QATAR UNIVERSITY

COLLEGE OF ENGINEERING

THERMODYNAMIC & THERMOECNOMIC OPTIMIZATION ANALYSIS OF NOVEL DIRECT OXY-COMBUSTION SUPERCRITICAL CO2 POWER CYCLES INTEGRATED WITH DRY AND WET PRECOOLER USING GENETIC ALGORITHM

BY

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ABSTRACT

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Title: Thermodynamic and Thermoeconomic Optimization Analysis of Novel Direct Oxy-Combustion Supercritical CO2 Power Cycles Integrated with Dry and Wet Precooler Using Genetic Algorithm

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As part of worldwide efforts to reduce the negative effects of global warming through the carbon neutrality plan by 2050 and implementation of the sustainability strategy set by Qatar National Vision 2030, three novel direct oxy combusted sCO2 power cycles are investigated. This thesis is intended to perform thermodynamic and thermoeconomic optimization analysis for the three cycles integrated with wet and dry precoolers. The first cycle (M1) is the basic sCO2 power cycle which consists of Gas turbine (GT), oxygen compressor (OC), fuel compressor (FC), gas compressor (GC), high-temperature recuperators (HTR), low-temperature recuperators (LTR), oxy-combustor, water separator (WS) and air separation unit (ASU). The second cycle (M2) and third cycle (M3) have similar components to M1 but with an additional preheater which is integrated in parallel with LTR for M2 and in parallel with LTR and HTR for M3. Each cycle configuration is studied in two conditions: a wet cooling condition where the exhaust fluid is cooled by wet pre-cooler (water) and a dry cooling condition where the working fluid is cooled by dry pre-cooler (Air) resulting in six different configurations. Using Engineering Equation Solver (EES) software, all of these configurations are thermodynamically modeled and optimized. Two optimization techniques: single and multi-objectives are performed in this study using a genetic algorithm (GA). These analyses are conducted to identify the most feasible

configurations and compare their performance from the energy, exergy, and economic perspective in their optimal conditions. In wet-cooling condition, the single objective optimization results showed that M3 cycle configuration has a promising potential as it has the highest optimal thermal efficiency compared with M2 (by 7.6%) and M1 (by 8 %) and the lowest levelized cost of energy (LCOE) relatively with M2 (by 3.8%) and M1 (by 4.3%). However, M1 obtained the highest optimal exergy efficiency by prevailing in minor differences compared to other configurations. On the other hand, in dry-cooling conditions, M3 has the highest thermal efficiency, the highest exergy efficiency with a minimal difference, and the lowest levelized cost of energy (LCOE). The reason lies in preheater integration which improves the cycle's thermal efficiency and minimizes LCOE by enhancing the functionality of the combustor and reduce the fuel consumption. It also increases the exergy destruction which affects the exergy efficiency negatively. In multi-objectives optimization where both the thermal efficiency and the exergy efficiency are maximized and LCOE is minimized simultaneously using weighting factors, M3 is considered as an optimal cycle configuration in both wet and dry cooling conditions. Based on these outcomes, the decision-maker is given a framework to choose the best optimal configuration that meets their energy and economic goals considering cooling conditions. In addition, sensitivity analysis is performed on the weighted factors of the multi-objective optimization to study the influence of varying weights on the objective functions and obtain the desired optimal configuration based on the decision-maker preference.

DEDICATION

Dedicated to my family, friends, and university instructors.

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CHAPTER 1: INTRODUCTION

The power generation industry is mostly reliant on thermal power plants, which account for more than 80% of global electricity output. Thermal power plants operate on a thermodynamic cycle, in which thermal energy from a heat source is transferred to mechanical energy. Fossil fuels currently account for over 85.2 percent of heat sources in thermal power plants around the world (Mohr et al., 2015). Burning fossil fuels results in carbon dioxide emissions and many other pollutants. Therefore, the power generation industry will inevitably shift to more sustainable and friendly heat sources. Thus, many researchers started to look for alternatives that satisfy the electricity demands and minimizing the CO2 emissions. Some of these approaches are to improve the current fossil fuel power plant performance by maximizing energy efficiency. Although this approach will decrease the percentage of CO2 in the air, it can't keep them steady as the combustion pollutants are still emitted into the environment. Second proposed approach is to integrate renewable energy sources with power cycles. Solar thermal energy, nuclear energy, and geothermal energy are among the heat sources that are thought to be the most promising possibilities in this area. In addition, waste heat streams can be used to recover a significant quantity of energy. Waste thermal streams dissipated from gas turbines, energy-intensive industries, and heavy-duty transportation devices are among the various sources of waste thermal streams. It is worth noting that in some parts of the United States, waste heat recovery (WHR) is actually regarded as an equivalent form of renewable energy use because the excess recovered heat produces no additional environmental emissions. However, this technology has a high energy storage cost, and the difficulty of controlling power packing makes it only accounts for less than 5% of overall power generation (excluding the hydropower industry). The third and best technology is creating novel power cycles like direct oxy-fuel combustion closed cycles. they include the benefits of the aforementioned technologies and solve their drawbacks as they have high energy efficiency and almost zero emissions. As a result, appropriate efforts must be taken to adapt or invent highly efficient yet economic power cycles that use unusual operating fluids. Over fifty pure working fluids and numerous multi-component organic and inorganic fluids have been proposed in the open literature to be used in various configurations of power cycles to address the aforementioned quest (Chen, Goswami, and Stefanakos, 2010; Wang, Zhao and Wang, 2010). The working fluid used has a significant impact on a power plant's economic viability and social acceptance. Environmental factors, safety problems, availability, and cost should all be considered while assessing the working fluid. Furthermore, the thermo-physical parameters of the working fluid, such as critical pressure, critical temperature, density, specific heat, viscosity, latent heat, and fluid stability, have a substantial impact on the efficiency and operating conditions of a thermodynamic power cycle. These features have an impact on the size and cost of power plant components, as well as the thermal performance of power cycles. H. Chen et al., (2010) tested 35 organic working fluids in subcritical and supercritical Rankine cycles in a large study. They do, however, suggest that among organic fluids, there are just a few that are relatively safe, affordable, and environmentally friendly. Although some organic Rankine cycles (ORC) may have reasonable efficiency, the organic fluids connected with them are primarily safe and beneficial for low-grade heat sources.

The direct oxy-combustion Brayton cycles using supercritical carbon dioxide (sCO2) have been proposed as one of the most promising options, given high efficiency for temperature range form (550 to 750 K) and also the techno-economic advantages of the Brayton cycle over the steam Rankine cycle. Supercritical carbon dioxide (sCO2) is safe for the environment, non-toxic, non-flammable, abundant, and cheap. Because its thermal dissociation temperature is above 2000 K, it is a fairly stable molecule. Furthermore, the thermophysical properties of sCO2 have been extensively explored, and they are readily available through academic and commercial databases. The critical pressure of carbon dioxide is 7.39 MPa, and the critical temperature is 304.2 K, which is extremely near to the typical ambient temperature (298.15 K). Supercritical carbon dioxide (sCO2) has the density of a liquid yet expands like a gas to fill a space. The sCO2 Brayton cycles exhibit outstanding performance and efficiency due to sudden changes in the thermodynamic characteristics of carbon dioxide at its critical point. The pressure drop in heat exchangers has little impact on cycle efficiency when operating at high pressures (e.g. heaters, recuperators, and coolers). Furthermore, supercritical carbon dioxide has a very large volumetric heat capacity and excellent heat transmission characteristics, allowing for small-scale recuperators. The sCO2 Brayton cycles are compact, resulting in minimal capital costs and a short building time. The sCO2 Brayton cycles, unlike the steam Rankine cycles, do not require clean water, which is one of the most important challenges in the power production industry. These cycles are the focus of our study because of their high cycle efficiency, compactness, excellent economics, and lack of water concerns.

1.1 Motivation.

Two variables dominate the future of the power generation industry: energy sustainability and economics. Energy will be humanity's first challenge in the next 50 years, according to Nobel Laureate Prof. Richard E. Smalley (2003), Four key concerns drive today's energy subject from the standpoint of sustainability:

The rising growth of energy demand is the primary source of concern. The present worldwide demand for energy now amounts to around 12.4 billion tons of oil equivalent (Btoe), according to British Petroleum's Energy Outlook (2013), and it is predicted to expand at a rate of 1.6 percent per year until 2030 when it will reach 16.5 (Btoe). This trend is even more pronounced for worldwide power demand, which is increasing at a 2.6 percent annual rate from 22.5 PWh in 2012 to 36 PWh in 2030, a 60 percent rise in 18 years. The second point of concern is the environment. Fossil fuels are used to meet more than 80% of global energy consumption and 67 percent of global electricity generation (Statistics, I.E.A., 2014). The largest source of greenhouse gas emissions, mostly CO2, is the combustion of fossil fuels, which has long been thought to be a major contribution to the global warming problem. According to the National Oceanic and Atmospheric Administration report of CO2 levels In May 2013, the average daily concentration of CO2 in the atmosphere topped 400 parts per million (ppm), the highest level in at least 800,000 years (US Department of Commerce, NOAA, 2021). The third point to consider is that fossil fuel reserves are limited and will eventually deplete. Indeed, fossil fuels like oil and gas are used as input feed for a variety of material and manufacturing industries, making them extremely precious and irreplaceable commodities. Finally, due to the geographically uneven distribution of fossil fuel resources, the fourth problem is related to energy security and international conflicts.

Furthermore, economic factors have a greater impact on the power generation business than environmental sustainability. In the highly competitive electricity market, the power production industry has always been driven to seek out breakthrough technologies that can give the maximum energy conversion efficiency at the lowest feasible cost. To underscore the importance of this issue, consider that a one-percentage-point increase in the overall efficiency of national power generation would result in a net annual income increase of $7.9 billion dollars. Furthermore, increasing the efficiency of electricity generation will significantly lessen the negative effects of pollution on the environment. It is also worth noting that any decrease in the capital or operating costs of power plants would result in a large rise in net profit.

In conclusion, both energy sustainability and economic concerns are critical for the power production industry's future. The next generation of power plants should be less reliant on fossil fuel supplies in terms of sustainability. Economic incentives, in addition to energy sustainability concerns, push the power generation industry to seek out less expensive, yet efficient energy conversion technology. In line with the aforementioned motives, the supercritical carbon dioxide (SCO2) Brayton cycles have a lot of potential in terms of size, efficiency, economics, and proper integration with a variety of sustainable heat sources. In consequence, the thermodynamic performance of these cycles is the subject of this research.

1.2 Thesis Objectives and Contributions.

This thesis performs optimization analysis on a novel technology that replace the existing fossil fuel power plants with sCO2 power plants. This technology produces electricity that can match grid demand, reuse 94% of the produced CO2 emissions in the combustion process and produce 2.75% clean water in compact footprint. Through performing single and multi-objective optimization, the decision maker is given a framework to select the optimal configuration that best match his energy and economic goals by investigating six cycle configurations integrated with wet and dry pre-cooler and presented in comparative study. In addition, the influence of the weights on the multi-objectives optimization are analyzed to offer the decision maker with the optimal configuration when he would like to consider the three objectives but has different preferences. According to the literature review, this study contributes to fill the following research gabs:

Table 1: Research Gaps vs Thesis Contributions

Research Gabs	Thesis contributions
Most of the optimization studies were dedicated for integrating this technology with renewable energy sources which contribute by less than 5 % to the overall power production in Qatar	This study will investigate three novel direct oxy combusted sCO2 power cycles perform a thermodynamic and economic optimization analysis in wet and dry cooling conditions
There is a lack of studies that consider the Levelized cost of electricity(LCOE) as an objective function in their optimization study.	This study consider optimization of LCOE based on current and reasonably estimated costs of the cycle components
Few studies performed both single and multiple objectives optimizations for thermodynamic and exergoeconomic objective function.	This study will perform two types of optimizations for the suggested configurations to get more insight into the optimized performance

The key objectives of the research study can be summarized as the following:

- Optimize novel power cycles and provide a reliable technological solution to the increasing power demand.
- Offer the decision-maker with a framework to choose the best optimal configuration that meets their energy and economic goals considering cooling conditions.
- Perform sensitivity analysis to study the influence of the weights on the weighted multi-objective function to obtain the desired optimal configuration based on the decision-maker preference.
- Investigate the influence of the cooling conditions and the cycle configurations on the performance indicator of the cycles in their optimal condition.

1.3 Dissertation organization

The layout of the thesis consists of five chapters including the current introductory one and it is organized as follows:

Chapter 2 consists of three subsections that provide a background description and literature review of supercritical CO2 power cycles with a focus on optimization-related literature, based on the papers gathered from the existing body of knowledge.

Chapter 3 describes the methodology followed in performing the thermodynamic modeling, the optimization analysis, and the validation of developed models.

Chapter 4 provides a detailed description of the three proposed cycles, demonstrates the thermodynamic and thermoeconmic optimization, analysis the single and multi-objective optimization result in both wet and dry cooling conditions, and present the sensitivity analysis for weighted multi-objective optimization.

Finally, **Chapter 5** highlights the key conclusion remarks as well as the future research directions.

CHAPTER 2: BACKGROUND AND LITERATURE REVIEW

This chapter provides a comprehensive and contextualized review of supercritical CO2 power cycles with a focus on optimization-related literature. Section 2.1 begins with an overview of the history of supercritical and how they evolved. Section 2.2 highlights the benefits of supercritical CO2 power cycles from different perspectives to illustrate why such a system is worthy of investigation. Section 2.3 includes a focused review on all optimization-related efforts in the area of supercritical CO2 power cycles optimization. The chapter concludes with a summary that points out the importance of the dissertation at hand and how it fills the research gaps within the current body of knowledge.

2.1 History of Supercritical CO_2 Cycle.

In recent years scholars and industry experts alike have vigorously embraced the use of supercritical CO2 in various technologies. Although the supercritical phenomenon of fluids was observed in the early 1800s by the French engineer and physicist Baron Charles Cagnirad de la Tour, the importance and practical applications of the discovery were only truly achieved in the last twenty to thirty years (Phelps et al., 1996). The following section presents the incremental developments of supercritical CO2 power cycles since their inception until the current times.

Interest in examining CO2 gas in power cycles began with Thomas Andrews and James Thomson’s in Belfast during the 1860s. For many reasons, much of their work was not published at that time. However, several of their notations and texts have survived and made their way to our time which proves to be of valuable contributions and initial predictors on the subject of CO2 gas liquefication using high levels of pressure and temperature. James had a peculiar interest in the transitional state of matter between solids, liquids, and gases. He played a major role in influencing Thomas Andrew's experimental efforts, professor of chemistry at the time. Andrews presented his first results in September 1861 at the Annual Meeting of the British Association in Manchester. He described an unknown phenomenon where with appropriate pressure and heat, carbonic acid would become indistinguishable between its liquid and gas state. It is what we call now, 'critical point of matter' (Rowlinson, 2003).

Around the mid-20th century, power generation systems were run vastly by the use of open power cycles such as Brayton and Rankine cycles which consume great amounts of water or air. To address this inefficiency, researchers have started looking for other alternatives, and CO2 as a working fluid in closed-loop cycles was gaining recognizable acceptance. Its potential key benefit relied on its characteristic of high thermal efficiency as it could be heated to high temperatures ranging between 350C and 800C. As well as its promising environment-friendly compact physical footprint and flexibility of operation. It is worth noting that most of the published literature at the time attribute the novelty of commercial use of closed-loop sCO2 cycles to a Swiss patent granted to Sulzer Ltd in 1950 (White, et al., 2021).

During the 1960's, Feher (1968) research on thermodynamic cycles concluded with the advocation for the use of CO2 as a working fluid in a supercritical state. He mentions that although the Rankine and Brayton cycles are inherently efficient, they still face considerable limitations. Some of these are the sensitivity to pressure drop, the need for high levels of heat and energy, and the large scale of turbines within which these cycles operate. Consequently, the researcher examined several working fluids, out of which, CO2 was chosen to be optimal for several reasons. It possesses comparatively low critical pressure, its stability throughout a range of temperatures, and the fact that it is abundant, non-toxic, and relatively cheap. Additionally, Angelino

(1969) examined various layouts and configurations of sCO2 cycles in comparison with traditional steam cycles. The researcher identified irreversibility in the cycles due to the change of temperatures between hot and cold fluids and concluded that CO2 cycles are promising in tackling these issues.

During the 1970s, the most recognized work belongs to Vaclav Dostal. His research on the application of sCO2 cycles on nuclear reactors earned him a doctoral of science from the Massachusetts Institute of Technology in 2004. The researcher optimized multiple supercritical cycle parameters and considered intercooling, reheating, recompressing, and recompressing. He concluded that the recompression cycle yielded the highest efficiency while still retaining operation simplicity (Dostal et al., 2004). Since Dostal’s work, there have been a great many studies spanning from the 1980’ up until the present day, examining diverse configurations and cycle architecture for different applications and industries. This is evidenced by the number of academic documents produced as well as patents granted in China, the United States, South Korea and other countries shown in Figure 1 (M. T. White et al., 2021). The most notable and referenced book was edited by (Brun et al., 2017) which has comprehensively summarized the use and applications of sCO2 power generation technologies.

