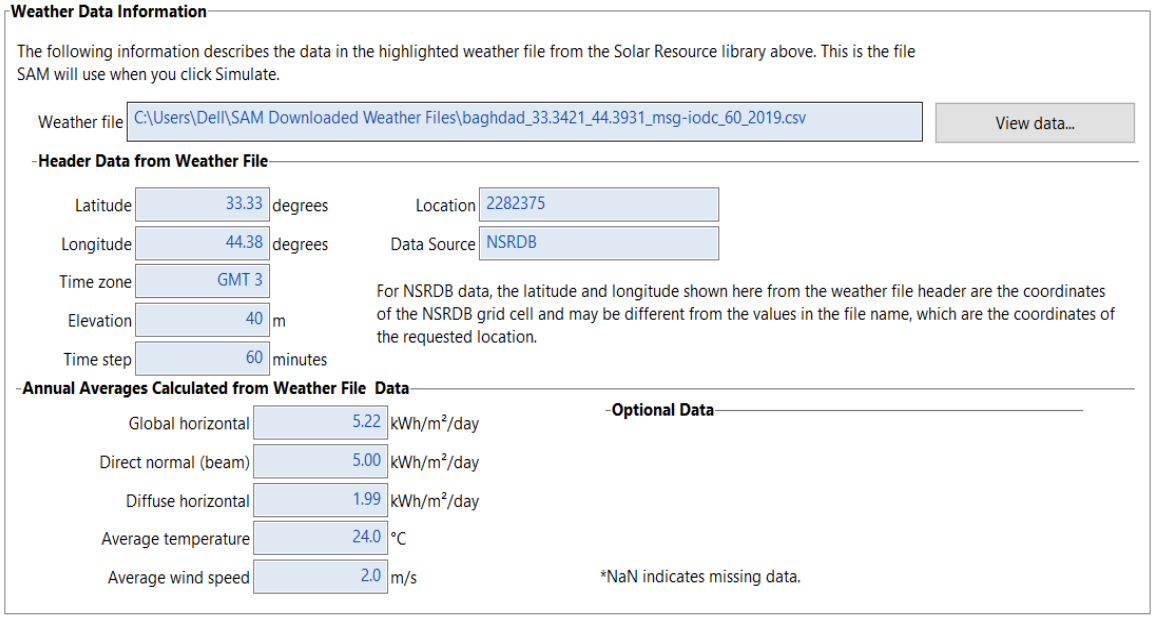


Table B3: System Design

Design Point Parameters

Solar Field

Design point DNI	900	W/m²
Target solar multiple	1.8	
Target receiver thermal power	630.00	MWt
Loop inlet HTF temperature	140	°C
Loop outlet HTF temperature	260	°C

Heat Sink

Heat sink power	350.00	MWt
Pumping power for HTF through heat sink	0.55	kW/kg/s
Model piping through heat sink?	☐	
Length of piping through heat sink	50.0	m

Choose Number of Loops

Thermal Energy Storage

Hours of storage at design point	6	hours

System Summary

Actual number of loops	259		Actual solar multiple	1.80	
Total aperture reflective area	1,010,100.0	m²	Actual field thermal output	631.63	MWt

Table B4: Solar Field Design Point

Solar Field Design Point

Single loop aperture	3,900	m²	Actual number of loops	259	
Loop optical efficiency	0.722		Total aperture reflective area	1,010,100	m²
Total loop conversion efficiency	0.695		Actual solar multiple	1.80	
Total required aperture, SM=1	559,716	m²	Actual field thermal output	631.63	MWt
Required number of loops, SM=1	144		Loop inlet HTF temperature	140	°C
Total tracking power	194,250	W	Loop outlet HTF temperature	260	°C

Table B5: Solar Field Parameters

Solar Field Parameters

Row spacing	15	m
Header pipe roughness	4.57e-05	m
HTF pump efficiency	0.85	
Piping thermal loss coefficient	0.45	W/m²-K
Wind stow speed	25	m/s
Receiver startup delay time	0.2	hr
Receiver startup delay energy fraction	0.25	-
Collector startup energy	0.021	kWhe/sca
Tracking power per SCA	125	W/sca
Number of field subsections	1	
Allow partial defocusing	Simultaneous ☑	

