Chapter 2

Literature review

This chapter covers the recent studies carried out in the field of integrated energy systems typically cogeneration and trigeneration systems. The literature in this chapter has been separated into four categories: energy and exergy analyses, exergoeconomic analysis, environmental analysis, and multi-objective optimization. The main objective of the current chapter is to determine the research gap, the thrust area of cogeneration and trigeneration systems. Finally, this chapter is concluded with the scope of the research work carried out in this thesis.

2.1 Energy and Exergy analyses

Energy analysis is a quantitative assessment that considers energy entering and departing the system and is based on the first law of thermodynamics [32]. Exergy analysis, which is based on the second law of thermodynamics, is a qualitative investigation that determines the magnitude of system inefficiencies as well as their causes and locations [27]. It provides a more practical performance indicator: second law efficiency, also known as exergy efficiency, which measures how closely a system performs to ideal performance. Exergy analysis therefore accurately pinpoints the gap available to develop more efficient energy systems by decreasing inefficiencies [17]. In thermodynamic performance evaluation, exergy analysis provides more insights and is more effective in efforts to increase the efficiency of a system than energy analysis [17, 26]. In energy analysis, the thermodynamic quality of the energy source is not taken into consideration. Exergy, on the other hand, is a measure of both quantity and quality. However, the data needed for exergy analysis, such as enthalpy, mass flow rate, entropy values, etc., may be acquired through energy analysis, hence one must first perform energy analysis before performing exergy analysis [17]. In fact, exergy analysis becomes more important in cogeneration and trigeneration systems because heat (typically in the form of steam or hot water) or cooling effect is produced beside electricity. It is misleading to regard heat and cooling effects similarly in the context of energy analysis because they do not have the same quality as electricity. Exergy analysis is therefore widely employed in cogeneration and trigeneration systems to increase their efficiency by lowering losses [98].

Energy and exergy analysis has been used extensively in many studies to assess the performance of cogeneration and trigeneration systems. Bejan et al. [17] presented one of the earliest works on the energy and exergy analysis of a cogeneration system. The cogeneration system under consideration uses a Recuperative GT cycle as the prime mover coupled with an HRSG to produce saturated steam. The cogeneration system generates a total of 30 MW of power and 14 kg/s of steam at a pressure of 12 bar. They defined the exergy efficiency of a cogeneration system as the ratio between the exergy supplied to the system and the system's total net output power plus the increase in the exergy of water passing through the HRSG. They also emphasized the distinction between exergy loss and exergy destruction in a system. They suggested that the exergy rejected from the system through flue gas or condensate should be regarded as an exergy loss. On the other hand, exergy destruction should be conceived as the loss of exergy in the system as a result of the existence of system irreversibilities. Another key study in this domain was carried out by Balli et al. [14] where the exergy analysis of a GT-HRSG-based CHP system was performed. They used an exergy flow diagram to illustrate the exergy destruction in each component of the CHP system. It was found that the combustion chamber (CC) had the highest exergy destruction accounting for 41.95% of the overall exergy destruction, followed by HRSG with 4.16%. In subsequent work, Balli and Aras [13] carried out the exergy analysis of another GT-HRSG-based CHP system that produces electricity of 99.15 kW and hot water of 155.40 kW. They evaluated the exergetic performance of each component, as well as the overall CHP system, in terms of exergy destruction and exergy efficiency. The exergy efficiency of the CHP system was found to be 35.80%. Additionally, they claimed that the highest exergy destruction occurred in CC.

In another study, Yoru et al. [98] conducted an exergy analysis of a CHP system installed in the ceramic industry in Izmir, Turkey. The system included two heat exchangers, six spray dryers, and three GT cycles with a combined power rating of 13 MW. According to their findings, the temperature of the surrounding air had a significant impact on the exergetic performance of the CHP system. They found that the exergy efficiency of the CHP system was 34.70% at an ambient temperature of 287.15 K. In a similar study, Rian and Ertesvag [64] evaluated the exergetic performance of a GT-HRSG-based CHP system at various ambient temperatures. They found that as the ambient temperature increased from 20 °C to 36 °C, the exergy efficiency of the CHP system dropped from 42.7% to 41.9%. The CHP systems discussed in the above studies [13, 14, 17, 64, 98] had the same GT-HRSG integration scheme. However, in some other studies, the exergy analysis was also performed on GT-HRSG-ORC configurations.

The ORC is an effective heat recovery technology commonly employed in integrated energy systems. Studies revealed that the cycle efficiency could be improved with a modification in the layout of Basic ORC. The most common modification is the addition of an internal heat exchanger (IHE) into the Basic ORC. This configuration is typically designated as Recuperative ORC [8]. It uses the IHE to preheat the working fluid at the condenser outlet using surplus heat available at the turbine exit. The dry working fluids are ideal for Recuperative ORC because there is enough sensible heat available for recovery at the turbine exit.Moreover, the use of an IHE will increase the thermal efficiency of the ORC if there is no upper limit to the temperature at which the flue gas must be cooled [18]. Regenerative ORC is another configuration [99] in which, a small amount of vapour is extracted from the turbine at a suitable pressure and mixed with the condenser outlet stream in a feed heater (FH). Consequently, the working fluid is preheated before its entry into the heat recovery vapour generator (HRVG) causing an efficiency improvement. The Recuperative-Regenerative ORC (RR-ORC) is the next modified configuration that incorporates both the IHE and the turbine bleeding into the Basic ORC.