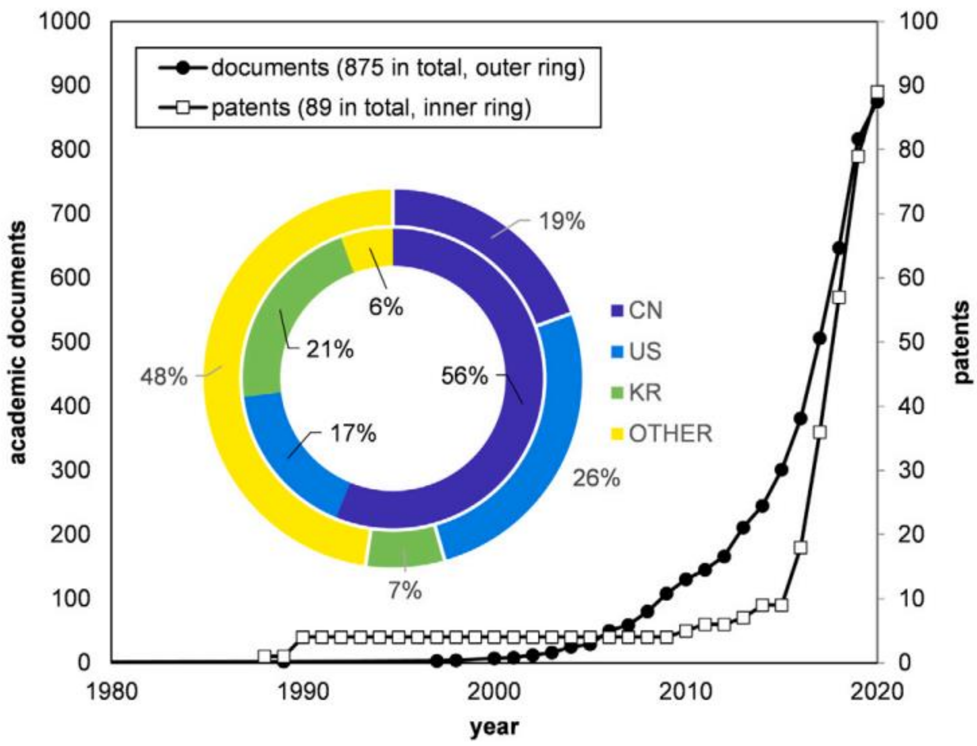


Figure 1. Evolution in the development of the sCO2 cycle (M. T. White et al., 2021).

In the modern present, countless papers have been produced on the supercritical CO2 cycle. Researchers have sought to apply the technology to various industries while assembling many configurations and layouts in order to optimize, increase efficiency and cut costs. To mention a few, Yuegeng Ma *et al.*, (2018) proposed a novel recompression sCO2 Brayton integrated with an absorption chiller (RSBC/AC) to be used for concentrated solar power (CSP) plants. Parametric, energy, and exergy analyses were performed, and the results showed that RSBC/AC had higher optimized thermal and exergy efficiencies than a standard sCO2 cycle. Additionally, Hou *et al.*, (2018) conducted exergoeconomic and parametric analysis to examine the efficacy of a proposed novel combined sCO2 regenerative cycles with organic Rankine cycle using the zeotropic mixture to be applied for waste heat recovery in gas turbines. The results showed the superiority and advantages of wasted heat utilization, higher efficiency, and lower cost for the proposed cycle compared with the combined sCO2 and ORC cycle. Finally, Liu *et al.*, (2019) performed a quantitative measurement analysis on a coal-fired power plant integrated with a recompression sCO2 power cycle. The results showed increased numerical efficiencies and optimization in the power plant performance in the cold and hot ends. Table 2 illustrate the historical evaluation of sCO2 power cycles.

Table 2. Historical Evaluations of sCO2 Power Cycles

Year	Key Related Events
19th century	For wide pressure ranges, Andrews and Thomson performed the validation test for Boyle's law to investigate the real gas effects of $CO_{2.}$ The work of Thomas Andrews was based on the study of continuity of the two different phases of the fluid along with the liquefaction and peculiar behavior of the gases (Rowlinson, 2003).
Mid-20th century	CO_2 gas is accepted for use as a working fluid in power generating cycles. This era was focused on the determination of new alternative fluids in closed-loop cycles to eliminate the limitations of Rankine and Brayton cycles (White, et al., 2021). The published literature in the mid-20th century was also focused on the condensation cycle comprised of the closed-loop power cycle of CO2. The idea was also patented on the name of Sulzer Ltd in 1950.
1960s	Carbon dioxide is a useful fluid for the pre-compression transcritical cycle; Feher research on thermodynamic supercritical cycle to evaluate the criticality of the operating parameters (Feher, 1968). Identification of irreversibility in the cycle due to inconsistency between heat capacities of cold fluids and hot fluids; Angelino investigated various layouts of supercritical and transcritical cycles to reduce irreversibility (Angelino, 1969).
1970s	Dostal proposed a sCO2 cycle for the applications in the nuclear power industry. Similar to the work of Angelino, the work of Dostal was focused on the range of cycles consisting of precompression, recompression, intercooling, and reheating. It was concluded that the thermal efficiency of the recompression cycle is the highest amongst all whereas the arrangement of the cycle is simplest (Dostal, 2004).
1980 – 2020	Since Dostal's work, researchers performed numerous investigative studies on the arrangement and applications of the cycles. Figure 1 demonstrates the progression of research in the period 1980-2000 (White, et al., 2021).

Year	Key Related Events
2000s	The number of patents regarding sCO2 increased significantly. South Korea, China, and USA are worth mentioning countries regarding sCO2 power technology (White, et al., 2021). It is worth mentioning that most of the research and development has been carried out for the application of sCO2 in power generation technology. US Department of Energy also published books on the aforementioned area of studies (Doğan, 2018).
2016	The book written by Brun and Dennis is a thorough guide regarding sCO2 power technology. The book is based on the comprehensive summary of power activities of sCO2 (Brun, et al., 2016).
2018	(Yuegeng Ma et al., 2018) proposed the sCO2 cycle model for concentrated solar power generation. (Hou et al., 2018) performed analytical analysis of the sCO2 cycle to model the CO_2-based mixtures in the cycle.
2019	(Liu et al., 2019) investigated the sCO2 technology with thermodynamic optimization and modeling with a detailed insight of the cycle components.

To summarize, supercritical CO2 cycle technology has witnessed massive developments since its inception in the 19th century and it is still rapidly improving to the current day. Numerous researchers have dedicated much of their interest to this technology by proposing many novel configurations and cycle combinations. This only suggests that the technology is promising and will lead to better practices in the power generation sector.

2.2 Benefits and Applications of Supercritical CO_2 Cycle

Since its emergence into worldwide research and industrial use, supercritical CO2 has gained incredible admiration both in the academic and practical sectors. This popularity is attributed to its various beneficial characteristics and low environmental footprint especially in the current times where we witness significant climate changes and face predicted realties of major harmful impacts to our mother earth because of damaging humankind commercial practices. Supercritical CO2 is non-toxic and non-flammable, so it is safe. As well as it is environmentally friendly as it can be literally captured from the air because it is abundant. Additional characteristics and applications will be discussed in the following paragraphs.

Supercritical CO2 can be used as a solvent. It is popularly used in green coffee decaffeination processes where sCO2 is pressured through the coffee beans which are then separated by spraying high pressurized water. The caffeine is then separated by the use of distillation, reverse osmosis, and other methods, and it can be commercially used by pharmaceuticals and beverage makers. Another popular application is its use as an extraction solvent. It is heavily used in dry cleaning and in the herbal supplement industry to remove organochloride pesticides as well as in creating essential oils in herbal distilleries. Stewart (2003) Estimates that as of 2003, over 100,000 kg of clothing materials have been processed with liquid carbon dioxide producing satisfactory results for both customers and business owners. It is non-toxic, non-flammable, and operates at a comparatively lower temperature which makes it advantageous over hexane or acetone steam distillation methods. Supercritical CO2 can also be used as a chemical reagent in the making of cheaper substitutes for thermoplastics or ceramic as it substantially increases strength by reacting with alkaline particles of gypsum and fully cured cement (Urbonas et al., 2016). Moreover, due to its ability to expand under heat and dissolve organic matter to propel enzymes functionality, it is used in the foaming of polymers, and it has been suggested to be used to support biological activity on outer space planets respectively.

In the power generation arena, numerous research efforts have been employed to investigate the efficacy and efficiency of sCO2 cycles (Persichilli *et al.*, 2012; Iverson *et al.*, 2013; Koytsoumpa, Bergins, and Kakaras, 2018; Crespi *et al.*, 2017). Due to its afro-mentioned characteristics and its chemical stability, it can be employed commercially as well as domestically, as a working fluid in heat removing pumps and water heating pumps. Traditionally, heat pumps function to remove heat in the space in which they are located, while sCO2 heat pumps are essentially stationed outdoors to remove heat from the outside atmosphere. Research illustrates that upgrading conventional air Brayton and steam Rankine-based cycles with sCO2 can pose increased economic and environmental improvements. Due to its flexibility, high fluid density, and superior thermal efficiency, it is compatible to be used with various energy sources as well as, it can be used in electricity-generating turbines. General Electric launched a sCO2 based turbine that converts heat energy to electrical energy. In comparison to traditional steam turbines, it proved to be 50% more efficient while only being 10% of the size (Talbot, 2016). Similarly, generation electricity in nuclear plants through the use of sCO2 could raise the units of electricity produced up to 45 percent due to the significant thermal efficiency of heated supercritical carbon dioxide (Dostal et al., 2004). Additionally, coal-dependent technologies can benefit from the use of gasifiers instead of classic furnaces by employing sCO2 to be injected in oil fields for higher yields. This can enable improved carbon sequestration and reduce environmental harm. However, one noticeable issue in the use of this promising technology is that the materials used are prone to be damaged by high temperatures, oxidation, creep, corrosion, and erosion (Parks, 2013). Therefore, further research and material evaluations have to be considered to tackle these issues.

Another use of CO2 supercritical drying is its application in the production of aerogels. While silica-based aerogels are the most common type, they can also be produced using carbon or metals. Supercritical CO2 assist in the processing of aerogels by exposing silica or carbon or aluminum to liquid carbon dioxide. After that, the liquid is heated and pressurized till it goes supercritical which allows the replacement of liquid by gas, creating nanometer-sized pores (*Aerogel.Org » Supercritical Drying*, 2004). Last but not least, supercritical CO2 is beneficial for use in the sterilization of medical equipment by combining it with the additive peracetic acid, as well as it is used in cleaning processes. Due to its non-destructive, non-abrasive, and residue-free nature, its applications have expanded to include cleaning various parts and machinery in the automotive, aerospace, medical and electronics industries among many others (A. White et al., 2006).

2.3 Optimization of Supercritical CO_2Cycles Integrated with Energy Sources

The supercritical carbon dioxide (sCO2) power cycle is an advanced technology that attracts the attention of many researchers. Providing high cycle efficiency with small equipment size and low emission are some of the advantages gained from utilizing sCO2 as a working fluid. To maximize these benefits, continuous researches have been conducted to optimize the sCO2 power cycle. The three figures below show the number of published papers on “Supercritical CO2 Brayton Cycle Optimization” according to the published year as shown in Figure 2, the country as shown in Figure 3, and subject area as shown in Figure 4. Figure 2 shows clearly the increase of publications starting from 2016 which means that optimizing sCO2 power cycles has captured the researchers’ attention in recent years and has reached its peak in 2020. Globally, China and America are at the forefront of countries interested in developing this technology, while regionally, Saudi Arabia ranks first in publishing research papers as shown in Figure 3. Also, according to Figure 3, Qatar shows a low rate of publications which proves the novelty of this technology and the urgent need to do a lot of research focuses on developing it based on the environment and the available resources especially that oil and natural gas are the cornerstones of Qatar's economy and account for more than 70% of overall government revenues. Figure 4 shows the number of publications in the top subject area: energy, engineering, and environmental science.

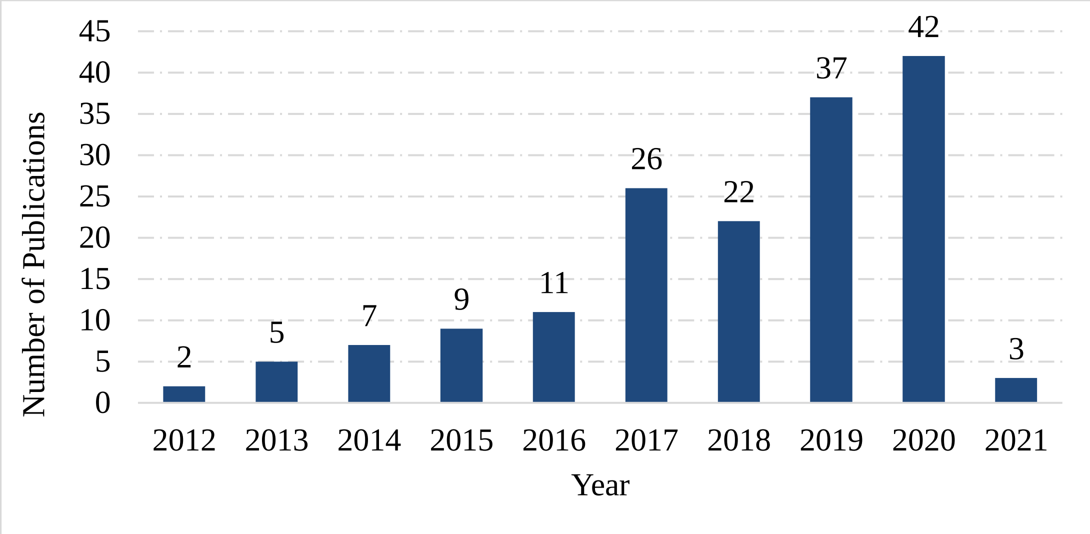


Figure 2. Number of publications per year.

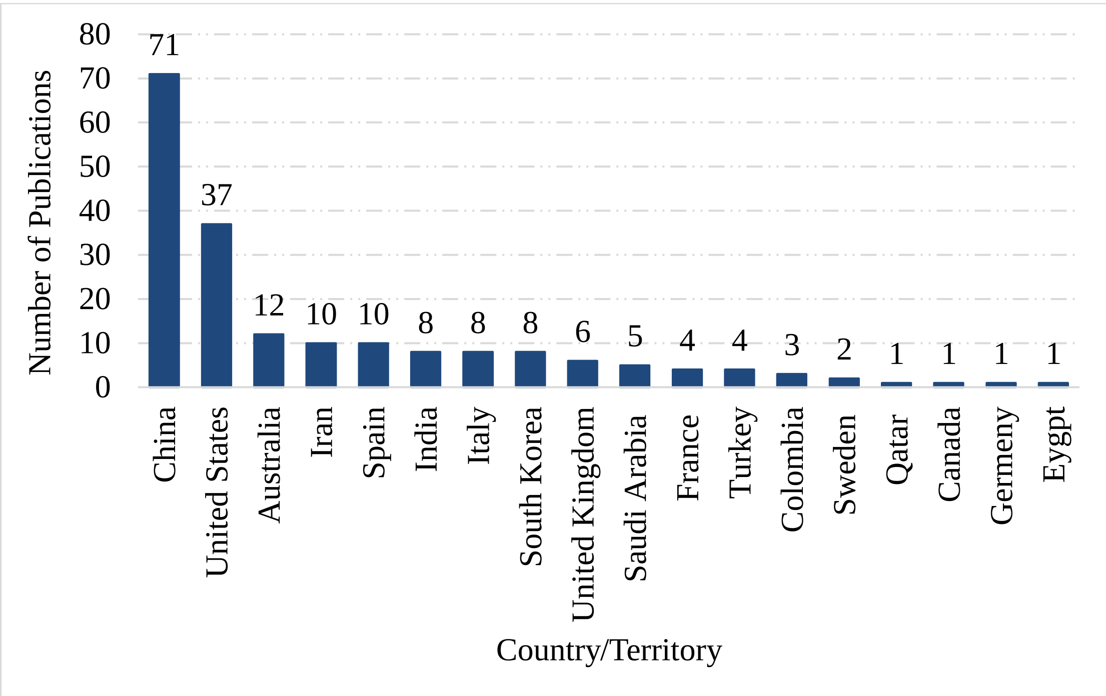


Figure 3. Number of publications by country/territory.

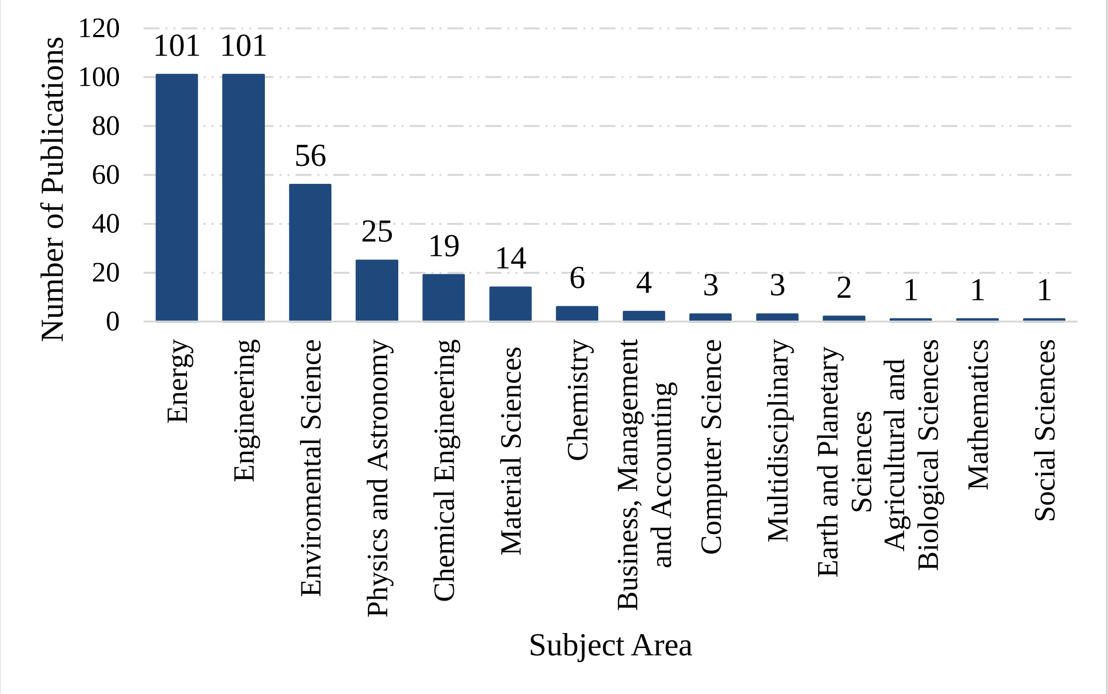


Figure 4. Number of publications by subject area.

Passing through many research papers, the Supercritical CO2 in the literature review has been utilized by the researchers in different ways either as a stand-alone power cycle or integrating with different heat sources. (Li et al., 2017) presents a comprehensive review of the different applications of sCO2 power cycles in different energy industries such as concentrated solar power (CSP), nuclear energy, and waste heat applications. The papers analyze the sCO2 power cycle from different perspectives thermodynamically and economically through performing the thermodynamic analysis (energy & exergy analysis) and exergoeconomic analysis. Also, some papers include sensitivity analysis to find out the parameters and components that highly impact the cycle performance. Figure 5 highlights the energy sources, the cycle configurations, and types of analysis.

