Chapter 1

Introduction

The growing greenhouse gas emissions and their negative effects on the climate are of great concern to the entire world. Extreme weather events such as tropical cyclones, heat waves, floods, and droughts are becoming more common and severe all over the world. In addition, the global average temperature is surging, sea levels are rising, and weather patterns are getting more unpredictable, all of which are major indications of climate change driven by the rise in greenhouse gas emissions. The constituents of greenhouse gas emissions are water vapour (H_2O), chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3) [44]. As per International Energy Association (IEA), CO_2 is the principal contributor to global warming among all greenhouse gases, and its emission rates have increased by 61% between 1990 and 2021 [32]. Meanwhile, some studies [2, 40] also suggested that the rise in worldwide demand for power, heating, and cooling is the main factor contributing to the increase in global CO_2 emissions. In fact, fossil-fuel-based electricity, heating, and cooling generation account for 65% of total CO_2 emissions, while transportation accounts for the remaining 35% [2, 40].

Fossil fuel use has surged significantly during the last three decades, increasing by several orders of magnitude. According to Ref. [39], global fossil fuel use was 199.18 EJ in 1971 but climbed to 490.25 EJ in 2019. The record-high consumption of fossil fuels is a result of the rapid growth in worldwide energy demand, especially in developing market economies due to population and industrial growth [22]. Global energy forecasts predict that the current energy crisis would intensify in the future, with global energy consumption projected to rise by 20-30% by 2040 [1]. Another issue is that fossil fuels have limited stock in nature and can therefore not be used indefinitely. In fact, the projected lifespans of coal, oil, and natural gas are 114, 52.8, and 50.7 years, respectively [13]. Meanwhile, the cost of producing energy is increasing as the price of fossil fuels rises along with the depletion of their reserves.

Fossil fuel-based energy conversion systems generate roughly 80.9% of global energy, with oil, coal, and natural gas accounting for 30.9%, 26.8%, and 23.2%, respectively [2]. Even though there has been great advancement in the field of renewable energy, it is still insufficiently reliable to replace fossil fuel-based power plants at this moment. Natural gas is the cleanest fossil fuel since its combustion emits less CO_2 into the atmosphere. Therefore, natural gas-powered energy systems offer a potentially viable option for meeting the global energy demand until renewable energy sources are adequately evolved to replace the current energy infrastructure. In fact, natural gas is marketed by the energy sector as the "bridge to renewable" and natural gas-powered energy systems are marketed as "bridge technology" [16]. Therefore, it is essential to employ cutting-edge design techniques to develop natural gas-driven energy generation systems that are more effective and sustainable in terms of both economics and the environment.

Gas turbine (GT) integrated energy systems, which are based on the waste heat recovery principle, are the most ideal for solving the energy crisis and laying the foundation for sustainable growth as far as the usage of natural gas is concerned [18]. In general, integrated energy systems involve the integration of multiple subsystems into a larger system in which the subsystems collaborate to improve efficiency. The major purpose of an integrated energy system is to achieve improved energy utilisation and efficiency when compared to separate systems [17]. One of the simplest and most widely used integrated energy systems is the cogeneration system. Cogeneration systems are based on the cascade utilisation of waste heat from the power generating unit. A cogeneration system, as the name suggests, produces two distinct types of energy from the same fuel source. The waste heat from a typical GT-based cogeneration system is transformed into useful thermal energy and employed for a variety of process heating applications. In recent studies, the conversion of cogeneration systems into trigeneration and multigenerational systems has been further investigated. Trigeneration systems, which produce electricity, heat, and cooling from the same fuel source, are more efficient at converting energy than cogeneration systems. Trigeneration systems are quite promising considering electricity, heating, and cooling as the three most essential components that make up the energy consumption in residential, commercial, and public buildings all over the world. In fact, the trigeneration of power, heating, and cooling combinedly account for about 65% of total CO_2 emissions [2]. Therefore, the development of efficient GT-based trigeneration systems could minimise carbon emissions by lowering fuel consumption, aiding in the slowdown of fossil fuel exploitation and environmental damage. A typical GT-based trigeneration system uses waste heat from the GT to produce chilled water, steam, and hot water.