Several studies incorporated various layouts of ORC in integrated energy systems. For instance, Anvari et al. [11] proposed a CHP system where Regenerative ORC was employed for recovering the waste heat from the exhaust coming out of the GT-HRSG cycle. They evaluated the performance by applying exergy analysis and reported that with the introduction of the Regenerative ORC, the overall exergy efficiency of the plant increased and the exergy destruction rate decreased. Additionally, they found that the CC alone is responsible for 64% of total exergy destruction. They further investigated the effect of various operating conditions on the exergetic performance of the CHP system. They observed that by raising the air compressor outlet and GT inlet temperatures, the exergy efficiency of the CHP system increases. However, they also noticed that as the condenser and evaporator temperatures of the Regenerative ORC rise, the exergy efficiency of the CHP system decreases. Yagli et al. [93] proposed a CHP system comprising Recuperative ORC and HRSG. The results showed that by incorporating HRSG and Recuperative ORC into a simple GT cycle, the exergy efficiency improved from 47% to 75.51%.

Exergy analysis has also been used in some other research studies to determine the performance of CCPP. Ersayin et al. [30] performed an exergy analysis of an operational CCPP located in Izmir, Turkey, utilizing the operational data gathered from the plant's control unit. The CCPP consists of two simple GT cycles that are individually coupled to two separate HRSGs, with the steam produced at each HRSG being utilized to drive an ST unit. They observed that CC shares 63% of the overall plant's exergy destruction. They also recommended adjusting the air-fuel ratio and lowering the amount of excess air that enters the CC to achieve optimum combustion and reduce exergy destruction. Oko et al. [60] investigated the exergy analysis of an operational GT-ST based CCPP that was augmented with an ORC to generate additional power. They observed that using the GT exhaust heat to drive ORC increased energy and exergy efficiency by 1.95% and 1.93%, respectively. The CCPP components exhibited varying levels of exergy destruction, with the CC having the highest at 59%. In the ORC, the evaporator showed the most exergy destruction at 62%. Ibrahim et al. [35] presented a detailed review article on the exergy analysis of a CCPP. They emphasized that while exergy analysis is a useful tool for evaluating the performance of a CCPP, it is also possible to reduce fuel consumption and air pollution emissions by suggesting a more efficient layout for the CCPP. Altarawneh et al. [9] performed the exergy analysis of CCPP located in Jordan. They also observed that the CC is the main source of exergy destruction in the plant. They also suggested some solutions to reduce the exergy destruction of the CC. They asserted that lowering the air-fuel ratio and preheating the air entering the CC could significantly reduce the irreversibilities in the CC.

Fontalvo et al. [31] investigated the exergetic performance of a CPC system that included a Rankine cycle as the prime mover and a single effect ACS as the cooling unit. They considered the ammonia-water mixture as the working medium for operating the overall system. The results showed that the absorber, boiler, and turbine are the prime source of exergy destruction in the system. They also reported that as turbine efficiency increases, the system's irreversibility reduces. Khaliq et al. [39] also performed an exergy analysis on a CPC system with an architecture identical to that examined by Fontalvo et al. [31]. They observed that the exergy destruction in each component varies significantly with flue gas temperature and pinch point temperature difference (PPTD). Rostamzadhe et al. [67] suggested a

CPC plant, using an ORC as the prime mover and an Ejector Refergriation System (ERS) as the cooling unit. They observed that the generator is the component with the highest exergy destruction. Consequently, they concluded that the exergy efficiency of the plant can be improved by either raising the generator pressure or lowering the evaporator pressure and condenser temperature. In another study, Sun et al. [75] compared the performance of a single-effect ACS and an ERS, separately integrated with an R113-operated ORC. They found that the exergy efficiency of the ORC-ACS based CPC system is better than the ORC-ERS based CPC system.

Trigeneration systems are often modified versions of cogeneration systems that use thermal energy to produce both heating and cooling, as opposed to a cogeneration system that only does one of the two [28]. The trigeneration systems are also popularly called combined cooling, heating and power (CCHP) systems. Based on the total amount of energy produced, CCHP systems can be classified into micro (20 kW), small-scale (20 kW-1 MW), medium-scale (1-10 MW), and large-scale ($>$ 10 MW) systems [92]. The size of distributed CCHP systems spans from less than 1 kW in residential buildings to more than 10 MW in hospitals or university campuses, and as much as 300 MW to deliver energy to an area of a city [2, 92]. CCHP systems have an even higher thermal efficiency than cogeneration systems since their waste heat recovery potential is greater than that of cogeneration systems [63]. The CCHP systems also have a lower environmental impact since they utilize waste heat instead of burning fossil fuels or using electricity to generate heating and cooling [72]. In countries where carbon taxes have already been implemented, CCHP systems can help to reduce the level of the taxes [28]. As a result, many countries throughout the world are actively implementing changes to their fossil fuel-based power plants to utilize waste heat for generating heating and cooling. To further increase overall performance, many researchers have investigated various CCHP system configurations and evaluated the performance using energy and exergy analyses.