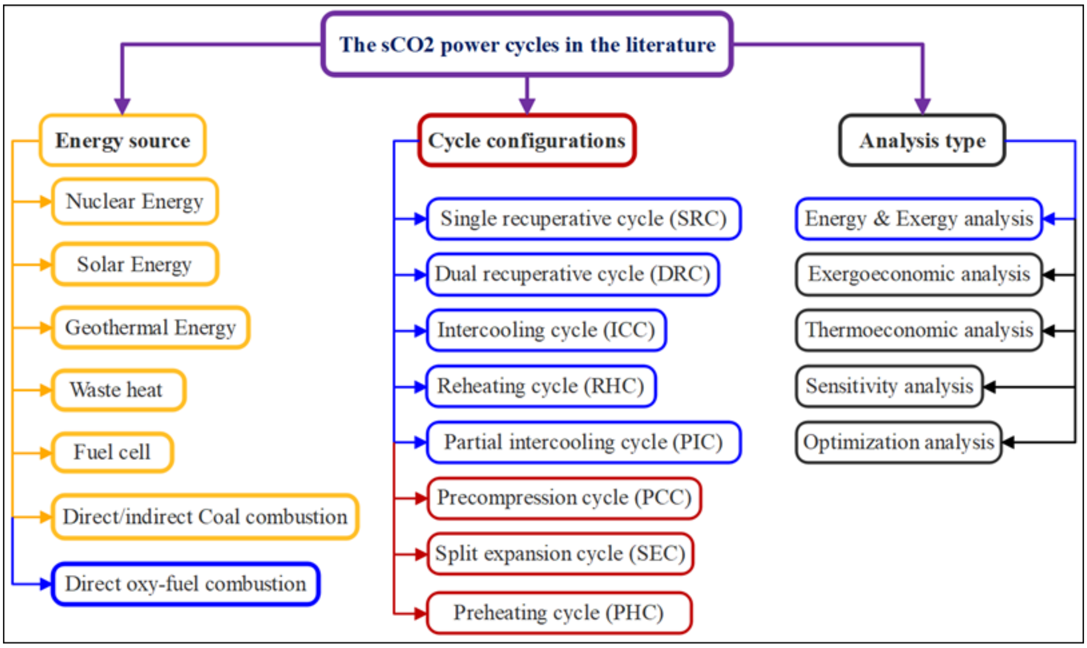


Figure 5. The sCO2 power cycles considered in the literature review(Sleiti & Al-Ammari, 2021).

In this paper a comprehensive literature review will mainly focus on optimizing various layouts for supercritical CO2 power cycles with respect to the optimization approach, the optimization types whether thermodynamically or exergoeconomic or both, and the optimized objective function whether single objective or multiple objectives. Table 3 summarizes the main papers and categorized them according to the heat source.

Table 3. Summary of the Main Papers Categorized Based to The Heat Source.

Heat Source Categorize	Study Reference	Thermodynamic Optimization (TOC) Exergoeconomic Optimization (EOC)	Single Objective Optimization (SOO) Multiple Objective Optimization (MOO)	Optimization Tool
Solar power	(K. Wang et al., 2021)	TOC	MOO	Genetic Algorithm (GA)
	(Khanmohammadi et al., 2020)	TOC & EOC	MOO	
	(Y. Ma et al., 2019)	TOC & EOC	SOO	
	(S. Trevisan et al., 2019)	TOC & EOC	MOO	
	(Y. Ma et al., 2018)	TOC	SOO	
	(Guo et al., 2019)	TOC	MOO	Nondominated sorting genetic algorithm (NSGA-II)
	(Kun Wang et al., 2018)	TOC	MOO	
	(Coco-Enríquez et al., 2017a)	TOC	SOO	New Unconstrained Optimization Algorithm(NEWUOA) Unconstrained Optimization Algorithm(SUBPLEX) Unconstrained Optimization By Quadratic(UOBYQA)
	(S. Trevisan et al., 2020)	TOC & EOC	MOO	Pareto

Heat Source Categorize	Study Reference	Thermodynamic Optimization (TOC) Exergoeconomic Optimization (EOC)	Single Objective Optimization (SOO) Multiple Objective Optimization (MOO)	Optimization Tool
Nuclear Energy	(Yuan et al., 2021)	TOC & EOC	SOO & MOO	Genetic Algorithm (GA)
	(Wu et al., 2018)	TOC & EOC	SOO	
	(M. Wang et al., 2016a)	TOC & EOC	MOO	
	(Syblik et al., 2019)	TOC	SOO	Cooling Cycles Optimization Computational Software (CCOCS)
	(Manente & Lazzaretto, 2014)	TOC	SOO	Sequential Quadratic Programming
	(Thanganadar et al., 2019)	TOC&EOC	MOO	Nondominated sorting genetic algorithm (NSGA-II)
Waste Heat Recovery	(Zhang et al., 2020)	TOC	SOO	Genetic Algorithm (GA)
	(Alharbi et al., 2020)	TOC&EOC	MOO	
	(Khadse et al., 2017)	TOC	SOO	
	(Hou et al., 2018)	TOC & EOC	MOO	
	(X. Wang & Dai, 2016)	TOC & EOC	SOO	
	(S. Wang et al., 2020)	TOC&EOC	SOO	Particle swarm optimization algorithm (PSO)
	(Mohammadi et al., 2020)	EOC	SOO	
	(Yang et al., 2020)	TOC & EOC	SOO	
	(Pengcheng Pan et al., 2020)	TOC & EOC	MOO	The Imperialist Competitive Algorithm (ICA)
	(Nami et al., 2017)	EOC	SOO	Direct Search Method

2.3.1 Concentrated Solar Power.

Meeting energy consumption is a worldwide challenge with reduced fossil fuel resources. Thus, researchers are looking for other sustainable energy sources to fulfill the continuous increase in energy demands. One of the renewable energy sources is solar energy which is considered a good alternative to conventional fossil fuel due to its availability and environmental benefits (Atif, 2014). Adopting sCO2 as heat transfer fluid can achieve thermodynamic efficiencies of 50% and above at high temperatures degrees captured by CSP (Ho & Iverson, 2013). Resulting in high system efficiencies with low cost and compact small power cycles which makes integrating sCO2 power cycles with CSP a promising technology (Vijaykumar et al., 2018). Recently, numerous studies have attempted to evaluate and optimize the performance of various sCO2 cycle configurations integrated with CSP through utilizing different optimization approaches. All of these papers have been reviewed and classified according to the used optimization approaches as summarized in Table 2 and will be detailed in the following lines:

I. Optimization using Genetic Algorithm (GA):

A considerable amount of literature has been published on utilizing Genetic algorithms (GA) as an optimization approach whether for multi-objective optimization or single-objective optimization for various purposes. The following paragraphs will illustrate and compare some of the most notable literature on the use of the tool.

Kun Wang et al., (2021) proposed a novel heat transfer fluid ($MgCl_2$-KCl) to be used in Solar power tower coupled with recompression sCO2 Brayton cycle (RCBC). Using a genetic algorithm (GA), a multi-objective optimization was implemented to compare the performance of MgCl2-KCl salt with conventional solar salt. Maximizing the thermal efficiency for the whole day ($\eta_{SPT,day}$)and the specific work (W) is the two optimized objectives functions.

The optimization problem was expressed as follows:

Maximize $\eta_{SPT,day}$ and W

Subject to:

- The hot salt temperature (t_b)

  $t_{\mathrm{b}} \in [t_{\mathrm{lower}}, t_{\mathrm{upper}}]$

  where $t_b \in [290\ ^{\circ}\mathrm{C}, 565\ ^{\circ}\mathrm{C}]$ for solar salt and $t_b \in [495\ ^{\circ}\mathrm{C}, 800\ ^{\circ}\mathrm{C}]$ for MgCl_2-KCl

- The min cycle pressure (P_l)

  $p_{\mathrm{L}} \in [7.38\ \mathrm{MPa}, p_{\mathrm{H}})$

- The reheating pressure (P_{th})

  $p_{\mathrm{rh}} \in [p_{\mathrm{L}}, p_{\mathrm{H}})$

- The split ratio (SR)

  $SR \in [0, 1]$

- The allocation ratio of recuperate conductance (UAR)

  $UAR \in [0, 1]$

In the genetic algorithm (GA) approach, the objective functions were chosen as fitness functions while the decision variables were defined as the chromosome. After the fitness function is defined, GA produced possible solutions which are a population of chromosomes that pass through mutation, crossover, and inversion operations. As a result, they found that MgCl_2-KCl system could obtain a little bit higher thermal efficiency and considerably larger specific work compared with conventional solar salt. Similarly, Trevisan, Guédez, and Laumert (2019) demonstrated that performing multiple objective optimizations (GA) can obtain near optimal solution sets. They carried out an analysis for the thermo-economic performance of a supercritical recompression Brayton cycle coupled with concentrated solar power CSP and paired with thermal energy storage. The sCO2 cycle efficiency, the capital expenditure (CAPEX), and the levelized of energy cost (LCOE) are the three parameters considered as objective functions. Theoretically, the optimization problem can be detailed as follows:

Maximize η_{sCO2} and Minimize CAPEX and LCOE

Subject to:

- Turbine Inlet Temperature (TIT)

  $600°C \leq TIT \leq 900°C$;

- Thermal Energy Storage Size (TES size)

  $8\ h \leq TES\ size \leq 14\ h$;

- The plant solar multiple (SM)

  $1.25 \leq SM \leq 3.25$;

They found that sCO2 cycle efficiency has a direct relationship with sCO2 turbine inlet temperature while there is an inverse relationship between CAPEX and LCOE considering thermal energy storage and split ratio as decision variables. In addition, the minimum leveled cost of electricity was estimated at 89.4 $/MWh for thermal energy storage that can last for 13.9 hours at full load and a solar power plant multiple of 2.47 hours corresponding to capital expenditure of around $73.4 million for the construction of a net electricity generation of 10MWh.

In contrast to the above, (Khanmohammadi et al., 2020) argued in their conclusion that their unoptimized system performance was superior to the optimized one. They performed tri-objective optimization (GA) for a power-refrigeration system that is supplied with solar energy by parabolic trough solar collector (PTSC) from the viewpoint of maximizing the net output and minimizing both the total exergy desaturation and total cost. The system consisted of three cycles including the Brayton cycle, transcritical Rankine cycle (TRC) for power generation, and vapor compression refrigeration cycle (VCRC) for cooling purposes. Their justification of the results was based on a trade-off among different objective functions where it was found that the optimized system produced comparatively worst values.

Researcher Yuegeng Ma had scoped interest in single-objective optimization. Along with his fellow researchers, he produced two single objective optimization papers (Ma et al., 2019; Y. Ma et al., 2018). In 2019, Ma et al investigated the optimal approach for integrating a recompression supercritical CO2 Brayton cycle (RCBC) with main compression intercooling (MCIC) in a solar power plant (SPT) from an exergoeconomic perspective. This was done by performing exergoeconomic optimization using a genetic algorithm aiming to minimize the total unit exergy cost of the SPT system and compare the results with a thermodynamic optimization that maximizes the SPT energy efficiency. The single objective optimization problem is shown below:

Minimize $C_{p,total}$ or Maximize η_{SPT}

Subject to:

- Pressure ratio of the main compressor (π_{MC})

  $2 \leqslant \pi_{\mathrm{MC}} \leqslant 8$

- Ratio of pressure ratio of main compressor(1) MC-1 (RPR_{MC-1})

  $0 \leqslant RPR_{\mathrm{MC-1}} \leqslant 1$

- Ratio of pressure ratio of turbine (1) T-1 (RPRT-1)

  if reheated, $0 < RPR_{\mathrm{T-1}} \leqslant 1$; otherwise $RPR_{\mathrm{T-1}} = 0$

- Split ratio in the main compressor side (SR)

  $0.5 \leqslant SR \leqslant 1$

- Effectiveness of high-temperature recuperator (eff_{HTR})

  $0.8 \leqslant eff_{\mathrm{HTR}} \leqslant 0.97$

- Effectiveness of low-temperature recuperator (eff_{LTR})

  $0.8 \leqslant eff_{\mathrm{LTR}} \leqslant 0.97$

- Pinch Point temperature difference

  Pinch point temperature difference$\geqslant 5\,°C$

The obtained result showed that the optimal $C_{p,total}$ is reduced by 8.94% from based on exergoeconomic optimization compared to conventional thermodynamic optimization.

Using the same optimization tool in 2018, (Y. Ma et al., 2018) conducted an optimization analysis for recompression sCO2 Brayton cycle (RCBC) integrated with absorption chiller and compared it with stand-alone sCO2 cycle. His objective was to maximum exergy efficiency η_{ex} or maximum energy effeciency η_{th}. The problem of optimization can be addressed as follow:

Maximize η_{ex} or η_{th}

Subject to:

- The pressure ratio of sCO2 cycle (PR)

  $2.2 \leq PR \leq 4$

- Effectiveness of recuperator (ε_{recup})

  $0.85 \leq \varepsilon_{\mathrm{recup}} \leq 0.95$

- Temperature approach in the generator (ΔT_G)

  $10 \leq \Delta T_G \leq 20$

- The concentration of lithium bromide-water solution (dX)

  $0.005 \leq dX \leq 0.09$

The result showed that the energy and exergy efficiencies are 5.19% and 6.12% higher than the stand-alone sCO2 cycle.

II. Optimization using the nondominated sorting genetic algorithm (NSGA-II) :

K. Wang et al., (2018) carried out a study to find the most suitable sCO2 Brayton cycles layout to be coupled with SPT. According to Pareto optimal fronts obtained from utilizing NSGA-II as a multi-objective optimization, they performed a systematic comparison of various sCO2 cycle layouts. Considering both the overall system efficiency and the specific work, the results showed that inter-cooling cycle layout and the partial-cooling cycle layout has the highest performance then the recompression and the precompression cycle layouts come in the second place, while the worst performant goes to the simple recompression cycle layout (K. Wang et al., 2018). The optimization problem can be detailed as follows:

Maximize η_{SPT} and W

Subject to:

- Hot salt temperature

  $290 \leqslant t_{s,b}(°C) \leqslant t_{upper}$

- Minimum cycle pressure

  $7.38 \leqslant P_{min}(MPa) \leqslant P_{max}$

- Intermediate pressure for reheating

  $P_{min} \leqslant P_{rh}(MPa) \leqslant P_{max}$

- Split ratio

  $0 \leqslant SR(-) \leqslant 1$

- Ratio of pressure ratio,

  $0 \leqslant RPR(-) \leqslant 1$

- Ratio of HTR conductance to total recuperate conductance

  $0 \leqslant UAR(-) \leqslant 1$

Guo, Lia, and Xu (2019) believed that mixing other gases with sCO2 can be effective in enhancing the performance of the solar power tower plant (SPT). So, he implemented the same analysis as (K. Wang et al., 2018) to compare the performance of four-cycle layout using three different mixes: standard sCO2 working fluid, sCO2 mixed with xenon (sCO2-Xe), and sCO2 mixed with butane. However, in contrast to the two objective functions considered in the above study (K. Wang et al., 2018), this study considered three objective functions: the specific work, temperature difference of the thermal storage system, and exergy efficiency of the cycles. The findings proved that adopting sCO2-Xe as a working fluid significantly improves the exergy efficiency compared with sCO2 cycles while adding butane has reverse effects. Also, intercooling and recompression cycles showed excellent results in exergy efficiency correspond to other analyzed cycles. Thus, the researcher was able to identify the most suitable cycle to be integrated with SPT based on the results revealed from multi-objectives optimization (Guo et al., 2019).

III. Studies using other optimization tools:

Proceeding efforts have been devoted by (Silvia Trevisan et al., 2020) on the same configuration to evaluate the effect of design characteristics for the CSP plant from an economic perspective by using the Pareto algorithm as multi-objective optimization. They found that a plant size of 10MWe can achieve a capacity factor higher than 50% with 100$/MWhe as LCOE as well as a low capital investment due to the small size of the plant. This makes it easily funded and installed. While increasing the size of the plant e.g. 50 MWe will lead to better LCOE (65 $/MWhe) along with an increase in the CAPEX (175 M $). Additionally**,** Coco-Enríquez, Muñoz-Antón and J. M. Martínez-Val (2017) utilized three unconstrained multivariable algorithms SUBPLEX (Rowan, 1990), UOBYQA (Powell, 2002), and NEWOUA (Powell, 2006) to assess four sCO_2 Brayton configurations (simple baryton cycle SBC, recompression cycle RC , partial cooling with recompression PCRC, recompression with main compression intercooling RCMCI) integrated with dual-loop solar power plants to optimize the cycles energy efficiency. They found that each cycle has a threshold conductance (UA) point above which the overall efficiency is stationary. The UA threshold values are as follows: 5000 kW/K for SB configuration, and UA= 20,000 kW/K for RC, PCRC, and RCMCI layouts (Coco-Enríquez et al., 2017b)**.**

2.3.2. Nuclear Power.

Supercritical CO 2 cycles have a useful application in the nuclear power industry. Nuclear power technologies, along with solar power systems, are at the forefront of thermodynamic cycle use. As a result, there is a wealth of literature available on various sCO_2 cycle topologies for nuclear power reactors.

I. Optimization using Genetic Algorithm (GA):

For Effective utilization of nuclear energy, the study of (Yuan et al., 2021) suggested a novel cooling and power system where the recompression Brayton cycle is integrated with ejector transactional CO_2 refrigeration cycle. The study analyzed the proposed system through performing single and multiple objectives optimization by Genetic algorithm (GA) and compare it with two types of separated cooling and power systems which are the conventional separated system and the ejector separated system. The proposed combined cooling and power system showed higher exergy efficiency and lower product unite cost than the separated ones.