1.1 Waste heat recovery

The thermal energy that is released into the environment by a process or equipment but which could otherwise be utilised profitably is termed waste heat. Waste heat cannot be avoided because to comply with the second law of thermodynamics, some thermal energy must be released into the environment when heat is transformed into mechanical work. According to an IEA report, waste heat accounts for 50% of the energy consumed in power plants [21]. Similarly, Johnson et al. [24] estimated that in a typical industry, waste heat accounts for 20-50% of total energy use. Therefore, it can be inferred that a sizeable amount of fuel energy is lost to the environment and turns into a potential source of thermal pollution. However, both the cost of fuel and environmental damage can be reduced if part of the wasted energy is retrieved employing waste heat recovery systems. Waste heat can be classified into three types based on the temperature at which it is rejected: high-temperature waste heat (>400°C), medium-temperature waste heat (100-400°C), and low-temperature waste heat (<100°C) [25]. The majority of waste heat in the high-temperature range originates from direct combustion. Combustion products generate waste heat in the medium temperature range, whereas parts and products of process equipment provide waste heat in the low-temperature range. During waste heat recovery, not only the quantity but also the quality of waste heat is crucial. Waste heat at a higher temperature has a higher quality due to the higher work potential and hence it is critical to recover high-temperature waste heat.

1.2 Integrated energy systems

The flue gas from traditional power plants carries away over 61% of the thermal energy, resulting in massive energy and monetary waste [6]. An energy flow diagram for a conventional power plant is shown in Fig. 1.1. As can be seen, a significant quantity of fuel energy is lost to the environment. Therefore, it is necessary to further recover the waste heat that was released into the environment to increase the fuel conversion potential of a conventional power plant. One of the most effective waste heat recovery strategies is the integration of thermodynamic cycles into the prime mover [25]. In this approach, the excess thermal energy from flue gas that would otherwise be dumped into the environment is used to produce various useable forms of energy such as power, heating, cooling, freshwater, hydrogen gas, etc.

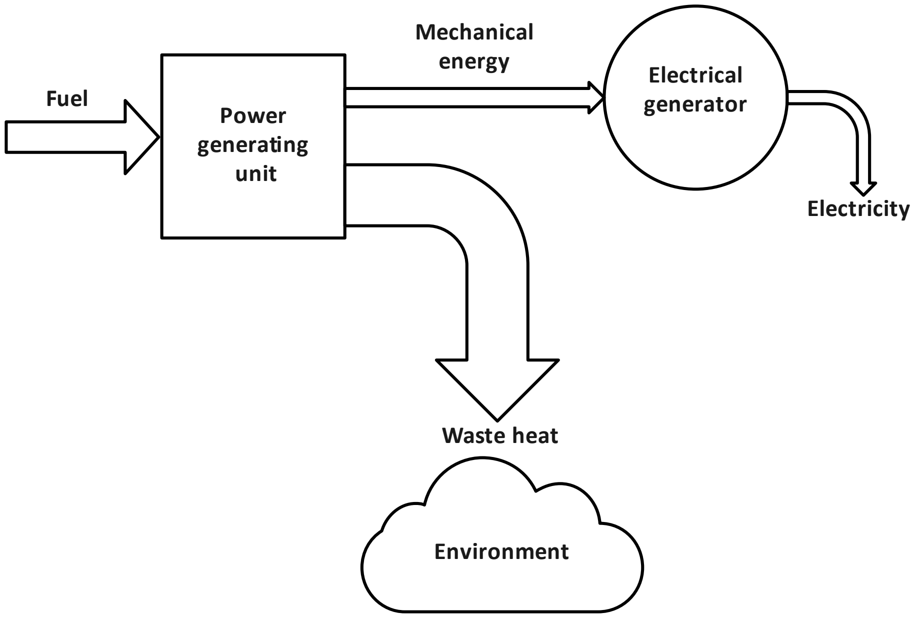

Fig. 1.1: Energy flow diagram for a conventional power plant [2].

1.2.1 Cogeneration systems

A cogeneration system converts waste heat from a power-generating unit into usable thermal energy, which can then be used for process heating, space heating, pool heating, or residential water heating. The cogeneration system, commonly known as the combined heat and power (CHP) system, is the most basic layout of integrated energy systems. The overall thermal efficiency of a CHP system is typically 40-50%, defined as the fraction of the fuel that is transformed into electricity and heat [2]. The exhaust gas from the prime mover is typically used to produce either steam using a heat recovery steam generator (HRSG) or hot water using a heat exchanger. A typical layout of a CHP system is shown in Fig. 1.2.