Khaliq [38] evaluated the exergetic performance of a GT-HRSG-ACS integrated system as functions of compressor pressure ratio, turbine inlet temperature, HRSG pressure and ACS's evaporator temperature. He reported that more than 80% of the total exergy destruction is accounted by the CC and the HRSG. Further, he observed that when the compressor pressure ratio increases, the exergy destruction at the CC and the HRSG decreases, whereas the opposite was true with the increase in turbine inlet temperature. It was also noticed that as the HRSG pressure rises, the exergy destruction in the ACS increases while it decreases in the HRSG. Furthermore, as the evaporator temperature rises, exergy destruction at the evaporator increases while it marginally declines in the other components of the ACS. Mohammedi et al. [57] considered a combined GT-ORC-ACS-based system where the GT exhaust was used first to drive the toluene-operated ORC and next to the ammonia-water-based ACS. Under the design conditions, the plant could produce 30 kW of net power, 8 kW of cooling and 7.2-ton hot water with 67.6% efficiency. They also performed a parametric study and found that, in comparison to ORC and ACS operating conditions, the GT cycle's operating conditions had a considerable impact on the overall performance of the CCHP system.

Sadreddini et al. [69] suggested a CCHP system consisting of a GT cycle, a compressed air energy storage system, ORC, and ERS. The proposed system generates 0.3 kW of cooling, 25.5 kW of heating, and 34 kW of power under base operating conditions. Also, they observed that the performance of the CCHP system was most affected by the operating conditions of the compressed air energy storage system. Additionally, it was revealed that CC alone is responsible for close to 50% of the total exergy degradation. Anvari et al. [12] proposed a CCHP system that is composed of a Recuperative GT cycle, HRSG, Regenerative ORC and a single-effect ACS. The proposed CCHP system produced a total of 33.60 MW of net power, 40.78 MW of process heat, and 1 MW of cooling load. They noticed a 2.5% improvement in exergy efficiency after Regenerative ORC was introduced to the GT-HRSG integrated system. Similarly, a 0.75% improvement in exergy efficiency was observed with the addition of ACS to the GT-HRSG-ORC integrated system. Additionally, they observed that the CC and the HRSG are the primary locations for exergy destruction, respectively accounting for 63.7% and 13.7% of the overall system's irreversibilities. Moreover, the ORC and the ACS each account for 2.3% and 0.5% of the total exergy destruction.

2.2 Exergoeconomic analysis

Exergoeconomic analysis is a comprehensive approach that incorporates the exergy concept and economic aspects. It provides information that is not available through traditional exergy analysis and economic evaluations but is critical to the design and operation of a cost-effective system [17]. Exergoeconomic analysis is performed at the component level of a system to determine the relative cost importance of each component and possible measures to increase the overall cost-effectiveness [80]. It also gives budgetary data for an energy conversion system, including fuel costs, equipment expenses, operating and maintenance costs, and total product costs as well as the costs of system inefficiencies [17, 49]. Such a plethora of information is especially useful in lowering the cost of the final product and making a system cost-effective. For cogeneration and trigeneration systems that produce multiple products as the output, exergoeconomic analysis is especially crucial since it enables the cost calculation of each product separately.

The foundation of exergoeconomic analysis was established by Tsatsaronis and colleagues [17, 77, 79, 81, 83, 84]. The exergoeconomic analysis has two distinct variations: specific cost and average cost. The average cost approach is based on the exergy costing principle, which is established on a set of propositions [17, 50]. On the other hand, with the specific cost approach, the expense of adding exergy to a stream is computed and applied to the unit that uses the exergy. Further, the cost of all external irreversibilities is imposed on the electricity if the power produced is the main output. A similar approach is applied to steam or chilled water if heating or cooling is the primary output of the system under consideration. Later on, however, the cost of all external irreversibilities is introduced to the final products (electricity, heating, or cooling) in proportion to the amount of exergy that each one of the product delivers [17]. The formulation of the cost balance equation, which allocates costs to energy sources, is a key stage in the exergoeconomic analysis. The most widely used approach to develop cost balance equations is the Specific Exergy Costing (SPECO) approach [1].