Wu, Wang, and Li (2018) proposed a novel combination of Recompression Brayton Cycle (RCBC) with Organic Flash Cycle (OFC) for nuclear power generation. They utilized a total of seven refrigerants for the organic flash cycle. It was observed that the coupling of the organic flash cycle with the SCO_2 cycle yields a 6.57%

enhancement in second law efficiency and a 3.75% reduction in total production costs. Moreover, n-nonane is observed as the most effective fluid for the organic flash cycle (Wu et al., 2018). They performed single objective thermodynamic and exergoeconcomic optimization analysis using Genetic Algorithm (GA) for the proposed system and compared it with the optimized stand-alone RCBC as well as optimized Recompression Brayton Cycle combined with Organic Rankin Cycle (RCBC/ORC). Maximizing the second law efficiency was the single objective of thermodynamic optimization analysis while minimizing the total product cost was the single objective of exergoeconomic analysis. The following lines highlight the optimization process:

For RCBC cycle, maximize η_{ex} or minimize $c_{p,tot}$ by choosing the compressor pressure ratio (PR_c) as a decision variable:

$2.2 \leq PRc \leq 4.2.$

For RCBC/OFC cycle, maximize η_{ex} or minimize $c_{p,tot}$ by choosing the following decision variables:

- Compressor pressure ratio (PR_c)

  $2.2 \leq PRc \leq 4.2.$

- The terminal temperature difference in the heater ($\Delta T_{t,HE}$)

  $8 \leqslant \Delta T_{t,HE}(°C) \leqslant 16$

- The pinch point temperature difference in the condenser ($\Delta T_{pp,CON}$)

  $5 \leqslant \Delta T_{pp,CON}(°C) \leqslant 15$

- The OFC evaporation temperature (ΔT_{04})

  $60 \leqslant T_{04}(°C) \leqslant 100.$

For RCBC/ORC cycle, maximize η_{ex} or Minimize $c_{p,tot}$ by choosing the following decision variables:

- Compressor pressure ratio (PR_c)

  $2.2 \leq PRc \leq 4.2.$

- The pinch point temperature difference in the heater ($\Delta T_{pp,HE}$)

  $8 \leqslant \Delta T_{pp,HE}(°C) \leqslant 16$

- The pinch point temperature difference in the condenser ($\Delta T_{pp,CON}$)

  $5 \leqslant \Delta T_{pp,CON}(°C) \leqslant 15$

- The evaporation temperature of the ORC (ΔT_e)

  $60 \leqslant T_e(°C) \leqslant 100$

- The Superheat temperature (ΔT_{sup})

  $0 \leqslant \Delta T_{sup}(°C) \leqslant 5$

The study revealed the following results:

- Comparing RCBC/OFC with basic RCBC the exergy efficiency for RCBC/OFC is higher than RCBC by 6.57% and the total product cost for RCBC/OFC is lower than RCBC by 3.57%.
- RCBC/OFC can be an alternative to RCBC/ORC as it has a slightly high exergy efficiency (60.37%) compared with RCBC/ORC (59.90%) and a relatively low total product cost of 12.40 $/GJ for RCBC/OFC and 12.47$/GJ for RCBC/ORC.

Similarly, Wang et al. (2016b) considered two objective functions which are maximizing thermal efficiency and minimizing the total product unit cost when investigating four different configurations for a combined CO2 cycle with organic ranking cycle (ORC) and compared them with two systems supercritical CO2 recompression cycle (system1) and the partial cooling transcritical CO2 cycle (system2). Using Genetic algorithm (GA), Four decisions variables have been constrained as follows:

- Compressor 1 inlet pressure (CIP1)

  3.4 MPa ≤ CIP1 ≤5.4 MPa

- Pump outlet pressure (POP)

  0 MPa ≤ POP ≤ 4 MPa

- Evaporator hot-side temperature difference (ΔT).

  20 K ≤ CIP1 ≤ 60 K

- Compressor 1 outlet pressure (COP1)

  COP1=20 MPa

The main results can be summarized as follows:

- All of the combined cycles show better thermal efficiency compared with the stand-alone CO2 cycles.
- For utilizing nuclear power, the optimal configuration is the combined simple CO2/organic Rankine cycle among the proposed cycles, which has the lowest Cptot and the highest thermal efficiency

II. Studies using other Optimization tools:

Contrary to the aforementioned studies, (Syblik, et al., 2019) carried out computational analysis and optimization for the cooling cycle in a fusion power reactor. The study is fundamentally focused on applying the computational algorithm for the optimization of sCO2 cycle.

(Manente & Lazzaretto, 2014) performed thermodynamic optimization using a sequential quadratic program to find out that the sCO2 cascaded layout in biomass power could reach an efficiency of 36%. This cycle can be considered as a good alternative to biomass-fueled internal combustion engines or the Organic Rankine cycle. In line with this research, (Thanganadar et al., 2019) analyzed five configurations for sCO2 cascade cycles from thermal and economic performance. He preferred to perform a multi-objective optimization rather than a cost-based single-objective optimization as the cost functions of the sCO2 components are uncertain and the optimization algorithm must search for the most efficient and least expensive designs.

2.3.3. Waste Heat Recovery.

Plenty of papers have used sCO2 for waste heat recovery applications. the following lines summarized the optimization-related papers.

I. Optimization using Genetic Algorithm (GA):

Wang and Dai (2016) investigated two possible layouts in which the waste heat generated by a recompression supercritical CO2 Brayton cycle (RCBC) used by a transcritical CO2 cycle (TCO2) or an Organic Rankine Cycle (ORC) to generate electricity. A genetic algorithm (GA) was used to undertake a single objective optimization study for either increasing exergy efficiency or reducing total product unit cost. The following is a comprehensive analysis:

For the sCO2/tCO2 cycle, maximize η_{ex} or minimize $C_{p,tot}$ (PRc, T01, P01)

- Compressor pressure ratio (PR_c)

$$2.2 \leqslant PRc \leqslant 4$$

- Turbine 2 inlet temperature T01 and pressure P01

$$80 \leqslant T_{01}(^{\circ}C) \leqslant 130$$
$$100 \leqslant P_{01}(bar) \leqslant 180$$

For the sCO2/tCO2 cycle, maximize η_{ex} or minimize $C_{p,tot}$ (PRc,T_e ΔT_E, ΔT_{sup})

- Compressor pressure ratio (PR_c)

$$2.2 \leqslant PRc \leqslant 4$$

- Evaporation temperature (T_e)

$$70 \leqslant T_e(^{\circ}C) \leqslant 130$$

- Pitch point temperature difference (ΔT_E)

$$3 \leqslant \Delta T_E(^{\circ}C) \leqslant 15$$

- Degree of superheat at ORC turbine inlet (ΔT_{sup}).

$$0 \leqslant \Delta T_{sup}(^{\circ}C) \leqslant 5$$

The results show that the exergy effecency of RCBC/TCO2 cycle was comparable with the RCBC/ORC cycle. However, when isobutane is used as a working fluid in the ORC, the maximum exergy efficiency was obtained (62.64%). On the other hand, the total product unit cost of the RCBC/ORC was a little bit lower than RCBC/TCO2. It is important to mention that the isobutane fluid record 9.60 $/GJ as the total product unit cost which is the lowest compared with other ORC working fluids. In similar to Wang and Dai (2016), Alharbi et al. (2020) proposed a system that utilizes the waste heat from RCBC to operate a conventional multi-effect desalination system and produce electricity and fresh water. In their analysis, the genetic algorithm performed single- and multi-objective optimizations to optimize the system design. Three objective functions were optimized energy utilization factor, exergy efficiency, and total product unit cost and they obtained the following results:

- In single-objective optimization: the value of maximizing the energy utilization factor improve by 7.13% while exergy efficiency increased by 0.56%, and the total product unit cost was minimized by 2.24%.
- In multi-objective optimization where an equal weighting coefficient is assigned for each objective. The energy utilization factor, the exergy efficiency, and the total product unit cost improve by 6.2%, 0.53%, and 2.1%, respectively

Hou et al. proposed a combined organic Rankine cycle (ORC) and regenerative sCO2 cycle for waste heat recovery from a gas turbine. Besides the observation of optimal production cost and exergy efficiency, the studies prove that the combination of regenerative SCO2 cycle with ORC is superior in thermal performance to the combination of basic SCO2 coupled with ORC (Hou, et al., 2018).

Zhang et al. proposed a novel model for the waste heat recovery of IC engines. A genetic algorithm is employed for the optimization of key operating parameters for the evaluation of the energetic and energetic performances of the system. Following are the key findings of the study (Zhang, et al., 2020):

- The exergy efficiency and thermal efficiency of the novel proposed system are 67.90% and 35.86%.
- The increase in the thermal efficiency of the system is observed with the increase in temperature at the inlet of the high-pressure turbine.
- The genetic algorithm optimization of the system performance indicators resulted in about 75% efficiency of waste heat recovery.

Khadse et al. (2018)performed thermodynamic optimization for recuperated and recompression sCO2 Brayton power cycles configurations for waste heat recovery applications. He found that a genetic algorithm is the best tool to perform optimization for nonlinear systems like Brayton cycles because it is a non-gradient-based evolutionary technique. As an objective function, the net cycle output power was selected because the most energy-efficient design in WHR may not necessarily produce the highest heat recovery and maximum power generation(Khadse et al., 2018).

II. Optimization using Particle Swarm Optimization Algorithm (PSO):

There are mainly three main researchers who used PSO for single-objective optimization. Yang, Wang, *et al.* (2020) carried out thermodynamic and exergoeconomic analyses for their proposed heat and power system. In their system, the produced waste heat from a supercritical CO2 recompression Brayton cycle (sCO2) is absorbed by a LiBr-H2O absorption heat pump (AHP). Comparing with the stand-alone sCO2 system, they found that the exergy efficiency of sCO2/LiBr-H2O AHP system improved by 13.39 % while the total product unit cost is minimized by 8.66 % (Yang et al., 2020). Likewise, the same analysis was done by Wang *et al* (2020) on a poly generation system which consists of a gas turbine cycle, a regenerative sCO2 Brayton cycle, an Organic Ranking cycle, and an absorption refrigeration cycle to investigate their system performance (S. Wang et al., 2020). On the other hand, Mohammadi et al (2020) utilized PSO algorithm to minimize the levelized cost of electricity of their novel triple power cycle. The findings showed that the total thermal efficiency and LCOE for a 100 MW cycle were 0.521 and $52.819/MWh, respectively (Mohammadi et al., 2020).

III. Studies using other Optimization tools:

For an ocean-going 9000 TEU container, Pan *et al.* (2020) proposed to use a recompression Brayton cycle as waste heat recovery for the main engine exhaust gas. Five objective functions were optimized using the implicit competitive algorithm to get the optimal operating parameters. Changing the system design may assist in reducing the fuel consumption in the ship auxiliary engine and the energy efficiency design index by around 1.01 % and 1.02 %, respectively while improving the ship main engine system's thermal efficiency by 3.23 % (P. Pan et al., 2020).

The direct search method was utilized by Nami. et. al(2017) to conduct exergoeconomic and exergoenvironmental optimization analyses for two cycles sCO2 recompression Brayton cycle and organic Rankine cycle combined with gas turbine and heat recovery steam generator. They aim to minimize the product cost that is based on the summation of operating and maintenance cost, exergy destruction cost, and environmental cost. The results revealed that the optimized condition reduced the cost by 0.58$/Gj (Nami et al., 2017).

2.4 Literature Review Closer.

To sum up, sCO2 power cycle technology has advanced dramatically since its start in the 19th century, and it is continually advancing at a rapid pace today. China and USA play a leading role in the development of sCO2 cycle with China dominating the technology patents. However, in Arabic countries, there are very limited researches and their progress is falling behind comparing with foreign countries. This proves the novelty of such technology and the need for conducting more studies. The performed studies in this thesis consider a contribution in this field and it is of great benefits to the Arab countries and Qatar in specific. In the open literature, the sCO2 showed various benefits and multi-uses in different sectors like the food industry, chemical, and energy due to its physical and chemical properties. Utilizing sCO2 as working fluids in power cycles contributes to improve the cycle efficiency, minimize the mechanical systems of the power plant, and gain it economic and environmental benefits. To this end, optimization models are required and essential for maximizing the benefits of such technology which will be the focus of our study.

The reviewed literature revealed that optimization-related studies in the field of sCO2 power cycles are limited. The system-level optimization-related studies received little attention because of the fact that sCO2 technology is still in their growing stage and hence undeveloped in our region. A few significant drawbacks were discovered and summarized from the few related papers that were accessible.

- Most of the studies were dedicated for integrating this technology with renewable energy sources which contribute by less than 5 % to the overall power production in Qatar. To close this gap and overcome their drawbacks, our study will propose three novel direct oxy combusted sCO2 power cycles and it will also perform a thermodynamic and economic analysis of these configurations in wet and dry cooling.

- There is a lack of studies that consider the Levelized cost of electricity(LCOE) as an objective function in their optimization study, there is no doubt that investors in such technology will look for their revenue against their paid cost, hence; any little changes to a power cycle's techno-economic aspects can transform a failed technology into a very promising one. Thus, Optimization of LCOE based on current and reasonably estimated costs of the cycle components is necessary to justify the optimized values of the other performance indicators (PIs) and will be considered in our study.
- Genetic algorithm has proved its efficiency in optimizing non-linear, discontinuous thermodynamic energy system performance which has multiple local optimums and cannot be solved by parametric or gradient-based optimization algorithms. In addition, The GA technique consider to be the most reliable tool and it is not impacted by guess values as other methods; hints, it was chosen in this study as the optimization tool.
- Few studies performed both single and multiple objectives optimizations for thermodynamic and exergoeconomic objective function. Our study will perform two types of optimizations for the suggested configurations to get more insight into the optimized performance.

CHAPTER 3: METHODOLOGY.

3.1 Introduction.

This study aims mainly to perform optimization analysis for three novel configurations of direct oxy-combustion sCO2 cycles integrated with wet and dry precooler to offer the decision-maker the optimal configuration from energy, exergy, and economic point of view. This study performs a system-level analysis where the focus is to understand the performance indicators of the system as a whole and how it is affected by the interactions between the components. This approach is called system-level lumped-volume which concentrate on the thermodynamic and economic performance of the direct oxy-combustion sCO2 cycles as a system; and it doesn't go deeply in the components level e.g. the design of the components. However, the performance of the components is mathematically modeled through EES software with accurate design parameters. The selected ranges for the design parameter are done based on comprehensive study to be reasonable and avoid conflicting with other aspects relate to design and manufacturing. This chapter is mainly to offer a brief description of the methodology used for analysis. Also, it is important to mention the study does not involve any experiments and it is mainly based on mathematical modeling.

3.2 Description of the modeling tool

Thermodynamic sCO2 cycles modeling begins by measuring the characteristics of the operation of the fluid. The National Standards and Technology Institute (NIST) created the REFPROP (version 9) database for the definition of CO2 thermodynamics and transport characteristics using an integrated library in the Engineering Equation Solver (EES). With the most precise equations and coefficients (Dostal et al., 2004), the REFPROP determines the state point for a fluid (Klein, S.A. and Alvarado, F.L., 2002).It offers exact CO2 thermophysical characteristics and other fluid characteristics.

3.3 Optimization Tool

I. Justification of using genetic algorithm.

The nature of energy systems is typically non-linear, has discontinuous thermodynamic performance and multiple local optimums. Such systems consist of many decision variables that lead to a multidimensional optimization area and make the relations between subsystems and mathematical equations get more complicated. Therefore, conventional gradient optimization algorithms are more time-consuming and, in some circumstances, impossible to use. Because the genetic algorithm (GA) offers specific benefits for optimizing problems, it was chosen in this study as the optimizing core for single and multi-target optimization techniques. GA is a strong evolutionary optimizing approach that may be employed to tackle almost any optimizing problem, unlike gradient-based optimization methods. Without being trapped in optimum local locations, GA is able to obtain global optimum at the same time optimize non-linear system with many decision variables. The basic benefit of GA is that neither analytically or numerically differentiation is required for the system equations which eliminates the requirement for further mathematical preparation and modelling difficulties. GA handles the system as if it is a black box. As shown in Figure 6, the optimizer and model are two separated entities. The optimizer evaluates the behavior of the system and it only interact with the simulator (computational model) through the decisions variables and the related values of the system performance indicators (or the fitness function). In addition, GA seeks the best global optimum, but gradient algorithms might be stuck in local optimum owing to an improper initial guess.

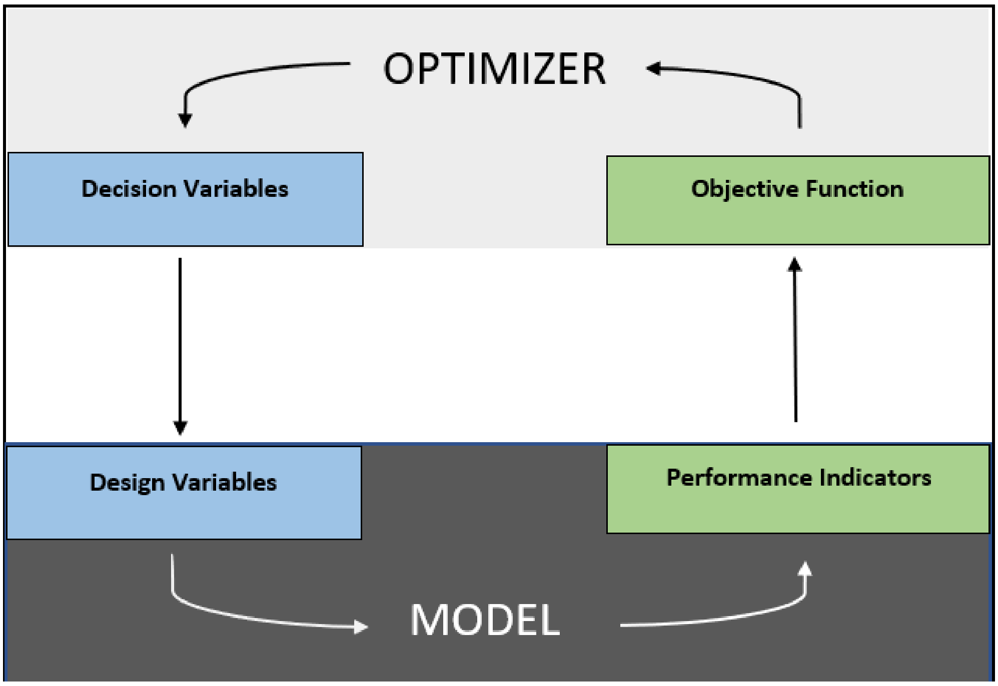


Figure 6: Interactions between the model and optimization tool in black box approach.