Heat Transfer Fluid

Field HTF fluid	User-defined...		Edit...
Field HTF min operating temp	20	°C	
Field HTF max operating temp	360	°C	
Freeze protection temp	10	°C	
Min single loop flow rate	1	kg/s	
Max single loop flow rate	12	kg/s	
Min field flow velocity	0.2	m/s	
Max field flow velocity	3.4	m/s	

	Cold Headers		Hot Headers	
Header design min flow velocity	2	m/s	2	m/s
Header design max flow velocity	3	m/s	3	m/s

Table B6: Collector Orientation, Mirror Washing and Land Area

Collector Orientation

Collector tilt	0 deg	Tilt: horizontal=0, vertical=90	Stow angle	170 deg	
Collector azimuth	0 deg	Azimuth: equator=0, west=90	Deploy angle	10 deg	

Mirror Washing

Water usage per wash	0.7	L/m²,aper.
Washes per year	12	

Plant Heat Capacity

Hot piping thermal inertia	0.2	kWht/K-MWt
Cold piping thermal inertia	0.2	kWht/K-MWt
Field loop piping thermal inertia	4.5	Wht/K-m

Land Area

Solar field area	624 acres	Non-solar field land area multiplier	1.1	Total land area	686 acres

Table B7: Single Loop Configuration

Single Loop Configuration

The specification below is only for one loop in the solar field.

Usage tip: To configure the loop, choose whether to edit SCAs, HCEs or defocus order. Select assemblies by clicking one or dragging the mouse over multiple items. Assign types to selected items by pressing keys 1-4.

Number of SCA/HCE assemblies per loop: 6 (●) Edit SCAs ( ) Edit HCEs ( ) Edit Defocus Order [Reset Defocus]

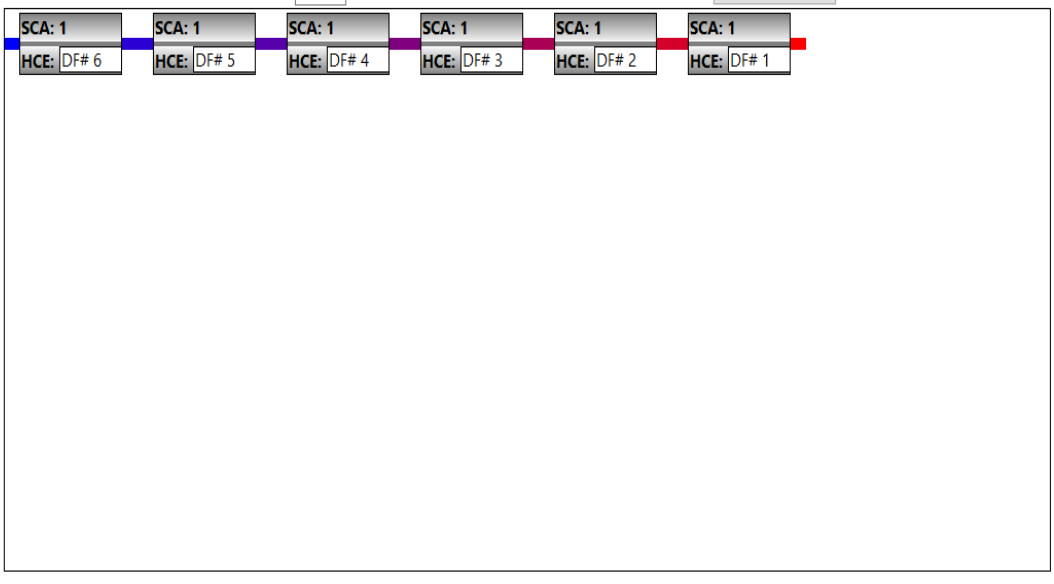


Table B8: Collector Information

Collector Library

Filter: Name

Name	Reflective aperture area	Aperture width total structure	Length of collector assembly	Num
Solargenix SGX-1	470.3	5	100	12
AlbiasaTrough AT150	817.5	5.774	150	12
Siemens SunField 6	545	5.776	95.2	8
SkyFuel SkyTrough (with 80-mm OD receiver)	656	6	115	8