The steam produced by the CHP system can also be used to generate additional power through the use of indirect or direct electrical conversion devices [2]. Such cogeneration systems are referred to as combined cycle power plants (CCPP). Indirect electrical conversion systems turn heat energy into mechanical work, which is subsequently converted to electricity by a generator. Steam turbine (ST) cycle, organic Rankine cycle (ORC), Kalina cycle, and ammonia water turbine (AWT) are

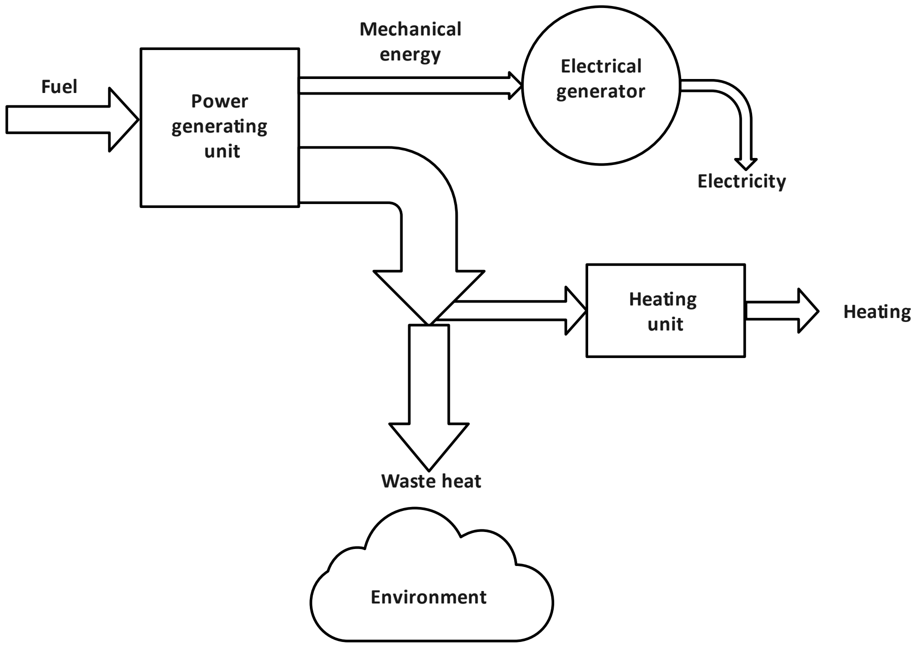

Fig. 1.2: Energy flow diagram for a typical CHP system [2].

some examples of indirect electrical conversion systems. On the other hand, direct electrical conversion systems are those that convert thermal energy into electricity directly. Thermoelectric generators, piezoelectric generators, thermionic generators, and thermophotovoltaic generators are some examples of direct electrical conversion systems. A very common CCPP layout is the GT cycle integrated with an ST cycle. Here, the HRSG plays a crucial role in recovering waste heat from the flue gas of the GT and subsequently delivering steam to operate the ST cycle. The thermal efficiency of a GT-ST-based CCPP can be as high as 60% [10]. The steam generated by such integrated systems can also be used for operating a thermally driven cooling system such as absorption cooling systems (ACS), adsorption cooling systems (ADS), and ejector refrigeration systems (ERS). The chilled water generated by the cooling units can further be used in heating, ventilation, and air conditioning (HVAC) systems. Since such integrated systems generate both power and cooling, they are termed combined power and cooling (CPC) systems.

1.2.2 Trigeneration systems

Trigeneration systems simultaneously generate power, cooling, and heating from the same source of fuel. They are the upgraded versions of CHP systems in which some portion of the steam is used to operate the cooling systems while the remaining is used for process heating. They are also known as combined cooling, heating, and power (CCHP) systems. An energy flow diagram for a typical CCHP system is shown in Fig. 1.3. It shows that as compared to cogeneration systems (CHP, CCPP, and CPC systems), the heat rejected to the ambient is less in CCHP systems. As a result, CCHP systems have a higher thermal efficiency than cogeneration systems, as well as lower CO_2 emissions per unit of output energy. CCHP systems are generally conceptualized as decentralized plants. It is because delivering chilled water, steam, or hot water requires insulated pipelines, and if the plant is close to the end-user, the loss will be lower, enabling supplying cooling and heating as outputs more profitable. In general, CCHP plants are a very attractive alternative for large buildings with a high demand for electricity, cooling, and heating, such as chemical and food processing industries, airports, shopping malls, hotels, and hospitals.