The system-level optimization is also doable with this optimization approach. In contrast to component-level optimization, system-level optimization takes into account not only the performance of components but also the interconnections between them. In other words, system-level optimization leads to optimize the performance of the whole system rather than individual component performance.

II. Description of GA as Optimizer core.

When using the GA, the first step is to define the optimization domain. The variation range of all decision variables defines the optimization domain. The fitness function (or objective function) is then defined based on one or more cycle performance metrics whether to be maximized or minimized. The Genetic Algorithm's functioning can be broken down into five steps:

1) A population of individuals is randomly generated and the identity of each individual is determined based on the values of the decision variables

2) The individuals are evaluated and classified based on their fitness function

(objective function) values.

3) The most appropriate individuals or those with the highest fitness levels are picked for the next generation as parents. This selected group shall be governed by the fundamental genetic rules (marriage, mutation, and talent conservation) which results in a new generation that has the same number of individuals as the previous one.

4) The fitness function is used to evaluate the new generation. It is expected that the incoming generation will outperform the previous generation because of their healthy parents.

5) The process of creating new generations is repeated until the algorithm converges, which occurs when the optimal goal (fitness) function changes a very small amount or ceases to change.

The following flow chart figure 7 shows how the Genetic Algorithm was implemented in our study. For more information on GA (Haupt and Haupt, 2004; Greenhalgh and Marshall, 2000) are good papers.

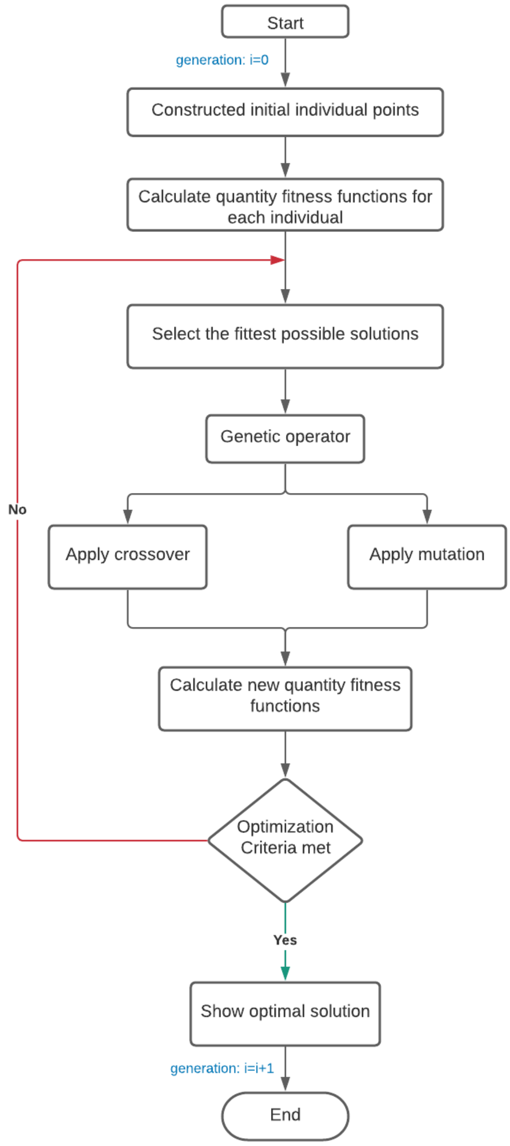


Figure 7: Genetic Algorithm Flow Chart

3.4 Model Validation

By comparing the findings with the data supplied by the original creators of the Allam cycle (Allam et al., 2017), the model design of the suggested configurations is validated. Furthermore, the findings of the model are compared to results obtained in Scaccabarozzi study (Scaccabarozzi et al., 2016). The main operating conditions in both situations were modified to be the same as those in (Allam et al., 2017; Scaccabarozzi et al., 2016) producing the same power output. A summary of validation results is shown in the table 4. Comparing the results of proposed models with (Allam et al., 2017) data indicate that the highest residual fuel energy error is (3.90%). This is because natural gas is treated as pure methane in this study which affects the quantity of heat produced by combusted fuel; while comparing with (Scaccabarozzi et al., 2016) data reveals that the highest error of outlet temperature of the turbine is 3.85%. This is due to a slight difference between the current research and Scaccabarozzi et al. in the mix of exhaust flow (Scaccabarozzi et al., 2016). Both sets of data include an error of less than 1% for the net electrical efficiency, which is acceptable for validation of the recommended model.

At T1 = 1150 ◦C , T6 = 26 ◦C , P1=,300 bar and P6 = 32.2 bar.

Table 4: The Results of The Proposed Configuration VS Published Results in The Literature for Validation (Sleiti, Al-Ammari, et al., 2021)

Item	(Allam et al., 2017)	Current study	Error (%)	(Scaccabarozzi et al., 2016)	Current study	Error (%)
Net electrical power output (MWe)	303	303	0.00	419.31	419.31	0.00
Thermal energy of the fuel (LHV) (MWth)	511	531	-3.91	768.31	775.2	-0.90
Tubine power output (MW)	-	453.8	-	622.42	637.2	-2.37
Recycle flow compression (MW)	77	78.4	-1.82	111.15	112.86	-1.54
NG compressor consumption (MW)	-	2.8	-	4.18	4.32	-3.35
ASU penalty (MW)	56	58.8	-5.00	85.54	83.86	1.96
Turbine outlet temperature ©	727	738.5	-1.58	741.2	769.6	-3.83
Recycle flow final temperature	-	762	-	721.2	734.8	-1.89
Turbine inlet flow rate	923	914.6	0.91	1271	1268	0.24
Total recycle flow rate (with oxygen) (kg/s)	881	890	-1.02	1353.9	1353.5	0.03
Net electrical efficiency (%)	59.3	58.84	0.78	54.58	54.09	0.90

CHAPTER 4: RESULTS AND DISCUSSION.

4.1 Description of sCO2 cycle configurations

In sCO2-based power cycle technologies, the optimization analysis is a fundamental step to obtain the most feasible configuration from an energetic and economic point of view. Further, the optimization analysis is needed to solve the trade-off countered between the optimum conditions for energetic, energetic, and economic performances. Moreover, with the costs of the additional components related to the temperature level through the turbine alongside the cooling method (dry-cooling vs. wet-cooling) increase, robust, thorough optimization analyses, single and multi-objective approaches, are urgent.

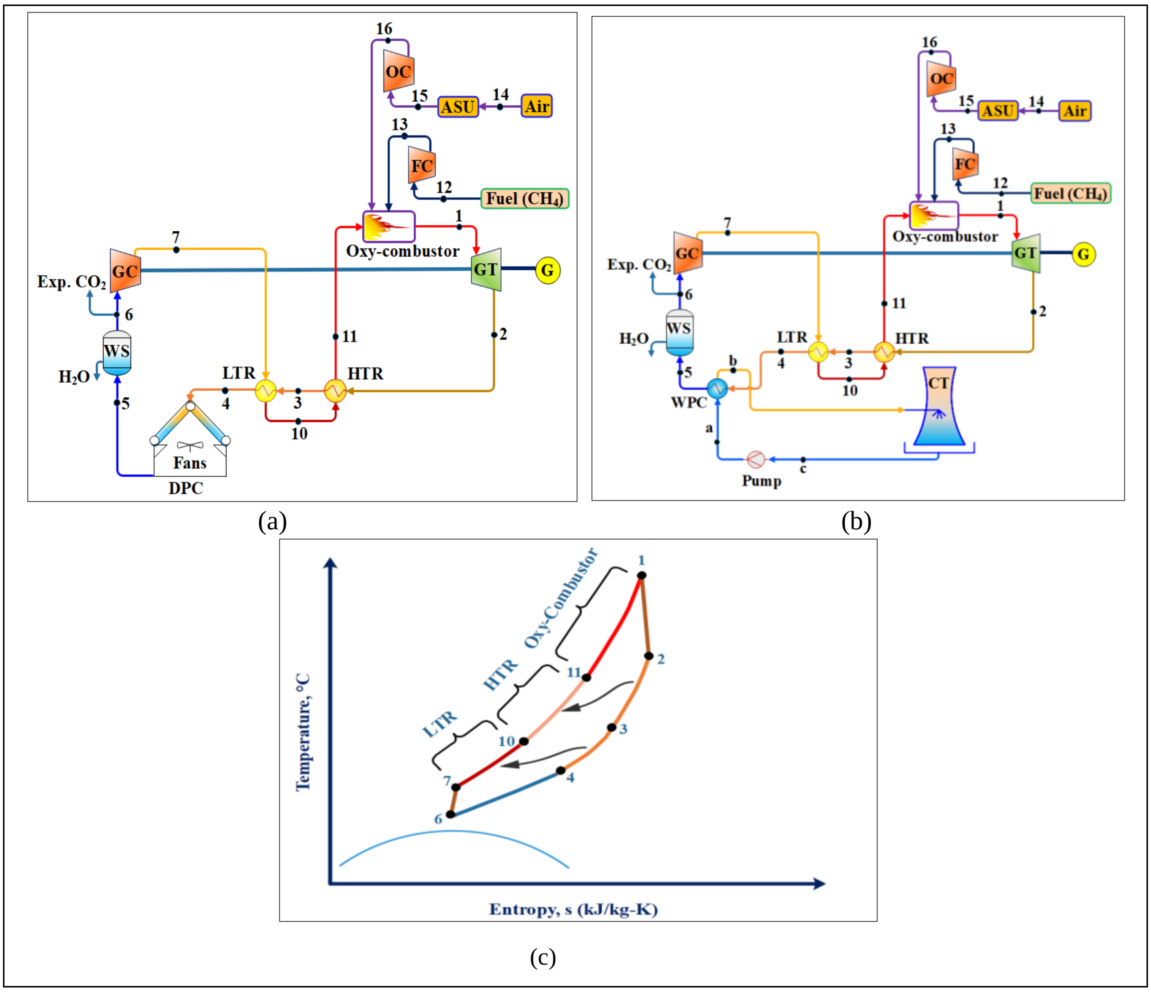


Figure 8: Basic configuration without preheater of the direct oxy-fuel cycle (M1) integrated with (a) dry precooler,(b)wet precooler,(c) T-s diagram, a presented in (Sleiti, Al-Ammari, et al., 2021).

In this chapter, three direct oxy combusted sCO2 power cycles operating at dry and wet cooling conditions are introduced to be analysed for optimum energetic, exergetic, and economic conditions. Despite the cooling method, each cycle is composed of six major components which are: oxy-combustor, gas turbine, HTR, LTR, precooler (DPC or WPC), water separator, and gas compressor. The oxy-combustor is connected with oxygen and fuel compressors as well as an air separation unit (ASU). These subunits provide compressed fuel oxygen and fuel to be mixed with the recycled sCO2 in the combustor. The reactants enter the turbine (state 1) at high pressure (200-300bar) and moderate TIT (550-750^{o}C) and expand to the low-pressure side (state 2). Then, the turbine outlet flow proceeds to the HTR (2-3) and LTR (3-4) to heat the recycled flow (7-11), as shown in figure 8. Then, the low-pressure flow is cooled in the precooler to a temperature of 50^{o}C in the dry precooler or 32^{o}C in the wet precooler. At the outlet of the precooler, further process is needed to remove the water content using a water separator. The purified CO_2 stream is then compressed to the desired high-pressure value, preheated by the LTR and HTR, and finally returned to the oxy-combustor to repeat the cycle. The excess CO_2 produced from the combustion process is exported at high pressure to be sequestrated or used in commercial applications (Sleiti et al., 2022) (Sleiti & Al-ammari, 2021).

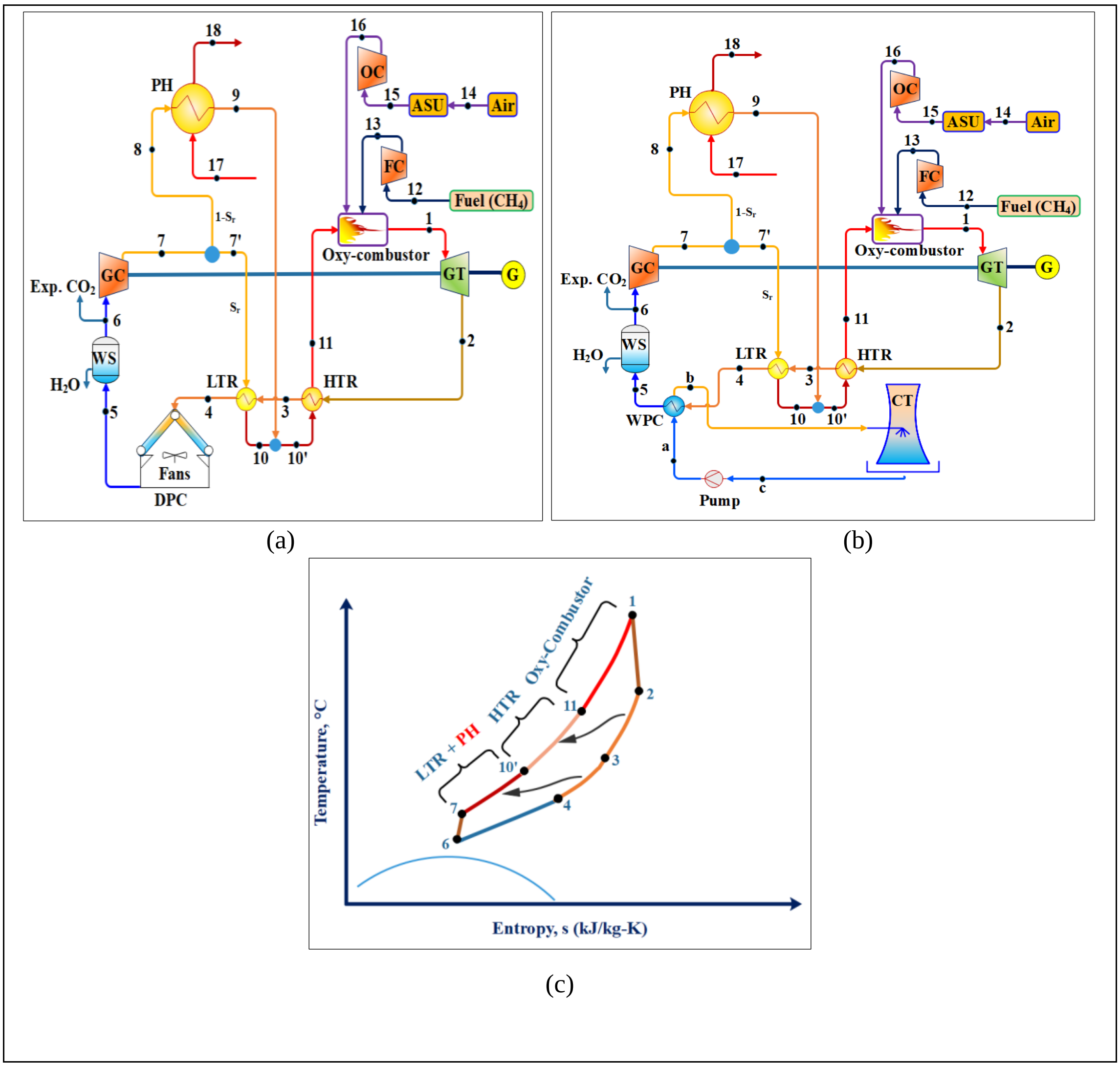
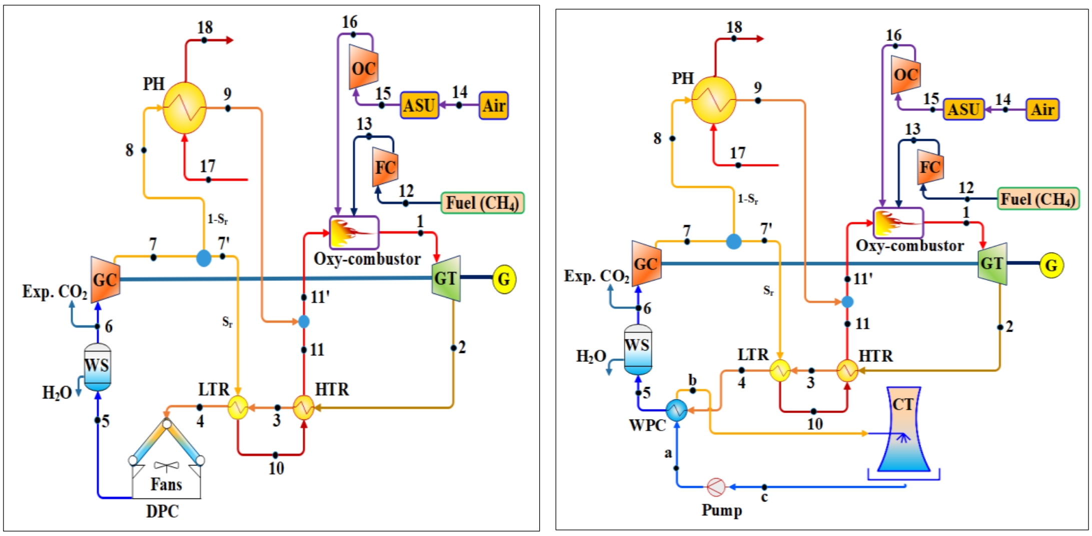
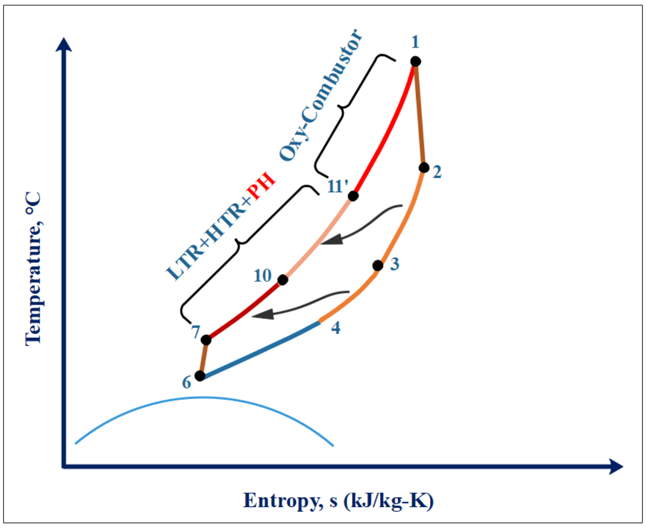


Figure 9: Second configuration of the direct oxy combusted cycle with a preheater integrated in parallel with the LTR (M2) and coupled with (a) dry precooler, (b) wet precooler, and (c) T-s diagram, as presented in (Sleiti, Al-Ammari, et al., 2021).