Lazzaretto and Tsatsaronis introduced the SPECO technique [46, 47] for a more precise exergoeconomic evaluation of plant components. According to this method, exergy streams are separated into fuel and product components [86]. However, the description of the product must be compatible with the reason for acquiring and employing the system. Fuel refers to the resources used to produce the product and need not always be an actual fuel like natural gas, oil, or coal [17]. The three basic processes in this method are: determining the energy streams, specifying the fuel and product for each system component, and establishing cost-balance equations. The SEPCO method has been widely implemented to study energy conversion systems [22, 23, 47, 62, 82, 83]. The SPECO approach offers a simple and basic framework for studying energy conversion systems, and it accelerates computation time by using a matrix formulation [41]. Therefore, for the exergoeconomic study of complex energy systems, such as cogeneration and trigeneration systems, the SPECO approach is typically preferred over other approaches.

In the past three decades, numerous studies on the exergoeconomic analysis of cogeneration and trigeneration systems have been conducted. One of the earliest substantial contributions was made by Balli et al. [15], who performed the exergoeconomic analysis of a CHP system by applying the SPECO approach. The results showed that the unit cost of electricity produced by the CHP system is 18.51 \$/GW. Besides, the total cost of components is highest for the GT followed by AC and CC. The study also showed that exergoeconomic analysis provides cost-based information that can be used to identify possible areas for improvement in a CHP system. Yildirim et al. [96] also employed the SPECO approach to perform an exergoeconomic analysis of a diesel engine-based CHP system with a power and steam generation capacity of 11.52 MW and 9 tons/h, respectively. The exhaust from the diesel engine is used to drive the GT cycle and the steam boiler in a cascaded manner. The results showed that the CHP system's capital investment, operating and maintenance, and total costs are 649, 149.6, and 810.2 \$/h, respectively. The GT has the highest exergoeconomic factor (88.3%), which is a crucial performance metric that assesses the contribution of the capital investment cost to the total system cost. Mert et al. [53] reported the exergoeconomic assessment of a GT-based CHP system at the Erdemir steel plant in Turkey. The system offers a production capacity of 39.5 MW of power and 80 ton/h of steam. The exergoeconomic analysis showed that GT is the most expensive component, followed by AC and HRSG, with capital investment costs of 85.46, 64.92, and 57.52 \$/h, respectively. Additionally, they observed that the cost of combustion gas was significantly greater than the price of other streams due to the exergy destruction in the CC.

Some studies [3, 42] also used parametric analysis to ascertain how changes in various operational parameters might affect the exergoeconomic performance of a CHP system. For instance, Ahmadi and Dincer [3] conducted the parametric analysis of a CHP system that included a Recuperative GT cycle and a single-pressure HRSG. The system could produce 33.3 kg/s of steam and 50 MW of power. According to the results of the parametric analysis, it was found that as the isentropic efficiency of the AC increases, the power consumption of the AC decreases while the fuel cost increases. Khaljani et al. [42] considered a Recuperative GT-HRSG-ORC-based CHP system and performed a parametric analysis considering total system cost as the exergoeconomic performance indicator. They found that the total system cost exhibited a decreasing-increasing trend with the increase in pressure ratio and AC's isentropic efficiency. The total system cost also followed a similar pattern with the rise in the GT's isentropic efficiency. They also found that the system cost rises linearly with the APH outlet temperature. However, it was observed that when the temperature of the GT outlet increased, the total system cost decreased in a roughly linear trend.

Furthermore, some researchers have used the SPECO approach to perform an exergoeconomic assessment of cogeneration systems configured as CCPPs [43, 58, 70] and CPC systems [45, 52]. Mohammadkhani et al. [58] presented an exergoeconomic analysis of a Gas Turbine-Modular Helium Reactor (GT-MHR)-based CCPP in which waste heat was recovered using two ORCs. The results revealed that the precooler, intercooler, and condensers had the poorest exergoeconomic performance. They also conducted a parametric study and found that while the unit cost of electricity drops with a decrease in GT inlet temperature, it increases with an increase in the AC pressure ratio, PPTD, and evaporator temperature. Sahin et al. [70] carried out an exergoeconomic analysis of a CCPP using a simple GT cycle as the prime mover which is further integrated with an ST cycle. They found that as the AC pressure ratio raises, the levelized cost of power decreases while system cost increases. Since the power output increases with an increase in the AC pressure ratio and does so at a faster rate than the rate at which the system cost rate rises, this justifies the drop in the levelized cost of power even amid an increase in the system cost rate. Kim et al. [43] used exergoeconomic analysis to evaluate the performance of a CCPP commissioned in Turkey that consists of two GT cycles, an ST cycle, and two HRSGs with different pressure levels. The results showed that the CC and condenser present a substantial opportunity to enhance plant performance by increasing capital expenditure. Further, the results indicated that reducing the output of the HRSGs and the exergy destruction of the ST and CC is desirable to enhance the plant's cost-effectiveness. Kumar and Singh [45] proposed a CPC system with a SOFC and an Intercooler-Recuperative GT cycle as the prime mover. An ORC and an ACS were utilized, respectively, to produce electricity and cooling from the waste heat generated at the prime mover. They performed the exergoeconomic analysis and found that the cost per unit of electricity of the proposed system is 1939.93 $/kW. They also noted that the proposed system's cost per unit of power is significantly lower than the SOFC-GT-ST integrated system [52] operating under identical conditions.

