ENERGY EQUIPSYS

Energy Equipment and Systems

ENERGY EQUIPSYS

ENERGY EQUIPMENT AND SYSTEMS

Parametric study and sensitivity analysis of a CHP system with a gas turbine engine as the prime mover

Manuscript Type

Research Paper

Authors

Mohammad Sedighi [a]
Ahmadreza Ayoobi [a*]
Mohammad Farmani [a]

[a] Aerospace Engineering Department, Shahid Sattari Aeronautical University of Science and Technology, Tehran, Iran

ABSTRACT

Combined Heat and Power (CHP) systems have attracted substantial interest in the past decades as they offer higher thermal efficiency than single power generation systems. Various parameters affect the performance of a cogeneration system, including environmental and operating conditions of gas turbine and Heat Recovery Steam Generator (HRSG) system. In this study, the effects of 15 substantial parameters on the performance of a CHP system are investigated using Thermoflow software. The most influential parameters are identified by performing a comprehensive parametric study and sensitivity analysis. The results indicate that only 3 parameters, including the percentage of gas turbine load, ambient temperature, and ambient pressure, affect the gross output power, i.e., increasing ambient temperature from -20 to 50 ^{o}C leads to an 8% increase in efficiency of the CHP system. In contrast, moving from the highest elevation in Iran to a beach can result in a 20% reduction in the output power of the cogeneration system. This is while 8 parameters significantly affect the efficiency of the cogeneration system. For instance, changing gas turbine load from 100% to 25% leads to a 25% reduction in the efficiency of the cogeneration system. Furthermore, the correlations between important input and output parameters are presented, which can be easily used for different environmental and working conditions of cogeneration systems and are, in fact, a roadmap for the feasibility of using this type of system in various regions and working conditions.

1. Introduction

Energy is one of the most pressing issues we face today. We consume a lot of energy, most of which comes from fossil fuel combustion. In reality, fossil fuels such as oil, coal, and gas account for 81 percent of world energy use. Burning these fuels releases a substantial amount of CO_2 into the atmosphere, harming

* Corresponding author: Ahmadreza Ayoobi
Aerospace Engineering Department, Shahid Sattari Aeronautical University of Science and Technology, Tehran, Iran
E-mail address: ar.ayoobi@ssau.ac.ir

the ecosystem [1]. This high amount of CO_2 will impact the ecosystem and contribute to global warming, which is a major issue in this century. As a result, we need an energy source that does not emit carbon, such as solar energy [2], or we need to develop methods to utilize less energy to combat global warming. The integrated solution will provide a more efficient, cost-effective, and environmentally friendly energy system. Combined heat and power systems (CHP), which use the waste energy from the prime mover to create heating and/or cooling, are among the well-proven and

commercialized energy systems that have gotten much attention in recent decades.

CHP systems employ a single power production unit as the primary source and create several usable outputs, making them a highly efficient, ecologically friendly, and cost-effective method of delivering heating, cooling, and electricity [3]. CHP uses some or all of the by-products for heating or cooling or as hot water for space heating at temperatures ranging from 80 to 130 degrees Celsius [4]. Buildings consume around 30% of total energy globally and produce 30–35% of CO_2 emissions due to energy use. This calls our attention to the importance of thinking about energy-efficient buildings [5]–[7]. CHPs have been widely used in buildings since they can provide both power and heating simultaneously, reducing energy usage while also being ecologically friendly. Some studies conducted exergy and optimization of CCHP for residential applications [8], while others researched and suggested novel CCHP systems for buildings utilizing various power production units [9].

Researchers have recently gone beyond the CHP system and proposed creating more than two valuable commodities to boost efficiency substantially. One of these instances is a combined cooling, heating, and power (CCHP) system, often known as a trigeneration system. Micro Gas Turbines (MGTs), fuel cells, and internal combustion engines are used as CCHP's major topping cycle, and the waste heat from these cycles is used to generate low- and high-temperature steam for heating and cooling loads, respectively. Depending on the demand and system design, heating and cooling output can operate concurrently or intermittently. Several pieces of research for CCHP systems have been undertaken, primarily focusing on modeling, design, exergy, and economic optimization [10]–[13].

Oliveira et al. [14] conducted experimental research using an ejector heat pump and a Rankine cycle to fulfill the heating, cooling, and electrical demands of a specific residential structure. Bruno et al. [15] investigated an MGT-based CCHP system. They looked at the effect of using post-combustion natural gas to boost the system's cooling capacity and found that the chillers' COP is higher while operating at higher temperatures. Based on the hotels' power usage, Cardona and Piacentino [16] performed complete research for certain hotels in Europe and constructed the primary CCHP system components, including the prime mover and absorption chiller.