In the basic configuration M1, the heat content of the low-pressure hot flow is not equal to the desired heat required for the preheating process through the LTR. This returns to the variation of the specific heat of the CO2 at high-pressure side (cold side) which is much higher than at low-pressure side. This makes the heat of the hot flow inadequate for the cold flow which yields insufficient performance for the LTR and thus reduces the thermal efficiency of the cycle. To solve this problem, part of the recycled flow should be preheated by a separate energy source (e.x. waste heat) as proposed by Sleiti et al. (Sleiti, Al-ammari, et al., 2021). This preheater (PH) can be connected in parallel with the LTR (M2) as shown in figure 9 or in parallel with both LTR and HTR (M3) as shown in figure 10. In these configurations, the preheating process of the recycles flow is enhanced which reduces the fuel consumed by the oxy-combustor and the oxygen required for the combustion process as well. Therefore, the energy consumed by the ASU is reduced, and the recuperators performance is improved which enhances the thermal efficiency of M2 and M3 over the basic cycle M1. However, the addition of an extra preheater increases the capital cost of the cycle and also affects the cooling load of the precooler. This, in turn, affects the economic feasibility of these cycles which dictate an optimized operation to bring the LCOE of these cycles to a completive level of the conventional gas Brayton cycles. Furthermore, the addition of the PH increases the exergy losses of the cycle, thus the design of the cycle components should be improved based on the guidelines of an exegetic analysis.



(a) (b)



(c)

Figure 10: Layout configuration (M3) of the direct oxy-combustor cycle with a preheater connected in parallel with both LTR and HTR (a) dry-cooling, (b) wet-cooling, and c) T-s diagram, as presented in (Sleiti, Al-Ammari, et al., 2021).

For the presented cycles, the precooling process is performed in dry-cooling or wet-cooling conditions. From an energetic prospective , wet-cooling is able to reduce the temperature to near critical temperature of the CO2 (32^{o}C) which minimizes the compression power. This is because of the dense behaviour of the CO_2 near its critical point (31^{o}C, 7.38 bar). However, wet-cooling seems to be more expensive than dry-cooling, particularly in the case of water scarcity. This increases the importance of the optimized operation at either wet or dry conditions to achieve the best economic performance of these cycles.

4.2 Thermodynamic and Thermoeconomic Modeling:

The thermodynamic and economic performance of the suggested configurations are studied. Both energy and exergy models of each component of the examined layouts are presented in Section 4.2.1. Section 4.2.2 describes the comprehensive model determining the LCOE. Finally, the generated model's outputs are then verified in section 4.2.3.

4.2.1 Thermodynamic modeling

To formulate the thermodynamic and the exergy model of the configurations, the mass, energy, and exergy balance equations of each component have been calculated as follows (Wu et al., 2018) (Sleiti, Al-Ammari, et al., 2021):

$$\sum \dot{m}_i = \sum \dot{m}_o \quad (1)$$

$$\sum \dot{Q} + \sum \dot{m}_i h_i = \sum \dot{W} + \sum \dot{m}_o h_o \quad (2)$$

$$\dot{E}_Q + \sum \dot{E}_i = \dot{E}_W + \sum \dot{E}_o + \dot{E}_D \quad (3)$$

The combination of physical and chemical exergies are used to represent the exergy of each stream not considering the kinetic and potential exergies changes(Sleiti, Al-Ammari, et al., 2021):

$$\dot{E} = \dot{E}_{ph} + \dot{E}_{ch} \quad (4)$$

$$\dot{E}_{ph} = \dot{m}\varphi \quad (5)$$

$$\varphi = (h - h_o) - T_0(s - s_0) \quad (6)$$

$$\dot{E}_{ch} = \dot{n}\left[\sum_{j=1}^{n} x_j e_j^o + RT_o \sum_{j=1}^{n} x_j \ln(x_j)\right] \quad (7)$$

Each kth component has fuel-product-loss exergies balanced equation and exergy efficiency which are formulated in the following Eqs, 8 and 9 (Luo & Huang, 2020) (Noaman et al., 2019)(Sleiti, Al-Ammari, et al., 2021).

$$\dot{E}_{D,k} = \dot{E}_{F,k} - \dot{E}_{P,k} - \dot{E}_{L,k} \quad (8)$$

$$\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} \quad (9)$$

The effectiveness approach was used to simulate the heat exchangers (LTR, HTR, preheater, and precooler) using Eq. 10 (Thanganadar et al., 2019)(Sleiti, Al-Ammari, et al., 2021).

$$\epsilon = \frac{\dot{Q}}{\dot{Q}_{max}} \quad (10)$$

To understand the influence of the preheater Eq. 14 formulates the thermal efficiency ηth without considering the preheating load (Sleiti, Al-Ammari, et al., 2021):

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{m}_f \times LHV} \tag{14}$$

where $\dot{W}_{net}$ is the system's net output power, expressed as (Sleiti, Al-Ammari, et al., 2021):

$$\dot{W}_{net} = \eta_g(\dot{W}_{GT} - \dot{W}_{GC} - \dot{W}_{FC} - \dot{W}_{OC} - \dot{W}_{pump} - \dot{W}_{ASU}) \tag{15}$$

To account for the preheater load, the cycle's overall efficiency $\eta_{th,overall}$ is stated as (Sleiti, Al-Ammari, et al., 2021):

$$\eta_{th,overall} = \frac{\dot{W}_{net}}{\dot{Q}_{PH} + \dot{m}_f \times LHV} \tag{16}$$

The cycle's total exergy is calculated as follows (Sleiti, Al-Ammari, et al., 2021):

$$\varepsilon_o = \frac{\sum \dot{E}_{P,k}}{\sum \dot{E}_{F,k}} \tag{17}$$

4.2.2 Thermoeconomic Modeling

The suggested configurations are evaluated economically by calculating LCOE using Eq. 18 (Wright & Scammell, 2017) (Sleiti, Al-Ammari, et al., 2021).

$$LCOE = \frac{PC - PV_{DTS} + PV_{LOC} - PV_{SC}}{LEP} \tag{18}$$

where PC stands for project cost that sum components and installation costs (provided in Eq. 19), PV_{DTS} represents the present value of the depreciation tax shield (provided in Eq. 20), PV_{LOC} represents the lifetime operating costs present value (provided in Eq. 21), PV_{SC} represents the present value of salvage costs (assumed \$0.00), and LEP represents the lifetime electrical production (provided in Eq. 22).

$$PC = \sum(Component\ cost + Installation\ cost)_k \tag{19}$$

$$PV_{DTS} = TR \times PC/(1 + DR)^{DP} \tag{20}$$

$$PV_{LOC} = n * (OMC + Cost\ of\ the\ fuel)/(1 + DR)^n \tag{21}$$

$$LEP = PUF \times n \times \dot{W}_{net} \times 8760 \tag{22}$$

TR represents the rate of tax (35%) (Wright & Scammell, 2017), DR represents the discount rate (2%) (Weiland & Lance, 2019), DP represents the depreciation period (10 years), n is the plant's lifespan (20 years), and PUF represents the plant utilization factor (85%). Table 5 shows the formulas for the components, as well as the cost of installation for component materials and manufacturing overhead, computed as a percentage of the component costs (Weiland & Lance, 2019).

Table 5:Cost Correlations of The Layout Components (Sleiti, Al-Ammari, et al., 2021)

Component	Component cost	Installation cost	
		Materials	Direct labor
Oxy-combustor	$Z_{oc} = 677203 \times \dot{Q}_{oc}^{0.6} \times f_{T.oc}$ $f_{T.oc} = 1 + 5.4 \times 10^{-5}(T_{max} - 550)^2$	8%	12%
Gas turbine	$Z_{GT} = 19538 \times \dot{W}_{GT}^{0.5561} \times f_{T.GT}$ $f_{T.GT} = 1 + 1.106 \times 10^{-4}(T_{max} - 550)^2$	8%	12%
Generator	$Z_G = 116577 \times \dot{W}_{net}^{0.5463}$	8%	12%
Gearbox	$Z_{GB} = 189693 \times \dot{W}_{GT}^{0.2434}$	8%	12%
Compressor	$Z_{GC} = 1316100 \times \dot{W}_c^{0.3992}$	8%	12%
HTR	$Z_{HTR} = 52.91 \times (UA)_{HTR}^{0.7544} \times f_{T.HTR}$ $f_{T.HTR} = 1 + 0.02141(T_{max} - 550)$	2%	3%
LTR	$Z_{LTR} = 52.91 \times (UA)_{LTR}^{0.7544} \times f_{T.LTR}$ $f_{T.LTR} = 1 + 0.02141(T_{max} - 550)$	2%	3%

Component	Component cost	Installation cost	
		Materials	Direct labor
Preheater	$Z_{PH} = 52.91 \times (UA)_{PH}^{0.7544} \times f_{T.PH}$ $f_{T.PH} = 1 + 0.02141(T_{max} - 550)$	2%	3%
Dry-Precooler	$Z_{DPC} = 35.18 \times (UA)_{DPC}^{0.75}$	8%	12%
Wet-Precooler	$Z_{WPC} = 52.91 \times (UA)_{WPC}^{0.7544} \times f_{T.WPC}$ $f_{T.WPC} = 1 + 0.02141(T_{max} - 550)$	2%	3%
Pump (Walraven et al., 2015)	$Z_{pump} = 10.51^3 \times \left(\frac{\dot{W}_{pump}}{4}\right)^{0.55} \times$	2.5	2.5
Cooling tower (Usman et al., 2017)	$Z_{CT} = 24.17 \times \dot{Q}_{wpc} + 2060.28$	2.5	2.5
ASU (Ebrahimi et al., 2015)	$Z_{ASU} = RefCost \times (Size/RefSize) \times OIF$, $RefCost = 151\ MillionUS\$(2019)$, $Size = \dot{m}_{o_2}\ RefSize = 52kgO_2/s, OIF = 1$	8%	12%

*$\dot{W}_{GT}$, $\dot{W}_{net}$, $\dot{W}_C$, and $\dot{Q}_{oc}$, are in MW, (UA) in $W/^oC$, $\dot{Q}_{WPC}$, and $\dot{W}_{pump}$ in kW.
**As a percentage of the component cost

4.3 Thermodynamic and Thermoeconmic Optimization Analysis

4.3.1 Optimization problem

In this chapter, six configurations of direct oxy combusted sCO2 power cycles integrated with dry and wet precoolers are optimized from thermodynamic and economic perspectives. The genetic algorithm (GA) is used as an optimization tool for the reasons mentioned in section 3.3 . In single-objective optimization, each objective is optimized severally, while for multi-objective optimization the weighted sum method has been chosen in this study to optimize the three objectives simultaneously. The constraints are formulated from selected decision variables which are common for both optimizations. The detailed analysis is highlighted in the following lines:

4.3.1.1 Single objective optimization

Maximize thermal efficiency (η_{th}) or Maximize overall exergy efficiency ($\varepsilon_{overall}$) or Minimize the levelized cost (LCOE)

Subject to:

- Maximum cycle pressure (P_h)

  $150 \leq P_h(bar) \leq 300$

- Minimum cycle pressure (P_l)

  $75 \leq P_l(bar) \leq 110$

- Maximum cycle temperature (T_{max})

  $550 \leq T_{max}(°C) \leq 750$

- Split ratio (S_r)

  $0.2 \leq S_r \leq 0.8\ (for\ M2\ and\ M3)$

4.3.1.2 Multiple objectives optimization

The only way to perform multi-objective optimization through EES is to use the weighted sum method. The objective function is formulated by multiple each objective with weighting coefficient as follows:

$$Max. MOF = w_1 \times \eta_{th} + w_2 \times \varepsilon_{overall} + w_3 \times (1 - \frac{LCOE}{C_{fuel}})$$

Subject to:

- Maximum cycle pressure (P_h)

  $150 \leq P_h(bar) \leq 300$

- Minimum cycle pressure (P_l)

  $75 \leq P_l(bar) \leq 110$

- Maximum cycle temperature (T_{max})

  $550 \leq T_{max}(°C) \leq 750$

- Split ratio (S_r)

  $0.2 \leq S_r \leq 0.8\ (for\ M2\ and\ M3)$

The weighting coefficients for η_{th}, $\varepsilon_{overall}$, and LCOE are W_1, W_2, and W_3 respectively, and they are assumed to be the same (W_1=W_2=W_3 = 1/3) since the three objectives are of equal significance. The fuel cost (C_{fuel}) is 7 ¢/kWhe (“Gas-Turbine Power Gener.,” 2016).

To use the equation the value of the objective’s functions should be normalized and make them all on the same scale from 0 to 1. The reason is that different orders of magnitude affect the calculation and may result in a biased optimization process in the favor of one objective over the other. Also, it is worthy to mention that the third objective is minimized (LCOE) while the other two objectives are maximized which are thermal efficiency (η_{th}) and exergy efficiency ($\varepsilon_{overall}$). The LCOE is formulated in a certain equation to fit the maximization weighted objective function.

4.3.2 Optimization domain

According to the parametric studies performed by (Sleiti, Al-Ammari, et al. 2021), the split ratio, the maximum and minimum cycle pressures, and maximum temperature have been found as the main operating conditions. In the optimization analysis, these parameters were chosen to be the decision variables that were given certain ranges within which they fluctuate between predefined upper and lower bounds. These bounds have been defined and coded in the optimization tool (GA). Table 6 shows the decision variables' upper and lower bounds which will be considered as the constraints of our optimization problem.

Table 6: The Range of The Decesion Varaibles

Decision Variables (Unit)	Lower Bound	Upper Bound	Configurations
Maximum cycle pressure P_h (bar)	150	300	M1 ,M2 and M3
Minimum cycle pressure P_l (bar)	75	110	M1 ,M2 and M3
Maximum cycle temperature T_{max} (℃)	550	750	M1, M2, and M3
Split ratio S_r	0.2	0.8	M2 and M3

It is important to mention that any individual associated with the decision variable violates the formulated constraints of the model and places the solution in the unfeasible region is deemed dead and will be eliminated from the GA population.

4.3.3 Single Objective optimization results analysis:

The table 7 shows the optimal values obtain through single objective optimizations for all the six cycle configurations which will be analyzed in the following lines:

Table 7: The Optimal Values of Single Objective Optmization

Cooling Method	Configuration	Objective Function	Decision Variables				Optimized Results		
			P_h, bar	P_l, bar	T_{max}, °C	S_r	η_{th}, %	$\varepsilon_{overall}$, %	LCOE, ¢/kWh$_e$
Wet Cooling	M1	$Max.\ \eta_{th}$	291.1	77.78	750	1.000	45.47	76.27	5.386
		$Max.\ \varepsilon_{overall}$	300.0	75.38	550	1.000	37.39	73.78	5.593
		$Min.\ LCOE$	283.4	83.72	750	1.000	45.52	76.67	5.386
	M2	$Max.\ \eta_{th}$	296.4	78.33	750	0.697	45.68	74.21	5.367
		$Max.\ \varepsilon_{overall}$	296.7	75.00	550	0.800	37.44	73.45	5.568
		$Min.\ LCOE$	300.0	90.75	750	0.600	45.46	74.48	5.363
	M3	$Max.\ \eta_{th}$	293.6	104.6	750	0.600	49.44	73.33	5.165
		$Max.\ \varepsilon_{overall}$	300.0	78.75	550	0.797	38.90	72.75	5.521
		$Min.\ LCOE$	240.0	92.48	750	0.600	49.29	74.04	5.163
Dry Cooling	M1	$Max.\ \eta_{th}$	299.8	86.97	750	1.000	44.06	74.60	6.802
		$Max.\ \varepsilon_{overall}$	300.0	75.00	550	1.000	34.78	72.71	6.894
		$Min.\ LCOE$	296.7	91.01	750	1.000	43.68	77.73	6.561
	M2	$Max.\ \eta_{th}$	298.3	83.85	750	0.729	44.81	75.40	6.538
		$Max.\ \varepsilon_{overall}$	299.1	75.24	550	0.797	34.83	73.61	6.865
		$Min.\ LCOE$	247.1	75.34	750	0.604	43.66	75.00	6.532
	M3	$Max.\ \eta_{th}$	277.1	102.4	750	0.605	47.46	75.13	6.282
		$Max.\ \varepsilon_{overall}$	292.5	76.76	550	0.800	36.17	73.78	6.792
		$Min.\ LCOE$	221.8	89.21	750	0.600	47.38	75.12	6.279

The analysis below is to find the optimal configuration for wet cooling according to single-objective optimization:

Wet cooling:

In several direct oxy-combustor cycles, the wet cooling method is used to reduce the temperature of the working fluid to a degree ranging between 15 °C and 33 °C. From a thermodynamic perspective, the ability to cool the fluid to such low temperature makes this method the best choice to be used for power cycles placed in hot climate conditions which need for large cooling demand.