Chitsaz et al. [21] studied the exergoeconomic performance of a SOFC-based CCHP system using the SPECO approach. The bottoming cycle, which included an ACS and a water heater, utilized waste heat from the SOFC to produce chilled and hot water simultaneously. They investigated the effects of the current density and the operating temperature of SOFC, and the fuel utilization factor on unit costs of electricity, chilled water, and hot water. They found that the cost per unit of electricity, chilled water, and hot water increased as the current density and operating temperature of the SOFC increased. However, they revealed that while the unit cost of electricity increased with an increase in fuel utilization factor, the unit cost of chilled and hot water was reduced. Doiphode and Najafi [29] used the SPECO technique to evaluate the exergoeconomic performance of a CCHP system composed of a GT cycle, ORC, and an absorption ammonia-water cycle. They reported that the generator and absorber of the cooling cycle exhibited the maximum exergy destruction costs due to significant irreversibilities resulting from heat transfer across a wide temperature difference. Further, the sum of the capital investment cost and the exergy destruction cost for the overall CCHP system was found to be 18.245 $/h.

Wang et al. [91] performed an exergoeconomic analysis of a GT-based CCHP system that includes a cascaded arrangement of ACS and water heater at the bottoming cycle. The results showed that the cost of producing chilled water and hot water by the CCHP system was 0.026 $/h and 0.0086 $/h, respectively, while the cost of producing electricity was 0.08 $/h. They also showed that the GT has the largest exergoeconomic factor (29%), which was due to its high capital cost, and the CC has the lowest exergoeconomic factor (1%), which was owing to its high exergy destruction. In another study, Wang et al. [90] proposed a GT-based CCHP system that included a Regenerative supercritical carbon dioxide (sCO_2) Brayton cycle, ORC, ACS, and a water heater. The main power generating unit was the intercooled-GT cycle and the sCO_2 Brayton cycle. The ORC was operated in succession to increase the power output using the exhaust gas from the GT cycle. Additionally, the remaining waste heat was utilized to operate the ACS to generate chilled water, and the heat rejected at the intercooler was used to produce hot water. The proposed CCHP system could generate 40.65 MW of power, 6.02 MW of cooling capacity, and 9.93 MW of heating capacity. They used the SPECO approach and reported that the CCHP system's overall exergoeconomic factor was 20.17%. They also reported that the CC experiences the highest exergy destruction rate due to the presence of combustion reactions, whereas the components in ORC and ACS experience lower exergy destruction rates.

In recent years, the hybridization of conventional CCHP systems with renewable sources of energy such as biomass and solar energy has become the research trend. Some of the research studies [87, 94], for instance, focused on co-firing natural gas and biogas in a GT-based CCHP system. The studies [87, 94] demonstrated that, co-firing biomass and natural gas in GT-based CCHP systems is possible, but the costs of the final products are more susceptible to the cost of natural gas than biomass. Some other studies [54, 88] also explored the possibility of integrating solar parabolic trough collectors into the GT-based CCHP systems. A solar-assisted GT-based CCHP system was proposed by Wang et al. [88] in which the solar parabolic trough collector is employed to pre-heat the compressed air entering the CC. For the production of chilled and hot water, they employed a single-effect ACS and water heater, respectively. According to exergoeconomic analysis, the cost of electricity was 81.6%, the cost of chilled water was 45.3%, and the cost of hot water was 7.4% of the cost of natural gas.

2.3 Environmental analysis

In light of the rapidly growing climate change and global warming issues, research focus has recently also shifted to environmental analysis of cogeneration and trigeneration systems. The simple premise that lowering fuel consumption, which may be accomplished by making the system more efficient, can minimise pollutants from an energy conversion system lays the foundation of the environmental analysis [6]. However, measuring the effect of environmental pollution emitted from an energy conversion system is the first and most important stage in environmental analysis. Otherwise, even after improving a system's efficiency, it may not be feasible to determine if the environmental impact has been reduced or not. In this regard, many studies [6, 61] have lately addressed the idea of examining the performance of cogeneration and trigenerational systems in terms of environmental parameters. There are two widely used metrics for estimating the environmental impact: specific CO_2 emission and environmental cost. The specific CO_2 emission is the quantity of CO_2 released per MWh of energy produced by an energy conversion system [61]. As the definition suggests, a specific CO_2 emission only considers CO_2 released during the combustion of the fossil fuel at the combustor. On the other hand, the environmental cost takes into account the emission of CO and NOx from the system's exhaust. It is calculated by adding the costs associated with each species (CO and NOx) considering the respective unit damage costs [6]. The specific CO_2 emission and environmental cost are extremely useful parameters in evaluating the environmental performance and paving the path for reducing the environmental impact.