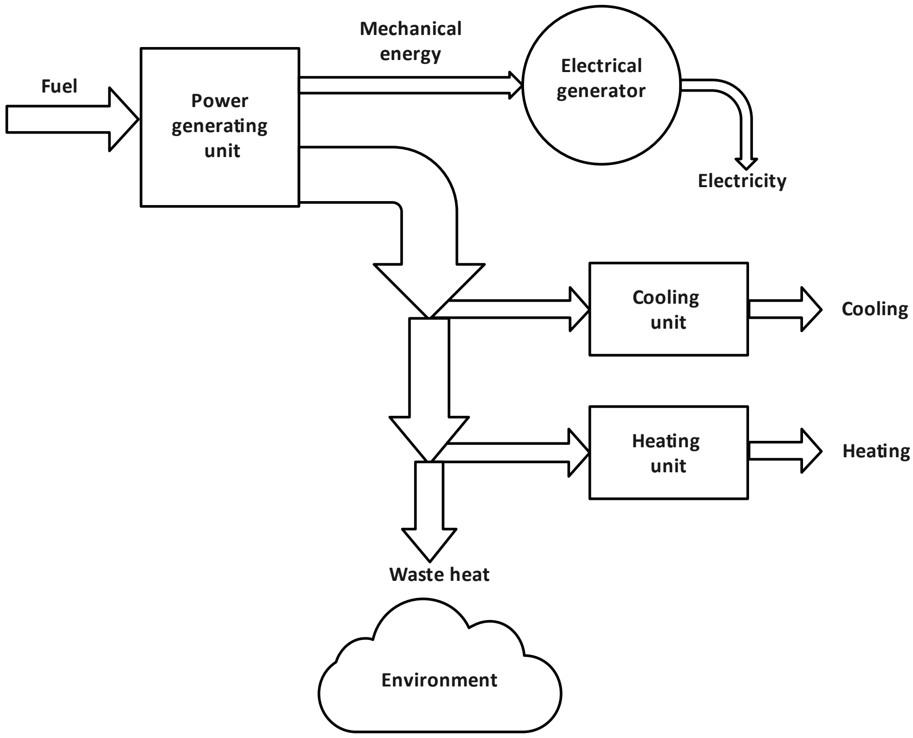

Fig. 1.3: Energy flow diagram for a CCHP system [2].

There are various advantages of a CCHP system which are listed in detail below:

(i) **Improvement in overall efficiency:** The overall efficiency of conventional fossil-fuel-based power plants with a single prime mover is typically less than 39% [7]. Thus, around 61% of the fuel energy supplied to the power plant is lost to the environment as waste heat. A trigeneration plant, on the other hand, uses waste heat from power generation units to operate cooling and heating systems without the need for additional fuel, thus improving the overall thermal efficiency by close to 60%.

(ii) **Reduction in fuel cost and greenhouse gas emission:** The trigeneration plant uses less fuel to generate the same output as compared to plants that generate power, cooling, and heating separately, resulting in lower fuel costs.

(iii) **Reduction in greenhouse gas emission:** Since the amount of fuel burned in a trigeneration system is lower for the same output rating as compared to a conventional plant, greenhouse gas emission is reduced significantly.

(iv) **Cooling system size reduced:** The size of the water cooling system, exhaust gas cooling system, cooling tower, water treatment plant, fans, heat exchangers, etc., are all reduced as the heat rejection from the trigeneration plant decreases.

(v) **Reduction of capital cost:** The capital cost of the trigeneration plant is lower than the conventional plant for the same output if the integration of subsystems is incorporated into the design stage. It is mainly due to the reduction of fuel cost, which accounts for 30% to 50% of total expenditures [5]. However, upon retrofitting, the capital cost of the trigeneration plant may exceed that of the conventional plant.

(vi) **Scope of additional revenue generation:** There is a scope for earning additional revenue by selling excess electricity to the grid.

Furthermore, trigeneration systems are classified based on the type of prime movers and the operation scheme. The power generating unit, which is the primary component of a trigeneration system, is referred to as the prime mover. A prime mover must be chosen as part of the initial design of a trigeneration system. This decision is influenced by several factors, including power, heating, and cooling demand, economic constraints, available fuel types, greenhouse gas emissions, and plant location, among others. The ORCs, GTs, STs, microturbines, and internal combustion engines are some of the typical prime movers used in trigeneration systems. The most popular prime mover among the aforementioned prime movers is a GT because of its low initial cost, high dependability, operating flexibility, and lower carbon emissions. The quick start capacity and a low weight-to-power ratio of GTs are further notable features. GTs may operate on a variety of fuels, including natural gas and residual oil.