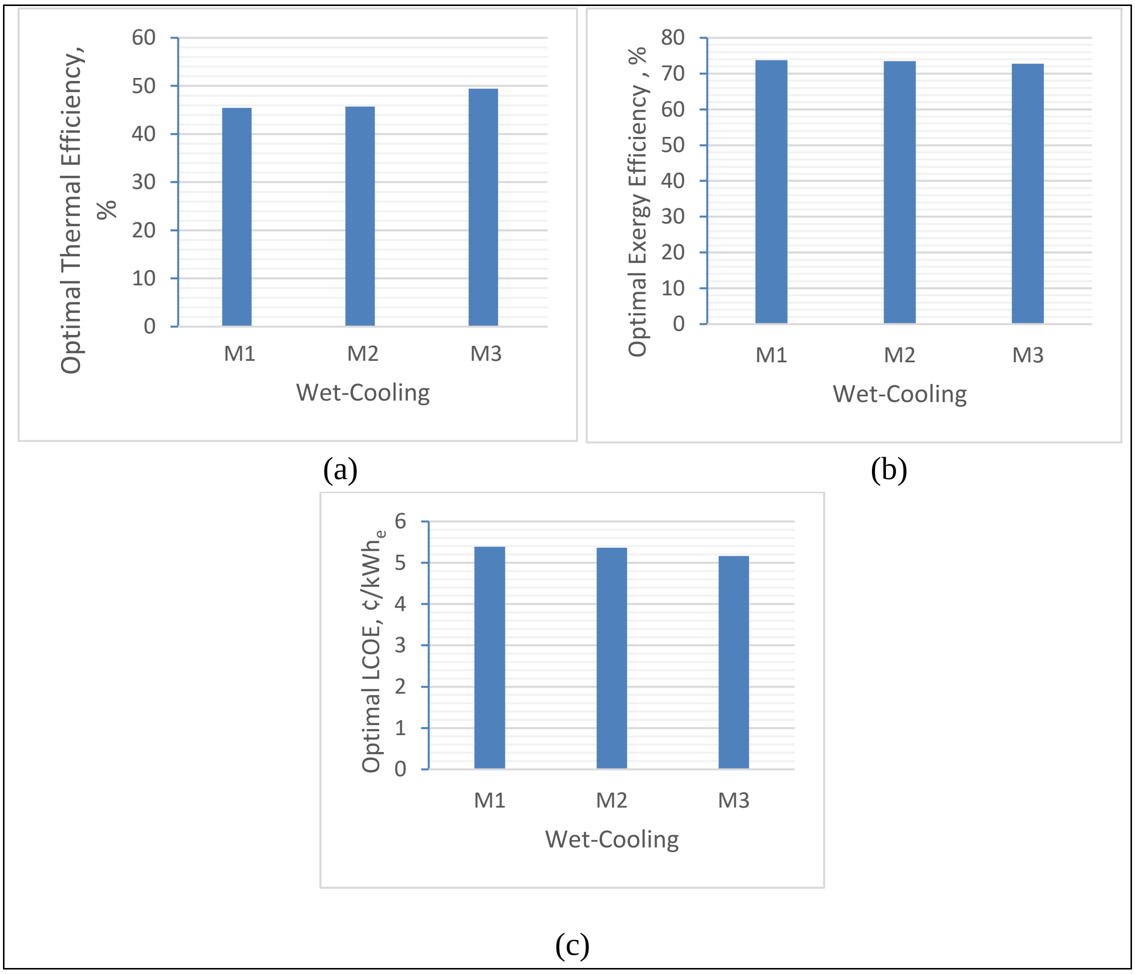


Figure 11: Single objective optimization results for three Layout configurations (M1,M2,M3) of the direct oxy-fuel cycle in wet-cooling condition (a) Optimal thermal efficiency (b) Optimal exergy efficiency, and c) Optimal levelized cost of energy (LCOE)

Considering the thermal efficiency as an objective function for single-objective optimization showed that M3 has higher optimal thermal efficiency than M2 by (7.6%) and M1 by (8%) at the following decision variables P_h = 293.6 bar, P_l=104.6 bar , T_{max}=750 ℃ and S_r=0.600. What makes M3 the optimal configuration for the wet cooling condition is integrating the preheater in parallel with both LTR and HTR which preheat part of the recycled sCO2 fluid. The preheating process has been suggested by (Sleiti, Al-Ammari, et al., 2021) to solve the great imbalance between the heat released by recuperates (2-4) and the heat necessary to raise the recycled sCO2 temperature (7-11). This reduces the fuel consumed by the oxy-combustor and the oxygen required for the combustion process as well. Therefore, the energy consumed by the ASU is reduced, and the recuperator's performance is improved which enhances the thermal efficiency of M3 over the basic cycle M1. In addition, M3 configuration has also been recorded as the lowest levelized cost of energy (LCOE) with 5.163 $¢/kWh_e$in their optimal condition at P_h = 240.0 bar, P_l=92.48 bar, T_{max}=750 ℃ and S_r=0.600. The LCOE of M3 is lower than M2 (by 3.8%) and M1 (by 4.3%). The reason is that one of the parameters that influence the value of LCOE is the component's cost. By adding the preheater, the heat transfer area in the recuperator is reduced which makes the design of the recuperators simpler and reduces their costs hints, LCOE is minimized. It is worthy to mention that wet cooling condition contributes in improving the thermal efficiency which minimizes the LCOE. Because reducing the temperature level at the recuperators' terminals increase the temperature difference between the cold and hot stream; thus, the needed heat transfer area is minimized making the size of the heat exchanger simpler and smaller. However, optimizing the exergy efficiency revealed that M1 has higher exergy efficiency than M2 (by 0.45%) and M3 (by 1.4%) at the following decision variables P_h = 300 bar, P_l=75.38 bar , T_{max}=550 ℃ and S_r=1.000.

To analyze the exergy efficiency, a comprehensive evaluation is conducted to locate the components that cause exergy destruction due to irreversible processes. The percentage of exergy destruction in the preheater, LTR, and HTR is greater in wet cooling than in dry cooling configurations due to the high difference between the temperature of the hot and cold streams. Thus, M1 is the optimal configuration in wet-cooling conditions from an exergy efficiency perspective. In addition, increasing the number of the components in the cycle creates different sources for exergy distraction which is not the case in M1 configuration as it has the lowest number of components Also, it can be noticed that the value of the split ratio (S_r) reach the upper limit. Based on the parametric analysis presented in (Sleiti, Al-Ammari, et al., 2021), the increase in the value of S_r reduces the inlet temperature at the precooler which greatly minimizes the rate of exergy destruction and increases the exergy efficiency of the cycle. To sum up, in the wet cooling condition it is recommended to select M3 if the objective is to maximize the thermal efficiency or minimize the LCOE and M1 if the objective is to maximize the exergy efficiency from single-objective optimization point of view as shown in Table 8

Table 8: Single Objective Optimization Results in Wet-Cooling Conditions

Single objective optimization for Wet- cooling condition			
Configurations	Optimal Results		
	Max η_{th}, %	Max $\varepsilon_{overall}$, %	Min LCOE
M1	45.47	**73.78**	5.386
M2	45.68	73.45	5.363
M3	**49.44**	72.75	**5.163**

The analysis below is to find the optimal configuration for dry cooling according to single-objective optimization:

Dry-Cooling:

The dry cooling method (cooling by air) is usually utilized in different direct sCO2 cycles to lower the working fluid temperature from 40℃ to 50℃. This method has proven to be effective in different weather conditions as well as being more cost-effective in terms of capital and maintenance cost comparing with the wet-cooling method.

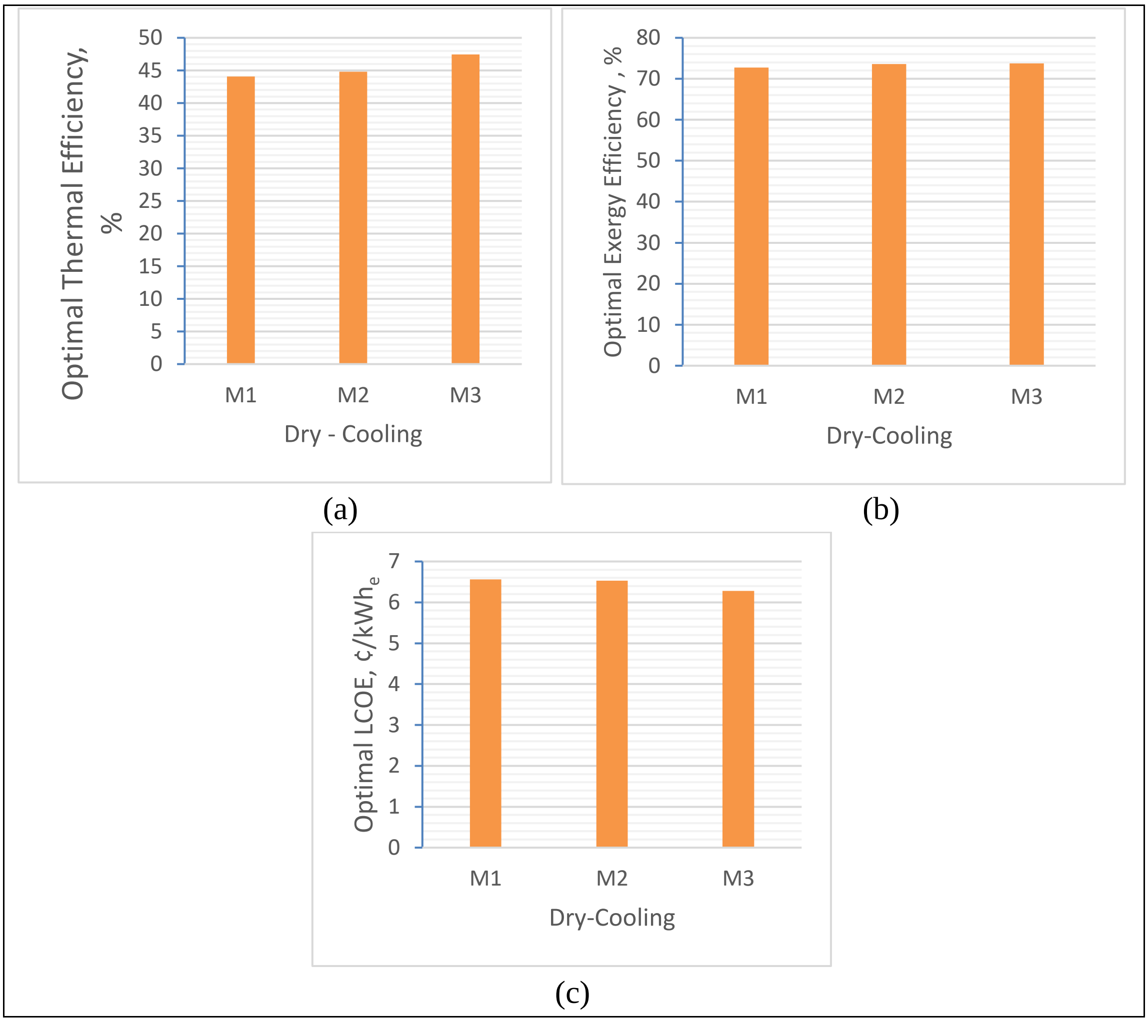


Figure 12: Single objective optimization results for three Layout configurations (M1, M2, M3) of the direct oxy-fuel cycle in dry-cooling condition (a) Optimal thermal efficiency (b) Optimal exergy efficiency, and c) Optimal levelized cost of energy (LCOE)

Performing the single objective optimization for dry-cooling configurations showed that M3 is the optimal configuration from energy, exergy, and economic perspective. Maximizing the thermal efficiency result in 47.46 % for M3 at P_h = 277.1 bar, P_l=102.4 bar, T_{max}=750 ℃ and S_r=0.605 as decisions variables. The thermal efficiency of M3 is higher than M2 (by 5.6 %) and M1 (by 7.2%). As expected, adding the preheater to the cycle plays an essential role in improving the thermal efficiency in both wet and dry cooling conditions. However, to understand which factor influence the thermal efficiency of the power cycle more whether the cooling condition or adding of the preheater let's compare the thermal efficiencies of M3 (with preheater) in dry cooling condition and M1 (without preheater) in wet cooling condition. The results showed that M3 (dry) has higher thermal efficiency than M1 (wet) by 3.8%, indicating that the preheater' improvement in reducing the fuel consumption and improving the functionality of the recuperators has more influence than wet cooling in M1 which minimize the compression power in GC due to the liquid state of sCO2. Also, if we compare M3 operates at the wet-cooling condition with M3 operates at the dry-cooling condition, the M3 (wet) thermal efficiency is higher than M3 (dry) by 4%. To conclude, both the wet cooling condition and the preheater improve the energy performance of the system; however, the cycle configuration (adding preheater) has more influence than the cooling condition. Considering the exergy efficiency as an objective function, M3 has also the maximum value of exergy efficiency with 73.78% at P_h = 292.5 bar, P_l=76.76 bar, T_{max}=550 ℃ and S_r=0.800. It is worth noting that we obtained the same value of exergy efficiency for M1 in wet configuration. However, the exergy performance in dry-cooling is higher than wet-cooling due to the large temperature difference between the hot and cold stream in wet cooling. Also, the preheater was effectively able to minimize the exergy destruction through the oxy-combustor by improving the recycled sCO2 temperature at the combustor inlet. From economic perspective, the LCOE of M3 is lower than M2 (by 4%) and lower than M1 (by 4.5%) at the following decision variables P_h = 221.8 bar, P_l=89.21 bar, T_{max}=750 ℃ and S_r=0.600. Beside that M3 has the highest thermal efficiency which leads to lower LCOE, the dry cooling condition is economically effective more than the wet cooling condition due to lower capital and maintenance cost. Cooling the working fluid by water is costly due to the water cost, the needed facilities like pipes, containers and permanent water source and the maintenance cost that results from water impurities which causing problems in the cycle components such as heat exchanger fouling. In summary, in dry cooling condition M3 is the optimal configuration for maximizing the thermal efficiency , maximize the exergy efficiency and minimizing the LCOE from single objective optimization point of view as shown in Table 9

Table 9: Single Objective Optimization Results in Dry-Cooling Conditions

Single objective optimization for dry-cooling condition			
Configurations	Optimal results		
	Max η_{th}, %	Max $\varepsilon_{overall}$, %	Min LCOE
M1	44.06	72.71	6.561
M2	44.81	73.61	6.532
M3	**47.46**	**73.78**	**6.279**

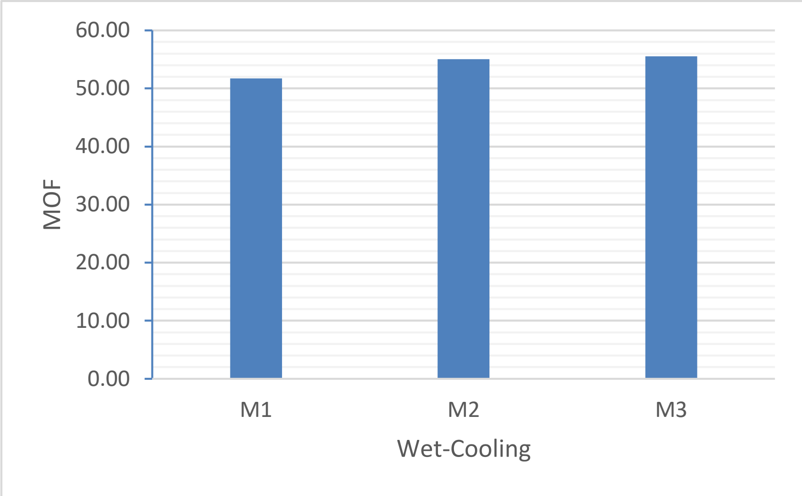
4.3.4 Multi objective optimization results analysis

The table 10 shows the optimal values obtain through multi-objective optimizations for all the six cycle configurations which will be analyzed in the following lines:

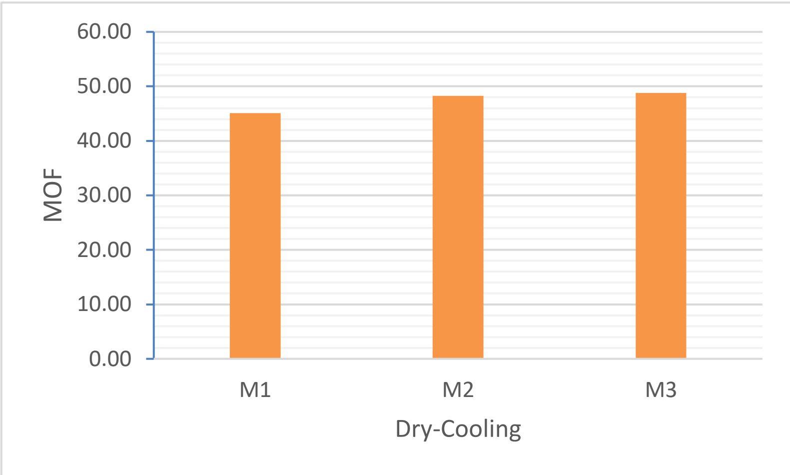
Table 10: The Optimal Value of Multi-Objective Optmization

Cooling Method	Configurations	Weights	Objective function	Decision Variables				Optimized Results			
				P_h, bar	P_l, bar	T_{max}, °C	S_r	η_{th} %	$\varepsilon_{overall}$ %	LCOE ¢/kWh$_e$	MOF
Wet Cooling	M1	0.33	*Max. MOF*	262.5	80.83	550	45.02	45.02	91.46	5.69	51.72
	M2	0.33	*Max. MOF*	225.2	81.02	550.2	52.86	39.33	88.82	5.35	55.07
	M3	0.33	*Max. MOF*	226.4	82.68	552.3	62.42	30.06	78.79	5.23	55.52
Dry Cooling	M1	0.33	*Max. MOF*	299.5	110	550.5	38.15	38.15	89.64	6.47	45.12
	M2	0.33	*Max. MOF*	284.1	110	554.2	44.23	32.86	87.78	6.11	48.24
	M3	0.33	*Max. MOF*	271.4	109.9	552.4	51.52	27.52	80.43	5.99	48.78

The analysis below is to find the best configuration according to Multi objective optimization.