Ahmadi and Dincer [3] performed the environmental analysis of a CHP system that comprises a Recuperative GT cycle integrated with a single pressure HRSG. They estimated the environmental cost related to CO and NOx emissions to assess the environmental impact. They calculated the CO and NOx emission rates in grams per kg of fuel using the semi-empirical equations reported in Ref. [65]. According to the semi-empirical equations, the emission rates are affected by the adiabatic flame temperature, non-dimensional pressure drops, and residence time in the combustion zone. They also showed the procedure for estimating the adiabatic flame temperature using the correlations used in Ref. [33]. Based on the environmental results, they deduced that higher isentropic efficiencies of AC and GT and higher GT inlet temperatures result in lower fuel consumption and, hence, lower environmental costs. In a similar study, Ahmadi et al. [5] assessed the environmental impacts of a CCPP that comprises a Recuperative GT-HRSG plant integrated with an ST cycle. The authors used both the environmental cost and specific CO_2 emissions to evaluate the environmental impact of the CCPP in a comprehensive manner. The sensitivity analysis showed that the environmental cost and specific CO_2 emission decrease with an increase in compressor pressure ratio. Additionally, the study claimed that by using efficient components and the lowest fuel flow rates in the CC, environmental consequences might be reduced.

The environmental impact of a GT-based CCPP was examined by Hosseini et al. [34] to study the effect of substituting a flameless burner with a duct burner for supplementary fire. They observed that the CO_2 emission decreased by 5.63% when the duct burner was replaced by a flameless burner. According to Kim et al. [44], reducing the exergy destruction in the ST and the CC can enhance the environmental performance of a GT-based CCPP. To reduce the environmental impact, they further suggested that the HRSG's design should be improved during the development phase. In a related study, Javadi et al. [37] used a parametric analysis to determine the influence of various operating parameters on the environmental impact of a GT-based CCPP. According to their findings, the environmental impact reduces as GT inlet temperature and AC isentropic efficiency increase. Additionally, they asserted that as the AC pressure ratio and GT isentropic efficiency increase, the environmental impact decreases. Jamnani et al. [36] performed the environmental investigation of a GT-based CCPP that includes a triple-pressure HRSG and a reheat ST cycle. The emission rates of CO, CO_2, NOx and unburned hydrocarbon were used to depict the environmental impact of the CCPP. They observed that the emission rates of CO_2 were substantially higher than the emission rates of CO, NOx, and unburned hydrocarbon. Additionally, they reported that the emission rates of CO_2 rise sharply as the part load of the CCPP rises, but the emission rates of the other species rise more gradually.

Ahmadi et al. [6] evaluated the environmental performance of a CCHP system using the environmental cost criteria. The CCHP system comprises a simple GT cycle, an ST cycle and a single-effect ACS. The emission rates of CO and NOx are typically included in the calculation of environmental cost, but Ahmadi et al. [6] included the emission rate of CO_2 in addition to the rates of CO and NOx for the first time. According to the findings, the suggested CCHP system had a lower environmental cost than the standalone GT cycle. They also conducted a parametric analysis to study the behaviour of environmental costs with various operating conditions. They found that the environmental cost of the CCHP system decreases when GT isentropic efficiency, GT inlet temperature and AC pressure ratio increase. In a similar study, Ahmadi et al. [7] conducted an environmental assessment of a CCHP system that included a Recuperative GT cycle, an ORC, a single-effect ACS, and a domestic water heater. The results revealed that the proposed CCHP system emits much less CO_2 than both the standalone GT cycle and a standard CHP system. According to the parametric investigations, the environmental impact of the proposed CCHP system is greatly influenced by the AC pressure ratio, the GT inlet temperature, and the GT isentropic efficiency. Additionally, they assessed the CCHP system's environmental sustainability using the parameter known as the sustainability index [25, 66], which correlates exergy with environmental sustainability. For all of the operating conditions that were taken into consideration for parametric analysis, they observed that the sustainability index follows a pattern similar to that of exergy efficiency and a trend opposite to that of the environmental impact.

Moghimi et al. [56] determined the influence of various operating conditions on the environmental impact of a GT-based CCHP system, which included a Recuperative GT cycle as the prime mover, a double-pressure HRSG, an ST cycle, an ERS, and a domestic water heater. They noticed that as they increased the AC compressor ratio from 5 to 25, the environmental cost rate initially decreased slightly before rising above that level as a result of the increased fuel usage. They then increased the GT inlet temperature from 1200 K to 1550 K and discovered that the environmental cost rate lowers with the rise in GT inlet temperature owing to a reduction in fuel use. Chahartaghi et al. [19] compared the environmental performance of a standalone ST-based power plant with an ST-based CCHP system for the same operating condition. The CCHP system includes a single-effect ACS and a water heater to recover waste heat from the boiler exhaust gas. They observed that the CO_2 emission of the CCHP systems is 15.83% lower than that of the standalone plant. Additionally, they asserted that the CO_2 emissions rate of the CCHP system considerably decreases as the steam inlet temperature and pressure are increased.