Collector types in loop configuration: Cold - 1 - 1 - 1 - 1 - 1 - 1 - Hot

Collector Type 1

Collector name from library: SkyFuel SkyTrough (with 80-mm OD receiver) — Apply Values from Library

Collector Geometry

Reflective aperture area	650	m²	Number of modules per assembly	8	
Aperture width, total structure	6	m	Average surface-to-focus path length	2.15	m
Length of collector assembly	115	m	Piping distance between assemblies	1	m

Optical Parameters

Incidence angle modifier coefficients	Edit array...		Geometry effects	0.952	
Tracking error	0.988		Mirror reflectance	0.93	
General optical error	1		Dirt on mirror	0.97	

Optical Calculations

Length of single module	14.375	m	End loss at summer solstice	1.000	
IAM at summer solstice	1.002		Optical efficiency at design	0.848	

Table B9: Thermal Storage

System Design Parameters

Heat sink power	350.0	MWt	Loop outlet HTF temperature	260.0	°C
Hours of storage at design point	6.0	hours	Loop inlet HTF temperature	140.0	°C

Storage System

TES thermal capacity	2,100.0	MWt-hr	Initial hot HTF percent	30	%
Available HTF volume	16,221	m³	Cold tank heater temperature set point	60	°C
Tank height	15	m	Cold tank heater capacity	0.5	MWe
Tank fluid minimum height	0.5	m	Hot tank heater temperature set point	110	°C
Storage tank volume	16780	m³	Hot tank heater capacity	1	MWe
Parallel tank pairs	1		Tank heater efficiency	0.99	
Tank diameter	37.7	m	HTF density	865	kg/m³
Wetted loss coefficient	0.3	Wt/m²-K	Field HTF can bypass TES to cycle	☑	
Estimated heat loss	0.32	MWt			

Table B10: System Control Parameters

Plant Energy Consumption

Fraction of rated gross power consumed all times: 0.0055 MWe/MWtcap

			Factor	Coeff 0	Coeff 1	Coeff 2		
Balance of plant parasitic	0	MWe/MWtcap	1	0	0.483	0	BOP	0 MWe
Aux heater boiler parasitic	0.023	MWe/MWtcap	1	0.483	0.571	0	Aux	8.485 MWe

System Availability

System availability losses reduce the system output to represent system outages or other events.

Edit losses... Constant loss: 4.0 %
Time series losses not enabled
Custom periods not enabled

Dispatch Optimization

Enable dispatch optimization	☐	Objective function time weighting exponent	0.99
Time horizon for dispatch optimization	48 hour	Maximum branch and bound iterations	35000
Frequency for dispatch reoptimization	24 hour	Solution optimality gap tolerance	0.001
Cycle startup cost penalty	87 $/MWe-cycle/start	Optimization solver timeout limit	5 sec
Receiver startup cost penalty	952 $/MWt-rec/start	Max. net heat leaving plant	1e+38 MWt
Heat generation ramping penalty	1 $/ΔMWt	Max. net heat leaving plant (incl. availability)	9.6e+37 MWt

Dispatch Control

☐ Use output fraction as maximum

Heat sink output fraction

Period 1:	1
Period 2:	1
Period 3:	1
Period 4:	1
Period 5:	1
Period 6:	1
Period 7:	1
Period 8:	1
Period 9:	1

The heat sink output fraction scales the heat sink input relative to design for the corresponding time-of-delivery period.

Use the schedule matrices to specify the month and hour of day for each of the nine periods.

Weekday Schedule

	12am	1am	2am	3am	4am	5am	6am	7am	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm	8pm	9pm	10pm	11pm
Jan	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Feb	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Mar	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Apr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
May	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Jun	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Jul	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Aug	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Sep	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Oct	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Nov	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Dec	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Weekend Schedule

	12am	1am	2am	3am	4am	5am	6am	7am	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm	8pm	9pm	10pm	11pm
Jan	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Feb	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Mar	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Apr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
May	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Jun	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Jul	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Aug	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Sep	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Oct	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Nov	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Dec	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1