The most efficient design of a combined cycle system is of particular importance, given its widespread usage as a preferred way of producing power. These systems primarily depend on the mass flow rate and gas turbine exhaust temperature. The entire efficiency of the combined cycle system is predicted to increase if HRSG is optimized. Furthermore, environmental factors have an impact on the output of a CHP system. Foster-Pegg [17] established the optimal evaporation pressure of the HRSG system to enhance the steam cycle efficiency via the bottom cycle analysis. Moreover, Chin and El-Masri [18] demonstrated that the ideal pressure might be stated regarding the gas turbine exhaust temperature. Karthikeyan et al. [19] studied the effects of different pinch and approach temperature variations on the steam-generating unit by modeling an HRSG in a cogeneration system.

Significant progress has been made in the analysis, design, and optimization of Combined Heat and Power (CHP) systems, which has led to their improved performance. However, this study offers a unique approach by comprehensively evaluating the impact of various parameters on the performance of such systems together, which has not been done before. Moreover, an extensive sensitivity analysis of the effective parameters on the performance of a typical CHP system has not been conducted previously. The primary objective of this research is to conduct a comprehensive parametric study and sensitivity analysis on the performance of a CHP system that uses a gas turbine engine as the prime mover. The distinguishing feature of this research is that Thermoflow software was used to perform a parametric study of fifteen parameters, and Minitab software was used to conduct sensitivity analysis. The most significant input parameters that affect the performance of a typical CHP system were identified. Additionally, the proposed correlations used the effective parameters that can be applied to calculate output parameters.

2. Methodology

To ensure an accurate representation of the combined cycle power plant, certain assumptions were made while modelling it. These assumptions include: considering the turbine, compressor, and pump to be adiabatic, considering all processes to be steady state and flow, using the ambient temperature and pressure as input conditions in the compressor, using ideal gases for both air and output gases from the combustion chamber, assuming the consumed fuel to be methane. By making the above assumptions, we ensured that the combined cycle power plant is accurately represented in the model. Considering a control volume for each component of the power plant, mass and energy balance relations can be calculated using, respectively

$$\sum_{i=1}^{n} \dot{m}_{in_i} = \sum_{i=1}^{n} \dot{m}_{out_i} \tag{1}$$

$$\dot{Q} - \dot{W} = \sum_{i=1}^{n} \dot{m}_{in_i} \left(h_{in_i} + \frac{v_{in_i}^2}{2} + gz_{ini} \right) \\ - \sum_{i=1}^{n} \dot{m}_{out_i} \left(h_{out_i} + \frac{v_{out_i}^2}{2} + gz_{outi} \right) \tag{2}$$

We have performed a comprehensive analysis of the effects of various parameters on the performance of a CHP system using Thermoflow V.19. A schematic diagram of the proposed CHP cycle is shown in Fig. 1.
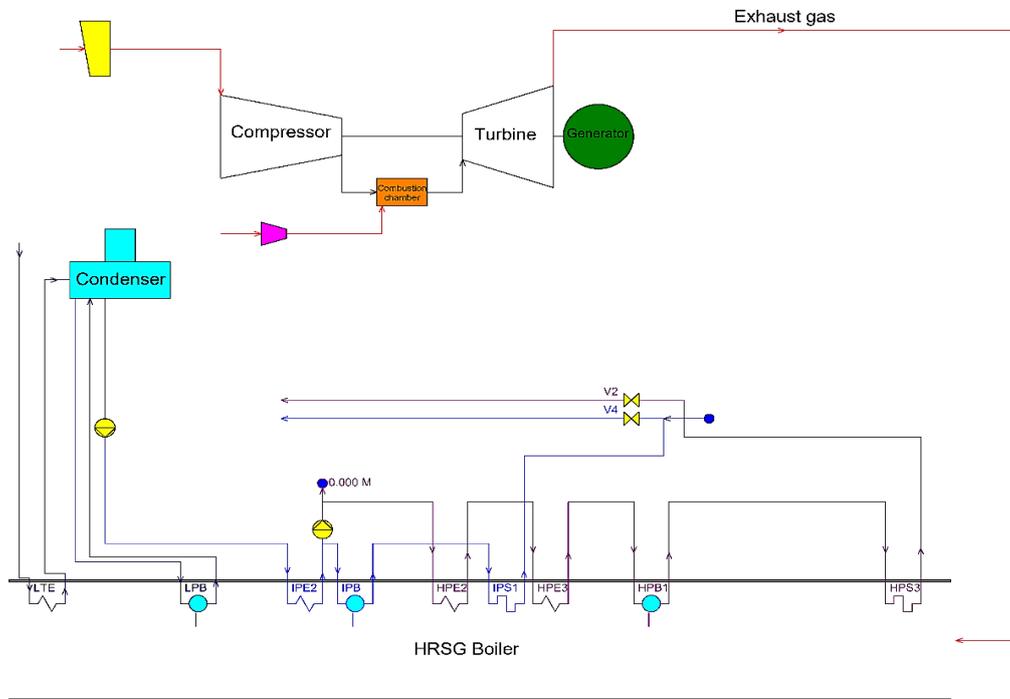