2.4 Multi-objective optimization

Multi-objective optimization is a subfield of operations research that deals with optimization problems involving multiple objective functions that must be optimized simultaneously. Multi-objective optimization has been used in numerous areas of science and engineering, where optimal choices must be made in the existence of trade-offs between two or more potentially conflicting objectives [20]. The trade-offs reflect a situation in decision-making where numerous conflicting objectives are present, and improving one of them will inevitably make the others worse. Nearly all real-world optimization problems deal with conflicting objectives that either need to be maximized or minimized. Hence, multi-objective optimization approaches are more practical than single-objective optimization techniques, which only deal with one objective. Furthermore, while a single-objective optimization algorithm's primary purpose is to find the optimal solution, a multi-objective optimization algorithm has two additional goals: convergence to the Pareto optimal solution and preserving a set of widely distributed Pareto optimal solutions [24]. Multi-objective optimization problems are solved by obtaining a set of optimal solutions, referred to as Pareto-optimal solutions. These solutions make up the Pareto-optimal front, which represents a trade-off between the objectives. In a nutshell, a Pareto optimal solution is a group of "non-inferior" options that specify a limit beyond which none of the objectives can be improved without compromising at least one of the objectives [55].

Multi-objective optimization has evolved into a powerful engineering tool for the design and development of energy systems. The goal of optimization is to achieve the optimal design concerning a set of predetermined constraints, and it involves either minimizing or maximizing one or more performance-related objectives of an energy system. In general, an ideal energy system must be economically viable, thermodynamically efficient and environmentally friendly. In this regard, multi-objective optimization based on exergoeconomic and environmental studies paves the way by incorporating objective functions such as thermal efficiency, exergy efficiency, system cost, and environmental cost of an energy system. It presents a comprehensive method for studying energy systems and provides a plethora of data to enhance the design in terms of overall performance, which was not feasible through conventional energy or exergy analysis [78].

Multi-objective optimization produces a set of optimal solutions; therefore, it is critical to select one solution for practical implementation. To address such problems containing several criteria, multi-criteria decision analysis, a subfield of operational research, is used. The multi-criteria decision analysis can be carried out using a variety of mathematical techniques, which are chosen based on the nature of the problem and the level of complexity ascribed to the decision-making process. There is a wide list of decision-makers available in multi-criteria decision analysis. Some of the popular decision-makers are the weighted sum model [89], weighted product model [89], Analytic Hierarchy Process (AHP) [89], and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [16]. Each decision-maker has its own set of benefits and drawbacks, and one decision-maker may be ideal for one problem but not for another.

Several studies on the exergoeconomic optimization of cogeneration and trigeneration systems were carried out in the last three decades. The first significant contribution was made by a team of researchers who suggested a GT-based CHP system for evaluating various exergoeconomic theories. Based on the initials of their names, they labelled the benchmark CHP system as a CGAM problem (Cristopher Frangopolous, George Tsatsaronis, Antonio Valero, and Michael Von Spakovsky) [81]. Their work became a well-known test case in the field of exergoeconomic optimization. They applied the Lagrange multiplier for minimization of the total system cost, however, the algorithm faced issues with escaping out of the local optima [85]. Later, Sahoo [71] performed the exergoeconomic optimization of the cogeneration system by using evolutionary programming. At an optimal operating condition, he observed a 9.9% drop in the system cost rate compared to the base case condition.

Toffolo et al. [76] optimized the CGAM problem considering exergy efficiency and total system cost rate as the objective functions. They applied the Genetic Diversity Evolutionary Algorithm (GDEA) to obtain the Pareto front which was incorporated with a genetic diversity evaluation method for diversity preservation. They concluded that reducing the total cost rate should not be the only concern in the decision-making phase because the exergy efficiency can be dramatically increased with a manageable rise in the total cost rate. In a similar study [48], they considered the environmental objective, in addition to the exergetic and the economic objectives, and formulated a three-objective optimization problem. They defined the environmental objective in terms of cost by considering the unit damage cost of CO and NOx and multiplying it with the respective emission rates. In this study also, they used GDEA and obtained a Pareto-optimal surface in the 3D objective space. They observed that the solutions corresponding to the minimum value of the economic objective led to a sharp increase in the environmental objective. However, they used a simple economic model, and could not give any decision criteria for choosing the final optimal solution. Later, Sayyaadi [74] incorporated a comprehensive economic model and also provided a simple decision-making procedure for choosing the final optimal solution with two objectives (exergetic and exergoenvironomic). The exergoenvironomic objective was formulated by adding the environmental cost rate to the system cost rate. In this study, he used the Multi-Objective Particle Swarm Optimization (MOPSO) and could eliminate the problem of infeasible solutions found in Ref. [76].

Likewise, by implementing Non-dominated Sorting Genetic Algorithm-II (NSGA-II), Ahmadi et al. [4] conducted the multi-objective optimization of a Recuperative GT cycle taking into account, the exergetic and the exergoenvironomic objectives. They obtained the final optimal solution using a simple decision-making criterion and found a 50.50% reduction in the environmental impact while comparing the results with a test case. In a similar work, Khaljani et al. [40] used NSGA-II to perform multi-objective optimization on a GT-ORC integrated system and found that, compared to the base case design, there was a 9.24% increase in energy efficiency and a 12.9% decrease in the overall cost rate. Yin et al. [97] optimized an ammonia-water power cycle-based CPC system applying NSGA-II. They considered the three pairs of objective functions: thermal efficiency and capital cost, exergy efficiency and capital cost, and total output and capital cost.