Trigeneration systems are also categorised as topping or bottoming cycle systems depending on their operation strategy [5]. The priority in the topping cycle scheme is power generation, therefore fuel is primarily delivered to the power generating unit, and waste heat is subsequently used to operate heating and cooling units. The topping cycle scheme is the most common in trigeneration systems. On the other hand, in a bottoming cycle scheme, thermal energy takes precedence, so the fuel is first delivered to the furnace for combustion, and then the residual heat is used to generate electricity. The bottoming cycle scheme is mostly used in the cement, chemical, petrochemical, and manufacturing industries.

The basic architecture of a typical trigeneration system based on a topping cycle scheme is shown in Fig. 1.3. As can be seen, the power generating unit, the heat recovery unit, and the cooling unit are the three primary components of a trigeneration system. The power generation unit converts the chemical energy of the fuel into shaft work and waste heat. The shaft work is then transformed into electricity with the help of an electric generator. The waste heat is then used to generate heating and cooling via the heat recovery and cooling units, respectively. The heat recovery units convert waste heat from the exhaust gas, coolant, and other sources of the power generating unit into usable forms of energy such as process heat, cooling, and additional power. They are primarily comprised of heat exchangers of various types depending on the application. The cooling units are heat-driven chillers that use the waste heat produced by the power-generating unit to produce chilled water. Alternatively, the steam or hot water generated by various heat recovery devices could also be used to operate the cooling units. The widely used cooling units in trigeneration systems are absorption cooling systems, ejector refrigeration systems and adsorption cooling systems.

1.3 4E analyses

Energy analysis is the basic foundation for the performance analysis of an energy conversion system. In energy analysis, it is initially assumed that the system's components are contained within an imaginary control volume. The energy interaction is then determined in the control volume using the laws of conservation of mass and energy. The energy analysis is performed to obtain a rough estimate of the performance of a system. Thermal efficiency is a commonly used performance parameter in energy analysis for power cycles, whereas COP is used for cooling cycles. Energy analysis, however, has the drawback of not being able to establish how far the system's performance is from the ideal optimal performance that can be achieved when the system is operated under reversible conditions. Exergy analysis, which is based on the second rule of thermodynamics, is commonly used to overcome the limits of energy analysis. Exergy is the maximum theoretically useful work that can be taken out of a system when it changes from an initial condition to a reference condition [9]. There is the potential for useful work whenever the system's properties diverge from those of the surrounding environment. However, as the system achieves equilibrium with its surroundings, the work drawing potential or exergy becomes zero. At that point, the system is said to be in a "dead state." Thus exergy is regarded as the combined property of the system and the surrounding.

Exergy analysis can detect the location, cause, and true magnitude of energy loss enabling more effective energy utilisation [3]. Thus, exergy analysis is a very valuable technique for designing and developing a new energy-efficient thermal system or upgrading an existing thermal system. Unlike energy analysis, which considers energy to be conserved, exergy analysis considers exergy to be destroyed. The presence of irreversibilities, such as heat transfer through a finite temperature difference, fluid friction, chemical reactions, and so on, causes exergy destruction in a system. Exergy analysis is a tried-and-tasted approach for enhancing the performance of a thermal system in which the main locations of irreversibilities are identified first, and then the irreversibilities are decreased by modifying the operating and design parameters.

Exergy analysis is sufficient for studying and improving the efficiency of a thermal system, but it does not address the economic aspects. An ideal thermal system must not only be efficient but also cost-effective. A thermal system can be made more efficient with the help of exergy analysis, but this does not guarantee that the system will be cost-effective. To address this shortcoming of exergy analysis, exergoeconomic analysis is employed, which is a combination of exergy analysis and economic concepts that provides a comprehensive system performance evaluation. Exergoeconomic analysis provides monetary information for a thermal system, such as fuel costs, equipment costs, operating and maintenance costs, and final product costs. It also provides expenses due to inefficiencies such as exergy destruction and exergy losses, knowledge of which is highly useful in making a thermal system cost-effective, that is, lowering the cost of the final product. Exergoeconomic analysis is particularly important for trigeneration systems that generate multiple products as output, such as electricity, process heat, and chilled water because it makes it possible for cost estimation of each product separately.