Fig. 1. Schematic of the proposed CHP cycle

Table 1. Specifications of "P+W ST6L-721" gas turbine

Parameter	No. of Shafts	RPM[1]	PR[2]	TIT[3] (°C)	TET[4] (°C)	Air Flow (kg/s)	Generation Power (kW)	LHV HR[5] (kJ/kWh)	LHV Efficiency (%)
Value	2	33000	6.9	888	513	3	486	16243	22.2

---

1. Revolution Per Minute
2. Pressure Ratio
3. Turbine Inlet Temperature
4. Turbine Exit Temperature
5. Low Heat Value Heat Ratio

The prime mover in this study was considered P+W ST6L-721, with a generation power of 486 KW. Other specifications of the utilized turbine are shown in Table 1. It should be mentioned that the selected gas turbine is just a sample to identify the effects of various parameters, and it does not matter what gas turbine is selected. We believe that our study can be generalized and applied to distinct gas turbines and various conditions independent of the gas turbine model.

In this research, we considered a gas turbine as the prime mover along with a three-effects HRSG system, including low, intermediate, and high-pressure sections. No steam turbine or desalination system was considered in this research.

As discussed earlier, a comprehensive study was performed on 15 selected parameters, which are tabulated along with their descriptions in Table 2. Here, due to the three levels of the HRSG boiler, three different temperature levels were considered as input parameters, while we only have two levels of pressure because the minimum pressure of HRSG is constant and equal to the ambient pressure. The difference between the gas temperature exiting the evaporator and the saturation temperature is known as the pinch point, which is a very important factor for the design of a heat exchanger. Here, the minimum allowable pinch points for three HRSG boilers are considered as the input parameters. Besides, feedwater approach subcooling, the difference between saturation temperature and feed water temperature entering the evaporator, is another significant input parameter considered. The evacuation of water from a boiler is recognized as a boiler blowdown. Its goal is to keep boiler water characteristics within specified ranges in order to prevent scale, carryover, corrosion, and other issues. Blowdown is also utilized to clear the system of any suspended solids. Here the percentage of the blowdown is considered another parameter to be analyzed. The range of parameters can also be seen in Table 2, extracted from the literature [20]–[23], and by considering a reasonable data range.

The Design of Experiment (DOE) technique is a time-saving and statistical strategy for achieving desired outcomes. In contrast to the traditional investigation (which alters one factor at a time), the DOE approach modifies many factors simultaneously, allowing for the evaluation of variable interactions [24]. The Response Surface Method (RSM) is a very well formal experimental design in which quantitative independent variables are linked to response variables using statistical models [24]. Here, Minitab Statistical Software was utilized for the analysis of data. Central Composite Design (CCD) method was used to generate 750 design points for the current study. CCD has been shown to be a resilient and efficient strategy when used in conjunction with RSM to design and optimize numerous issues in many fields of study [25]–[27]. Furthermore, we have implemented a full quadratic scheme for the analysis of data with RSM. Besides, plant gross output power, plant net output power, the efficiency of the plant, and total HRSG area have been considered the output parameters.

3. Results and Discussion

3.1. Goodness of the Fit

The goodness of the model prediction for output parameters is tabulated in Table 3, which presents the coefficient of determination for each output parameter. The coefficient of determination, abbreviated as "R squared" in statistics, is the fraction of variation in the dependent variable that can be anticipated by the independent variable(s). The results show an R squared of more than 99% for gross and net output powers, around 99% for the efficiency of the system, and approximately 95% for the total surface area of HRSG, which are rational values for a response surface study according to the literature [28].