(a)



(b)

Figure 13: Multi-objective optimization results for three Layout configurations (M1,M2,M3) of the direct oxy-fuel cycle (a) Weighted multi-objective function for wet-cooling condition (MOF) (b)Weighted multi-objective function for dry-cooling condition (MOF)

Performing multi-objective optimization and comparing the MOF results for M1, M2, and M3, it is shown that M3 is the optimal configuration for maximizing both the η_{th} and $\varepsilon_{overall}$ and minimizing the LCOE. The value of MOF depends on the selected weights that determine the decision-maker preference and the trade-off between the objective function values. In this case, the decision-maker gives equal importance for all three objectives with the weight of 0.33. Based on results, in wet and dry cooling conditions M3 has higher thermal efficiency than M1 (wet) by 27.88 % and M1 (dry) by 25.95%. It also has lower LCOE than M1(wet) by 8.9% and M1 (dry) by 7.97%. Contrary, M1 has higher exergy efficiency than M3 (wet) by 13.85% and M3 (dry) by 10.27% which is a small difference comparing with thermal efficiency and LCOE values. This makes the energy and economic performance of M3 configuration better than the exergy performance of M1 configuration. Comparing M2 with M3, it is shown that M3 has higher thermal efficiency than M2 (wet) by 15.3 % and M2 (dry) by 14.14 %, and lower LCOE than M2 (wet) by 2.4 % and M2 (dry) by 1.97 %. On the other hand, M2 has higher exergy efficiency than M3(wet) by 11.3% and M3 (dry) by 8.4 % which makes M3 outperform M2 in multi-objective optimization (MOF). To conclude the integration of the preheater, improve the thermal efficiency and minimize the LCOE but it increases the exergy distraction of the cycle making M1 (without preheater) and M2 (preheater connect to LTR only) obtain better exergy performance. Analyzing the optimal configuration M3 for multi-objective optimization, it can be seen that M3 at wet cooling condition obtain better results in term of maximizing the thermal efficiency and minimizing the LCOE. The maximum energy efficiency for M3 is 62.42% (wet) at T_{max} = 552.3 ^oC, P_h = 226.4 bar, P_l = 82.68 bar, and S_r = 0.73 and 51.52 % (dry) at T_{max} = 552.4 ^oC, P_h = 271.4 bar, P_l = 109.9 bar, and S_r = 0.63 while the LCOE is minimized for M3 (wet) by 5.225 ¢/kWh$_e$ and M3 (dry) by 5.992 ¢/kWh$_e$.. The reason is that wet-cooling condition significantly reduce the temperature of fluid creating a high-temperature difference between the hot and cold stream and increasing the heat exchange which enhances the thermal efficiency. Also, it leads to minimizing the LCOE as simpler and smaller recuperators are enough to perform the required task. For the same reason, the exergy distraction of wet-cooling is higher than dry cooling make it results in better exergy efficiency. The exergy efficiency is maximized for M3 (wet) by 78.79% and M3 (dry) by 80.43%. Also, it is suggested that high-pressure ratio is better for wet-cooling setups while low-pressure ratios is advised for dry-cooling configurations to maximize both thermal and exergy efficiency and minimize the LCOE. The results are summarized in below table 11.

Table 11:Multi Objective Optimization Results in a Wet and Dry Cooling Condition

Multi-Objective Optimization (MOF)					
Cooling Method	Configurations	Optimal results			
		Max η_{th}, %	Max $\varepsilon_{overall}$, %	Min LCOE	MOF
Wet-Cooling	M1	45.02	91.46	5.692	51.72
	M2	52.86	88.82	5.352	55.07
	M3	62.42	78.79	5.225	**55.52**
Dry-Cooling	M1	38.15	89.64	6.47	45.12
	M2	44.23	87.78	6.11	48.24
	M3	51.52	80.43	5.992	**48.78**
Wights		0.33	0.33	0.33	

4.4 Sensitive analysis for weighted multi-objective optimization

In this chapter, the multi-objective optimization results are presented and discussed in three subsections with the variation of the energy efficiency weight (W_1), exergy efficiency weight (W_2), and LCOE weight (W_3) from 0.25 to o.45. The variation of the weighting coefficient depends on the final goals of the optimization process. For instance, higher weight is given for W_1 if the optimization process is aimed to compares different configurations and/or minimizes the fuel consumption and emissions. If the design of the components is the target of the optimization process, then a higher weight is given for W_2. For the most feasible and economic scenario, W_3 is given the highest weight. Therefore, it is important to investigate how significant the variation of the weighting coefficients affects the performance indicators in the multi-weighted objective function, which is presented in the following subsections.

4.4.1 Weight coefficient of the thermal efficiency (W_1)

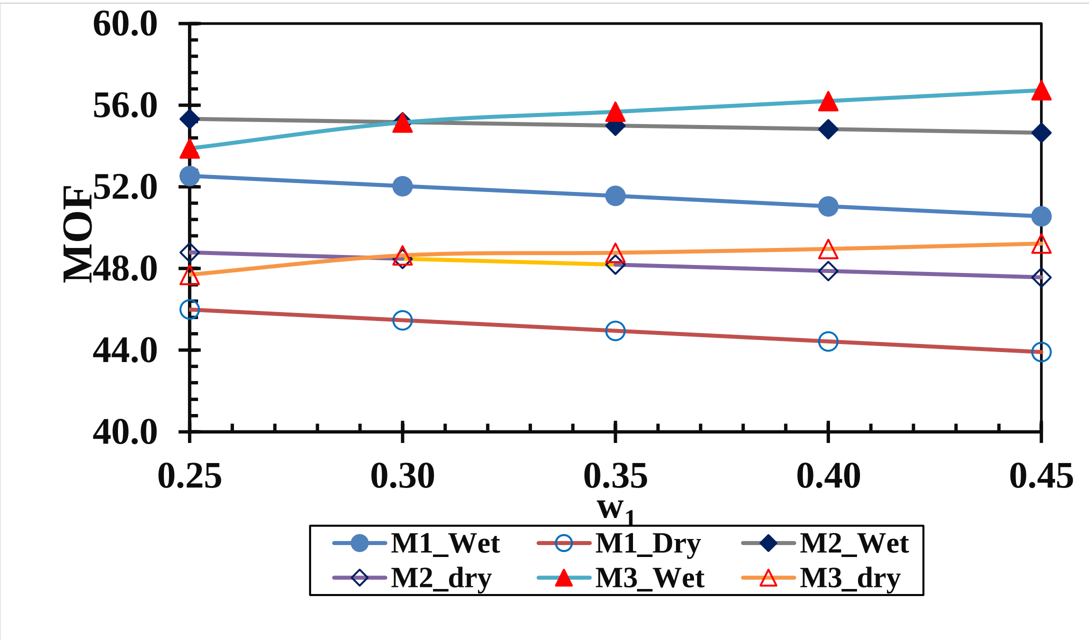


Figure 14: Variation of the weight coefficient of the thermal efficiency (W_1).

According to Figure 14, the increase of weight coefficient of the thermal efficiency (W_1) decrease the value of the multi-objectives function (MOF) for all the configurations except for M3 integrated with wet and dry precooler. As shown, the MOF value for M3 (wet) increased by 5.3% over the range make it the best configuration from multi-objective optimization in wet and dry cooling conditions. However, from 0.25 to 0.3 the M2 (wet) is better than M3 (wet) due to its high exergy efficiency which during this range it gives higher weight than the thermal efficiency wight e.g. at W_1=0.25 the $W_2 = 0.375$ while at W_1=0.3 the $W_2 = 0.35$ result in higher MOF for M2. Once the thermal efficiency is given higher weight the value of MOF for M3 (wet) exceed M2 (wet). Also, from the data M3(wet) has higher thermal efficiency and lower LCOE than M2 (wet) while the exergy efficiency of M2 (wet) is higher than M3 (wet) due to preheater integration. The same scenario is applied on dry cooling configuration as shown the MOF of M3(dry) increased by 4.7% which make it the best configuration. Also, M2(dry) is better than M3(dry) for range less than W_1=0.3. In addition, all the wet cooling configurations obtain better MOF values than dry cooling configurations which shows that wet cooling play a role in improving the thermal efficiency.

4.4.2 Weight coefficient of the exergy efficiency (W_2)

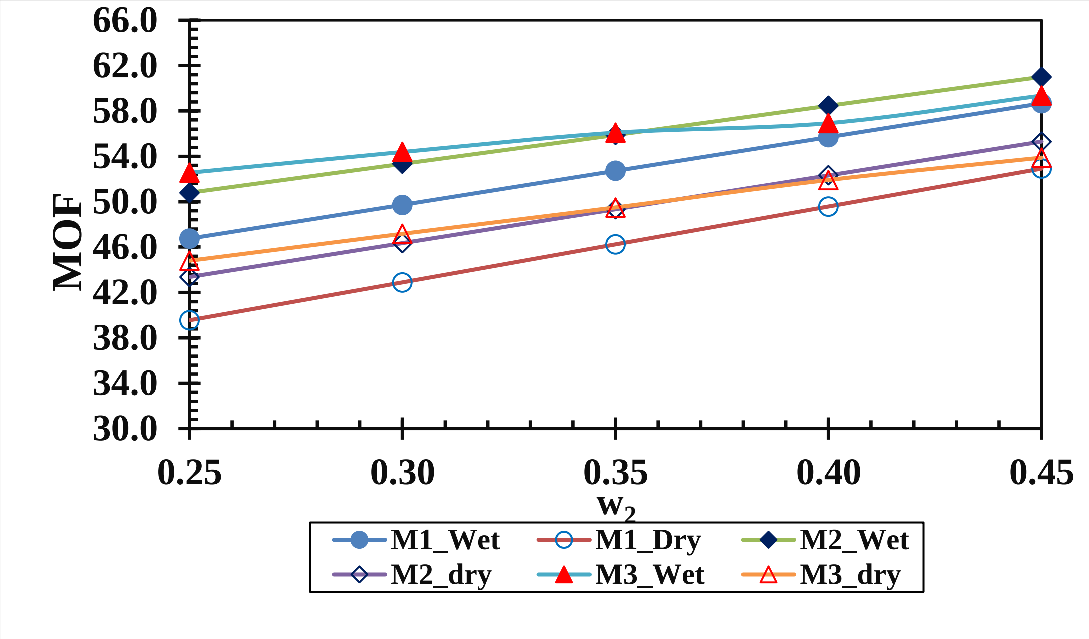


Figure 15:Variation of the weight coefficient of the exergy efficiency (W_2).

As shown in Figure 15 the values of MOF for all the six configurations are linearly increasing with the increase of the exergy efficiency weight coefficient. This gives an indication that the exergy efficiency has a high influence on the value of multi-objective function comparing with the other two objectives. In wet-cooling condition, from 0.25 to 0.35 M3(wet) has the highest MOF value which increased by 23.86 % while from 0.35 to 0.45 M2 (wet) become the highest which increased by 20%. Analysing the objective functions at each MOF value, M3(wet) result in higher thermal efficiency by 16.4% and lower LCOE by 2.7% than M2 (wet) for wights up to W_2=0.35 which is the range that gives higher weights to the energy and economic performance indicators. However, from 0.35 and higher the thermal efficiency of M3(wet) has dropped and become higher by only 0.37% while the LCOE increased and become higher than M2 (wet) by 1.5%. This affects the maximization objective function and decreases it giving the chance to MOF for M2(wet) to increase by increasing the exergy efficiency. Similarly, in dry cooling condition M3(dry) consider the best configuration for weights up to W_2=0.35 while M2 (dry) exceed M3 (dry) for wights above W_2=0.35.

4.4.3 Weight coefficient of the LCOE (W_3)

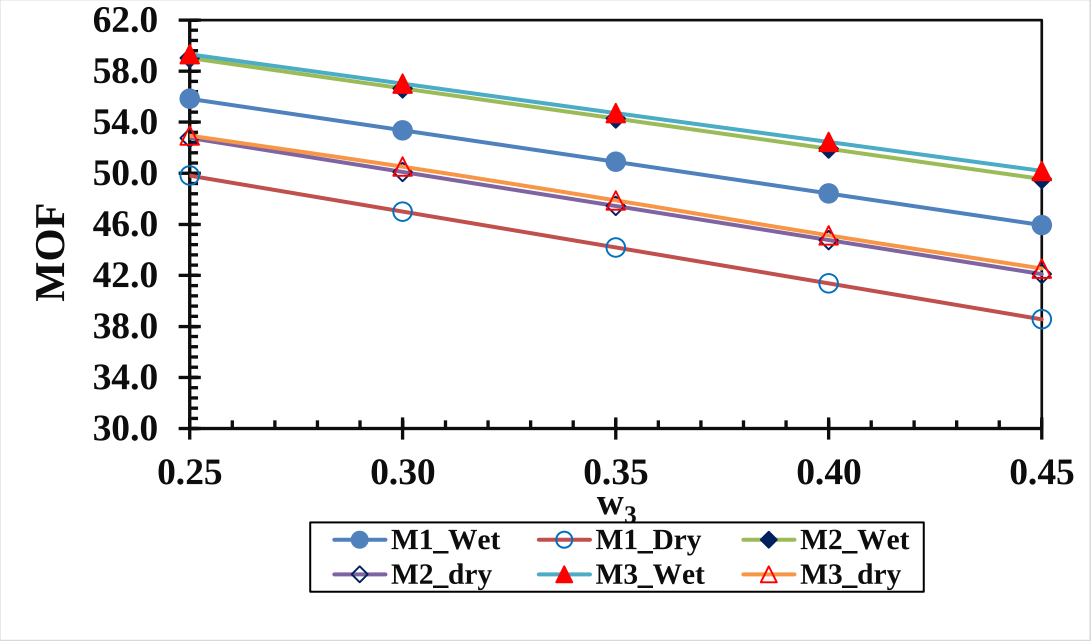


Figure 16:Variation of the weight coefficient of the LCOE (W_3)

Figure 16 shows the decreasing of MOF values for all the six configurations in wet and dry cooling condition as the weight coefficient of the LCOE (W_3) increasing. It is important to mention that as the value of MOF is maximized, the LCOE is minimized due to the LCOE formula in the weighted objective function. Clearly, MOF for M3(wet) gives the maximum values no matter the value of the weighting coefficient. Also, M2(wet) gives almost similar MOF results as M3 (wet) which could be a promising configuration. The MOF value of M3 (wet) and M2 (wet) is decreased by 26.56% and 16% respectively. A good justification could be in the increasing of the thermal efficiency which leads to minimizing LCOE. Following the same pattern, the dry cooling configurations show that M3(dry) and M2(dry) are the best configurations from a multi-objective function optimization point of view. The MOF value of M3 (dry) is decreased by 19.7% while M2 (dry) is decreased by 20.22 %. Based on the percentage values, the variation of the weight coefficient of the LCOE (W_3) is significantly affecting the value of MOF.

To sum up, based on the above graphs in wet cooling condition, the best configuration that maximizes both thermal efficiency, exergy efficiency, and minimized the LCOE is M3(wet), while M3 (dry) is recommended for the dry cooling condition. To obtain the best optimization results, the following wights are recommended in weighted multi-objective optimization for wet cooling condition and dry cooling condition W_1=0.275, W_2=0.45 W_3=0.275 to obtain the Max value of MOF.

CHAPTER 5: CONCLUSION AND FUTURE WORK

Three novel cycle configurations have been proposed and analyzed from energy, exergy, and economic performance through performing thermodynamic and thermoeconomic optimization. The first investigated cycle (M1) was the basic direct oxy-fuel sCO2 cycle without preheater (Figure 9). The second analyzed cycle (M2) consists of the same cycle components as (M1) with a preheater integrated with LTR (Figure 10) while the third studied cycle (M3) integrates the preheater in parallel with LTR and HTR (Figure 11). These cycles have been analyzed in two cooling conditions: the wet cooling condition where the cycles are equipped by wet precooler (WPC) and the dry cooling condition which integrates dry precooler (DPC) resulting in six configurations. Besides utilizing supercritical CO2 (sCO2) as the working fluid which proved its rule in improving the performance indicator of the thermodynamic cycles, the proposed cycles are able to produce pure drinking water and export a small amount of CO2 which could be used in other commercial purposes.

To offer the decision-maker a framework to choose the best optimal configuration that meets their energy and economic goals considering cooling conditions. Single and multi-objective optimizations were performed using a Genetic algorithm (GA) as an optimization tool. This tool was chosen in this study due to its ability to deal with the nature of the energy system. Such a system is non-linear, consists of multiple local optimums, and has many decision variables creating a multidimensional optimization area. GA is a powerful optimization algorithm that is able to find the best global optimum and not get trapped in local ones. In addition, it doesn't depend on a differential mathematical formula that simplifies the model and mathematical computations.

Thermal efficiency (η_{th}) , exergy efficiency $(\varepsilon_{overall})$ and levelized cost of energy (LCOE) were the three optimized objectives severally in single-objective optimization and simultaneously in multi-objective optimization using the weighted sum method. The optimization analysis was performed for all six configurations in both wet and dry cooling conditions and the findings were presented in a comparative study. In addition, sensitivity analyses were performed to study the influence of the wights on the weighted multi-objective optimization and find the optimal configuration according to the decision-maker preference. The main results of this study are summarized as follows:

- The single objective optimization for wet-cooling configurations showed that M3 has the highest optimal thermal efficiency compared with M2 (by 7.6%) and M1 (by 8 %) and the lowest levelized cost of energy (LCOE) relatively with M2 (by 3.8%) and M1 (by 4.3%). However, M1 obtained the highest optimal exergy efficiency by prevailing in minor differences.
- In dry-cooling condition, M3 has higher thermal efficiency than M2 (by 5.6 %) and M1 (by 7.2%), lower LCOE than M2 (by 4%) and M1 (by 4.5%), and the lowest exergy efficiency with a minimal difference from single-objective optimization prospective
- In multi-objective optimization, M3 is considered as an optimal cycle configuration in both wet and dry cooling conditions.
- The sensitivity analysis showed that W2 and W3 has more influence on the value of MOF than W1
- Varying the weights from 0.25 to 0.45 showed that M3 is the optimal configuration in wet and dry cooling conditions.
- Both wet-cooling and pre-heater integration improve the thermal efficiency of a cycle; however, the cycle configuration (adding preheater) has a higher

influence than the cooling condition

- Wet-cooling creates higher exergy destruction than dry-cooling due to the large temperature difference in the recuperators making the exergy performance of dry cooling better.
- Improving the thermal efficiency of the cycle leads to better LCOE
- Preheater improves the energy performance of the cycle (thermal efficiency) but it negatively affects the exergy performance (exergy efficiency)

As this study is in the development stage, the following areas could be considered for future development and research studies:

- Components level optimization could be implanted to find the optimal design of the cycle's components such as heat exchangers and turbines which significantly affect the performance indicators.
- Various optimization algorithms can be implemented to perform single and multiple objective optimizations like PSO, NSGA II, and Pareto and compare their results with GA used in this study.
- Improve the programming code and modify it to generate the set of the Pareto fronts for multi-objective optimization which gives a better understanding of the optimal solutions.
- Perform a parametric study to customize the control parameters of the genetic algorithms (GA) according to the nature of the optimized power cycle which increases the effectiveness of the used tool.

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