Research focus has recently switched to environmental analysis of energy conversion systems to lower pollution given the rapidly expanding climate change and global warming challenges. The foundation of the environmental analysis is the fundamental idea that reducing fuel consumption, which may be achieved by increasing system efficiency, can limit emissions from an energy conversion system [4]. The first and most crucial step in environmental analysis is quantifying the impact of the pollutants that an energy conversion system emits into the environment. Otherwise, it might not be possible to tell whether or not the environmental impact has decreased even after a system's efficiency has been increased. The specific CO_2 emission and environmental cost are two often used metrics for measuring the environmental impact. The quantity of CO_2 released per MWh of energy produced by an energy conversion system is defined as the specific CO_2 emission. As the definition suggests, a specific CO_2 emission only considers CO_2 released by the exhaust of a thermal system. The environmental cost is a more complete metric because it considers CO, CO_2, and NOx emissions in addition to CO_2 emissions. In assessing environmental performance and laying the foundation for decreasing environmental impact, both metrics are crucial.

A synergetic approach based on the principles of energy analysis, exergy analysis, exergoeconomic analysis, and environmental analysis (commonly referred to as 4E analyses [23, 28, 34]) can be used to design and develop a thermal system that is efficient, cost-effective, and has a low environmental impact. The 4E analyses is a more comprehensive performance assessment method that estimates key system characteristics related to all areas of energy conversion. The objective/ contribution of 4E analyses of a thermal system are as follows [23, 28, 34]:

(i) Determine the heat and work interactions at each component of a thermal system.

(ii) Identify the source, magnitude, and location of exergy destruction and losses in a thermal system.

(iii) Understand the cost-formation process and assess the system cost rate, which includes fuel, equipment, operation and maintenance costs, as well as the cost of thermodynamic inefficiencies (exergy destruction and exergy losses).

(iv) Estimate the environmental impact of pollution emitted by thermal systems.

The steps taken in the 4E analysis are depicted in Fig. 1.4. It demonstrates that energy analysis is a prerequisite for exergy and environmental analysis, and exergy analysis is a prerequisite for exergoeconomic analysis.

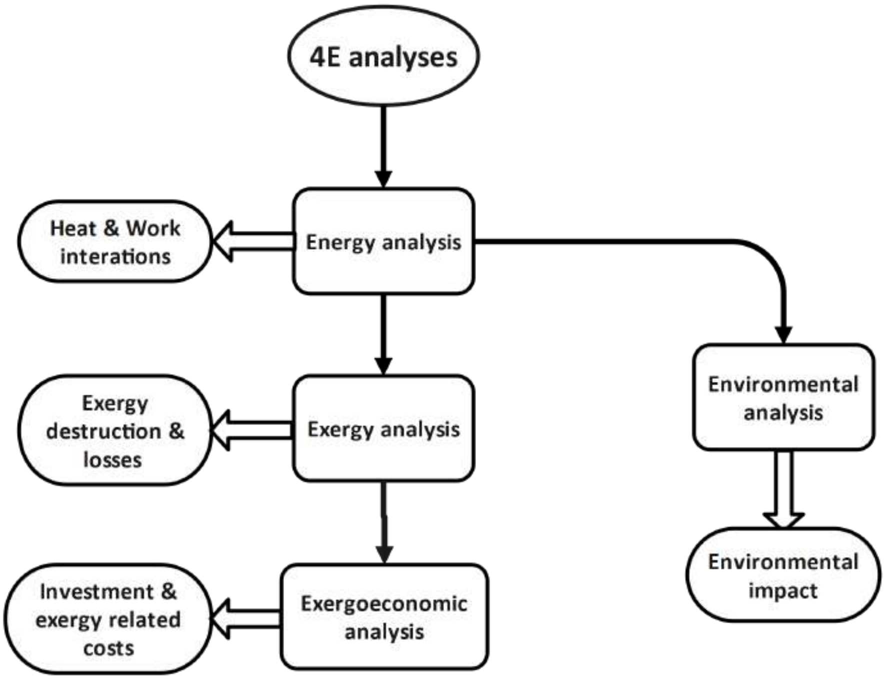

Fig. 1.4: A block diagram showing steps of 4E analyses [2].

1.4 Multi-objective Optimization

Multi-objective optimization has emerged as a potent engineering technique for the development of energy systems. Multi-objective optimization deals with problems that include several conflicting objectives and, one objective cannot be improved without worsening the others. In general, the goal of multi-objective optimization is to find the optimum design conditions for a given set of constraints, and it encompasses either the minimization or maximization of multiple conflicting objectives. Contrary to single-objective optimization, where only one objective is maximized or minimized, multi-objective optimization has tremendous applications. 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 [14].