Additionally, to further assure the accuracy of the results, regression plots of the predicted model were analyzed, which are shown in Fig. 2. Taking a look at these plots indicates how closely the outputs match the target values. As can be seen, a perfect prediction can be seen in the results. It should be noted that these parameters do not have dimensions, and whatever the points on these plots get closer to the diagonal line, the results are more accurate and best fitted to the actual data.

Table 2. Effective parameters analyzed their effects on the performance of the CHP system

No.	Parameter	Symbol	Unit	Min	Max
1	Ambient Pressure	P	bar	0.81	1
2	Ambient Temperature	T	ºC	-20	50
3	Ambient Relative Humidity	H	%	10	90
4	Makeup Water Source Temp.	T_M	ºC	5	35
5	GT Power as % of Site Rating	G	%	25	100
6	Main HP Process Pressure	P_{HP}	bar	25	150
7	Main HP Process Temp.	T_{HP}	ºC	250	400
8	Main IP Process Pressure	P_{IP}	bar	5	20
9	Main IP Process Temp.	T_{IP}	ºC	120	250
10	HPB Minimum Allowable Pinch	$Pinch_{HP}$	ºC	10	30
11	HP Feedwater Approach Subcooling	App_{HP}	ºC	2	10
12	IPB Minimum Allowable Pinch	$Pinch_{IP}$	ºC	10	30
13	IP Feedwater Approach Subcooling	App_{IP}	ºC	2	10
14	LPB Minimum Allowable Pinch	App_{LP}	ºC	5	20
15	LPB Blowdown	LPB	%	1	10

Table 3. Effective parameters analyzed their effects on the performance of the CHP system

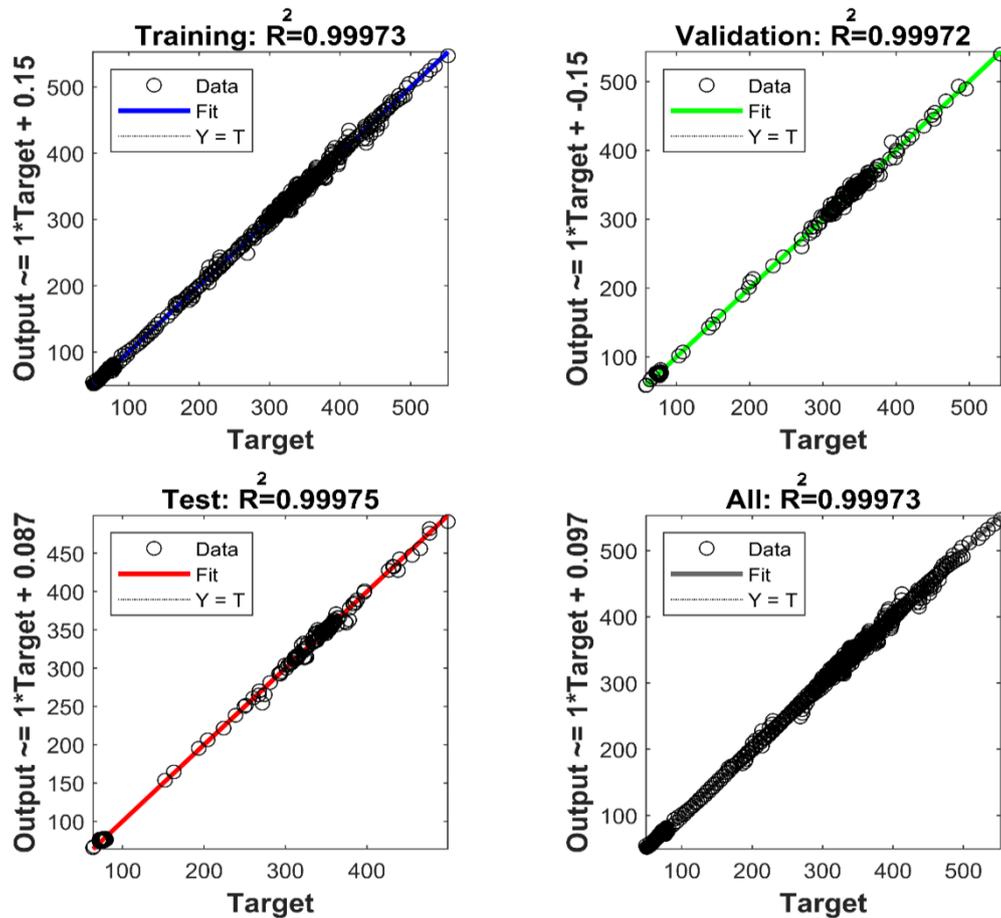| Output Parameter	R squared (%)
Plant Gross Output	99.91
Plant Net Output	99.91
CHP Efficiency	98.98
Total HRSG Surface Area	94.90