Sadeghi and Ameri [68] performed multi-objective optimization of an integrated energy system that comprises a photovoltaic cell, SOFC, GT, and electrolyzer, implementing the Pareto envelope-based selection algorithm (PESA). They considered the annualized cost and CO_2 emission as the objective functions to minimize both. Luchun et al. [51] of late performed multi-objective optimization of the CGAM problem using energy, economy, and environmental impact as objective functions. The Pareto set was obtained using the Adaptive Range Multi-Objective Genetic Algorithm. They also presented a straightforward method for determining the final optimal solution, in which they choose the solution that is closest to the utopian solution. Finally, they demonstrated a multivariate analysis using clustering and dimensional reduction to show the relationship between the decision variables and the objective functions.

Aminyavari et al. [10] performed multi-objective optimization of a SOFC-GT cycle applying a multi-objective genetic algorithm (MOGA). They used the TOP-

SIS decision-maker to achieve the best set of design variables. In another study, Musharavati et al. [59] used MOGA for the optimization of an intercooled-GT system considering the exergy destruction rate, electricity cost, and energy efficiency as the objective functions. In their study, they also used the TOPSIS decision-maker for selecting the final optimal solution. Sanaye et al. [73] proposed a trigeneration system for the combined production of power, process heat and cooling. They also used the MOGA to optimize the proposed system, with exergy efficiency and system cost rate as objective functions. They used TOPSIS and the Linear Programming Technique for Multidimensional Analysis of Preference (LINMAP) to select the final optimal solution after obtaining the Pareto front. They noticed that both decision-makers selected the same Pareto front member as the final optimal solution. Moghimi et al. [56] presented a GT-based CCHP system that comprises a duel-pressure HRSG, ST cycle, ERS and a water heater at the bottoming cycle. They used MOGA to optimize the proposed system considering levelized annual cost and exergy efficiency as the objective functions. To select the final optimal solution they used LINMAP decision-maker.

2.5 Scope of the present work

In this research work, four novel GT-based combined power and cooling (CPC) systems are proposed. The CPC system configurations include a simple gas turbine cycle as the topping cycle (prime mover) and a steam turbine cycle, a recuperative organic Rankin cycle and absorption cooling systems as the bottoming cycle. The four systems are different in terms of subsystem layouts and integration schemes in the bottoming cycle. In two of the systems (system-I and system-II), back-pressure steam turbines and recuperative organic Rankine cycles are used; however, in system-III and system-IV, recuperative organic Rankine cycles are completely replaced with the condensing-type steam turbines. Additionally, system-I and system-IV include two absorption cooling systems, one driven by wet steam and the other by flue gas. System-II and system-III, on the other hand, only have one flue gas-driven absorption cooling system. The study aims at evaluating the performance of the CPC systems based on energy and exergy.

Next, four different ORC configurations *viz.,* the Basic ORC, Recuperative ORC, Regenerative ORC, and Recuperative-Regenerative ORC (RR-ORC) are considered for analysis to have more understanding of their performance from an exergoeconomic viewpoint. This study begins with a parametric analysis that is performed to investigate the effect of certain parameters such as evaporator temperature, condenser temperature, and pinch point temperature difference on the performance of each of the ORC configurations. Next, a multi-objective optimization is performed to optimize the performance of the four configurations using Pareto Envelope-based Selection Algorithm-II (PESA-II) with exergy efficiency and the system cost rate as the objective functions. Pareto fronts, representing the set of optimal solutions, are obtained for each configuration, and multi-criteria decision analysis is carried out using the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) to select the best optimal solution. Next, the exergetic and exergoeconomic performance of the four ORC configurations is evaluated at their corresponding optimal conditions to provide a comparative assessment.

Again in this research, another four GT-based combined cooling heating and power (CCHP) systems are considered for energy, exergy, exergoeconomic, and environmental (4E) analyses at their optimal conditions. These CCHP systems have the same basic layout and integration scheme as in the previously mentioned CPC systems. However, in the CCHP systems, the simple GT cycle is replaced with a Recuperative GT cycle and the Recuperative ORCs with RR-ORCs. In addition, water heat is introduced to recover the waste heat from the exhaust gas into hot water. A parametric analysis is performed first to determine the impact of key operating conditions on the performance of the CCHP systems. Then those operating conditions are used for performing a multi-objective optimization applying PESA-II considering energy efficiency, exergy efficiency and total cost rate as the objective functions. Thereafter, multi-criteria decision analysis is performed by using the Entropy-TOPSIS decision-maker to determine the best optimal solution from the Pareto front. The performance of the CCHP system is also compared with that of the earlier proposed CPC systems for the same operating conditions. Further, to show the benefit of optimization, the values of the objective functions are compared at the optimal and the base case conditions.

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