Earlier multi-objective optimization problems were solved using the classical approach that was mainly based on transforming the multiple objectives into a single objective [14]. The major drawbacks of the classical methods are the high computational cost and poor convergence. In this regard, multi-objective evolutionary algorithms (MOEAs) have evolved as a popular option for solving the problems associated with conflicting objectives. The MOEAs solve the optimization problems in their original form and give the Pareto-optimal front with just one execution with a comparatively less computational cost. The MOEAs are population-based algorithms that initiate with a set of randomly generated solutions called population and proceed towards obtaining the Pareto-optimal solutions, stochastically.

Multi-objective optimization generates a set of optimal solutions; consequently, it is necessary to choose one solution for practical application. Multi-criteria decision analysis, a branch of operational research, is applied to solve such situations with multiple criteria. Depending on the nature of the problem and the degree of complexity assigned to the decision-making process, a variety of mathematical techniques can be used to do the multi-criteria decision analysis. To achieve the optimal operating conditions for energy conversion systems, it is therefore required to combine multi-objective optimization with multi-criteria decision analysis.

The general mathematical formulation for a multi-objective optimization problem is shown in Eq. (1.1) [12].

$$
\begin{aligned}
\text{Determine} \quad & x = (x_1, x_2, x_3, \ldots.., x_n)^T \\
\text{To optimize} \quad & f = (f_1(x), f_2(x), f_2(x), \ldots.., f_q(x))^T \\
\text{Subject to} \quad & g_i(x) \leq 0 \ ; \quad i = \quad 1, 2, ..., m \\
& h_k(x) = 0 \ ; \quad k = \quad 1, 2, ..., p \\
& x_j^{(l)} \leq x_j \leq x_j^{(u)} \ ; \quad j = \quad 1, 2, ..., n
\end{aligned}
\tag{1.1}
$$

where x, f, g and h denotes decision variables, objective functions, inequality constraints and equality constraints, respectively.

1.5 Motivation and research objectives

Energy is the key to the sustainability of human existence. It is also the measure of prosperity and development in a society. However, the rapid growth in population and industrialization has increased the global energy demand in terms of electricity, heating and cooling to a great extent and resulted in energy crises [41]. Around 80% of the current global energy consumption is fossil fuel-based despite the substantial progress over the last few decades in the field of renewable energy [29]. Thus, to meet the growing demand, fossil fuel, which is already limited in nature, is burned excessively. The pollution caused due to the burning of fossil fuels, especially the emission of greenhouse gases like CO_2, has led to many environmental issues, such as global warming and climate change [44]. Besides, conventional power plants are relatively inefficient and, could convert only about 30%-35% of the fuel's available energy into power and, the large portion of the remaining energy is rejected to the ambient in the form of low-grade heat that eventually adds up to thermal pollution [35].

A study predicted that by the year 2050, the global energy demand would increase by more than double [30]. Therefore, research is being carried out continuously to develop more efficient, sustainable, cost-effective, and clean energy conversion systems to mitigate the growing multidimensional energy demand. In this regard, trigeneration systems are one such technology that has emerged as an optimal energy generation option with promising energy conversion efficiency. A lot of research studies related to trigeneration systems were carried out in the past. These are discussed separately in Chapter 2. Upon surveying the literature, some research gaps are observed that are listed as follows:

(i) The architecture of the subsystems must be carefully chosen because even modest modifications to one subsystem can have a major impact on the overall performance of the integrated system. Meanwhile, the decision to choose a particular architecture for the subsystems is based on the intent to maximise the energy utilisation of the waste heat. Investigating the performance of the integrated system under various configurations is a suitable approach to carrying out such a study. Despite the significance of the subsystem architecture, only a few studies [33, 37, 38] have examined at the prospect of enhancing the performance of integrated systems by reducing inefficiencies through adjustments to the integration scheme or the subsystem layout. Eight GT-ST-ACS-based integrated system layouts were the subject of a study in Ref. [33], while in Refs. [37, 38], the performance of two Kalina-ORC-based integrated system layouts was compared. In the above studies, a simpler integration strategy was used to connect only a few subsystems to utilize the waste heat. However, waste heat may be recovered more effectively with a more robust integration approach.

(ii) Often ORCs are employed as subsystems in integrated systems. Based on the literature review, it was observed that there are four common ORC layouts (Basic ORC, Recuperative ORC, Regenerative ORC and RR-ORC), and according to the study [36], the RR-ORC has the maximum efficiency when compared to its counterpart. Although some studies [8, 15, 19, 26, 27, 31, 43] have compared the performance of specific ORC configurations (Basic ORC, Recuperative ORC, and Regenerative ORC) just using energy and exergy analysis, there is presently no study available that compares the four ORC layouts using exergoeconomic analysis. Further, each configuration is designed to work ideally under a specific set of operating conditions and comparing the configurations at the best-operating conditions obtained through optimization is preferable. However, all of the research mentioned above have evaluated the performance of the ORC configurations in predefined operating conditions. Therefore, it is necessary to conduct a study that compares the widely used ORC configuration while operating at optimal operating conditions.

(iii) There are studies on multi-objective optimization and 4E analyses of GT-based CCHP systems in the literature. But in almost all of those studies, the architecture of the integrated system is basic, using the GT exhaust to operate either a power cycle or a cooling cycle or both while recovering some waste heat to provide a heating load. For instance, 4E analyses and multi-objective optimization of GT-ST-ERS scheme [34], GT-KC-ERS scheme [42] and SOFC-GT-ORC-ACS scheme [45] is performed in recent years. However, due to architectural and operational complexity, the GT-ST-ORC-ACS integration scheme has not been studied using 4E analysis and multi-objective optimization.

(iv) Bottoming ST cycles can either be a back-pressure type ST or a condensing type ST. However, condensing type ST is used in the majority of integrated systems. But, according to studies [11, 20, 29, 33], in a condensing type ST, the condenser is the component that destroys the most exergy. The back-pressure type ST cycle loses power but has a reduced rate of exergy destruction because it does not need a condenser. Another selection aspect that is crucial when choosing a component is the investment cost. However, no study compares the thermodynamic performance and economic aspects of a back-pressure type ST and a condensing type ST in the literature.

Based on the above-mentioned literature gaps, the proposed research has been carried out with three key objectives:

(i) Energy and exergy analyses of four different combined power and cooling systems integrated with a topping gas turbine plant.

(ii) Exergoeconomic investigation and multi-objective optimization of different ORC configurations for waste heat recovery.

(iii) Multi-objective optimization of four Recuperative gas turbine-based CCHP systems and 4E analyses at optimal conditions.

1.6 Outline of thesis chapter

The thesis is organized into six chapters. The organization of each chapter is described as follows:

Chapter 1: Introduction

This chapter begins with a brief review of the present global energy scenario and then moves on to a discussion of waste heat recovery technologies. The discussion continues with cogeneration and trigeneration energy systems, 4E analyses, multi-objective optimization. Following that, this chapter discusses the motivation and objectives of the research work carried out in this thesis. Lastly, this chapter concludes with the outline of the thesis.

Chapter 2: Literature review

This chapter gives a detailed review of the published work in the field of 4E analyses of cogeneration and trigeneration systems. Following that, works on multi-objective optimization of cogeneration and trigeneration systems are also presented. Thereafter, this chapter is concluded with the scope of the present work.

Chapter 3: Energy and exergy analyses of four different combined power and cooling systems integrated with a topping gas turbine plant

In this chapter, four novel GT-based CPC systems are proposed. In these systems, the exhaust heat of the topping GT plant is utilized for power and cooling generation. The STs and Recuperative ORCs are used for power generation by integrating those in a completely different arrangement. The ACSs are driven respectively by steam and exhaust gas for the generation of cooling load. The performances of the proposed systems are compared based on energy and exergy analysis.

Chapter 4: Exergoeconomic investigation and multi-objective optimization of different ORC configurations for waste heat recovery

In this chapter, the performance of four ORC configurations *viz.,* Basic ORC, Recuperative ORC, Regenerative ORC, and Recuperative-Regenerative ORC are carried out based on exergoeconomic analysis. The performance of the ORC layouts is evaluated at their optimal operating condition obtained using multi-objective optimization considering the exergy efficiency and the system cost rate as objective functions. The goal of this chapter is to choose the best-performing ORC layout in terms of efficiency and cost-effectiveness.

Chapter 5: Multi-objective optimization of four Recuperative gas turbine-based CCHP systems and 4E analyses at optimal conditions

In this chapter, the four configurations of CPC systems are upgraded to CCHP systems. The modifications include adding a water heater to turn the excess heat from the exhaust gas into hot water, replacing the simple GT cycle with a Recuperative GT cycle, and replacing the Recuperative ORC with the best-performing ORC layout obtained in Chapter 4. The performance of the CCHP systems is then evaluated at the optimal operating condition obtained by performing multi-objective optimization based on 4E analyses. This chapter also presents a parametric analysis to illustrate the impact of various key operating conditions on the overall performance.

Chapter 6: Conclusions and future scopes

The significant findings and recommendations drawn from this study are presented in this chapter. The potential scope of future study in the area of CCHP systems is also highlighted at the end of this chapter.

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