Fig. 2. Regression plots of fitted values

3.2. Sensitivity Analysis

An analysis of how the uncertainty in the output of a mathematical model or system can be split up and assigned to different sources of uncertainty in its inputs is known as sensitivity analysis [29]. Sensitivity analysis may aid in the identification of crucial control points, the prioritization of additional data collection or study, as well as the verification and validation of a model. The sensitivity analysis here is performed by the Pareto charts, which is a well-known tool for predicting and identifying the importance of data in a sensitivity analysis [30].

As it turns out from Fig. 3, only three parameters, including the percentage of gas turbine load, ambient temperature, and ambient pressure, affect the gross output power of the cogeneration plant and other parameters can be neglected compared to these three parameters (Fig.3a). However, in addition to the three parameters mentioned, the main line pressure of the high-pressure section of the recovery boiler is an effective parameter for the net output power (which is defined as the total power minus the power consumption of the power plant) (Fig.3b).

In general, the efficiency of the cogeneration system, in the long run, is considered the most important parameter for a cogeneration system, which in fact, specifically affects the cost of initial investment and maintenance of the power plant. Examination of the Pareto chart and the corresponding sensitivity analysis reveals that 8 parameters influence the efficiency of the CHP system (Fig.3c), while 11 parameters affect the surface of the heat recovery boiler (Fig.3d). This is noteworthy to say that although 11 parameters affect the total surface area of the HRSG boiler, since the efficiency of the cogeneration system is the most important parameter for any concurrent production system, in the present work, 8 main parameters have been considered as effective parameters and the other 7 parameters have been removed due to their little impact on the output parameters. These 8 parameters, in order of affecting the efficiency of the cogeneration system, are as follows:

- GT Power as % of Site Rating
- Ambient Temperature
- Main IP Process Pressure
- IPB Minimum Allowable Pinch
- Main HP Process Pressure
- Main HP Process Temperature
- IP Feedwater Approach Subcooling
- Ambient Pressure

3.3. Effects of input parameters on the performance of the cogeneration system

#### 3.3.1.Effects of ambient pressure

Anything that modifies the air intake's mass flow or density impacts the gas turbine's performance. Pressure, temperature, and humidity in the surrounding area all affect air density. The air density falls as the height of the site rises. Fig. 4 shows the effects of ambient pressure on the output parameters. As it turns out, the total output power of the gas turbine (Fig. 4a), along with the net output power of the power plant (Fig. 4b), increases almost linearly with increasing ambient pressure. At decreasing ambient pressure, the net power output decreases because the amount of air available decreases owing to a decrease in air density. Other researchers previously observed this phenomenon, and all confirmed that increasing ambient pressure leads to an increase in the generated power [31], [32]. As a result, the exhaust gas flow is reduced, and the power output is reduced as well. This, in fact, means that in areas with higher altitudes where the ambient pressure is lower, the production capacity of the power plant is reduced, which is very important in the discussion of cogeneration system designs. For example, the installation of this turbine in a coastal city, which has an ambient pressure of 1.015 bar, provides a power of about 380 kW in net power, while if the same system is installed in a highland city with an altitude of 1500 meters and ambient pressure of 0.861 bar, it will provide about 310 kW of net power, which shows a 20% reduction in output power.

As seen in Fig. 3, the ambient pressure at first glance does not significantly affect the efficiency of the cogeneration system (Fig. 4c). It only nonlinearly increases the system efficiency by about 0.8%. Although this is not a significant amount, it is necessary to mention that in the long run and over several years, this amount of difference in efficiency can also cause a substantial difference in the system's economic efficiency. Today, the world's largest power plants are trying to increase system

efficiency by one percent, so it is important to consider this.

On the other hand, ambient pressure has a very significant effect on the surface of the heat recovery boiler, in such a way that the total temperature of the boiler will increase from 340 square meters to 400 square meters when the ambient pressure varies between 0.8 and 1 bar (Fig. 4d). This is very influential in the initial investment debate. The larger the surface of the heat recovery boiler, the more pipes are used to build it, which will significantly increase costs. Therefore, although increasing the ambient pressure has positive effects on the output power and efficiency of the system, it leads to a rise in the heat level of the recovery boiler and an increase in the initial cost of the cogeneration system.
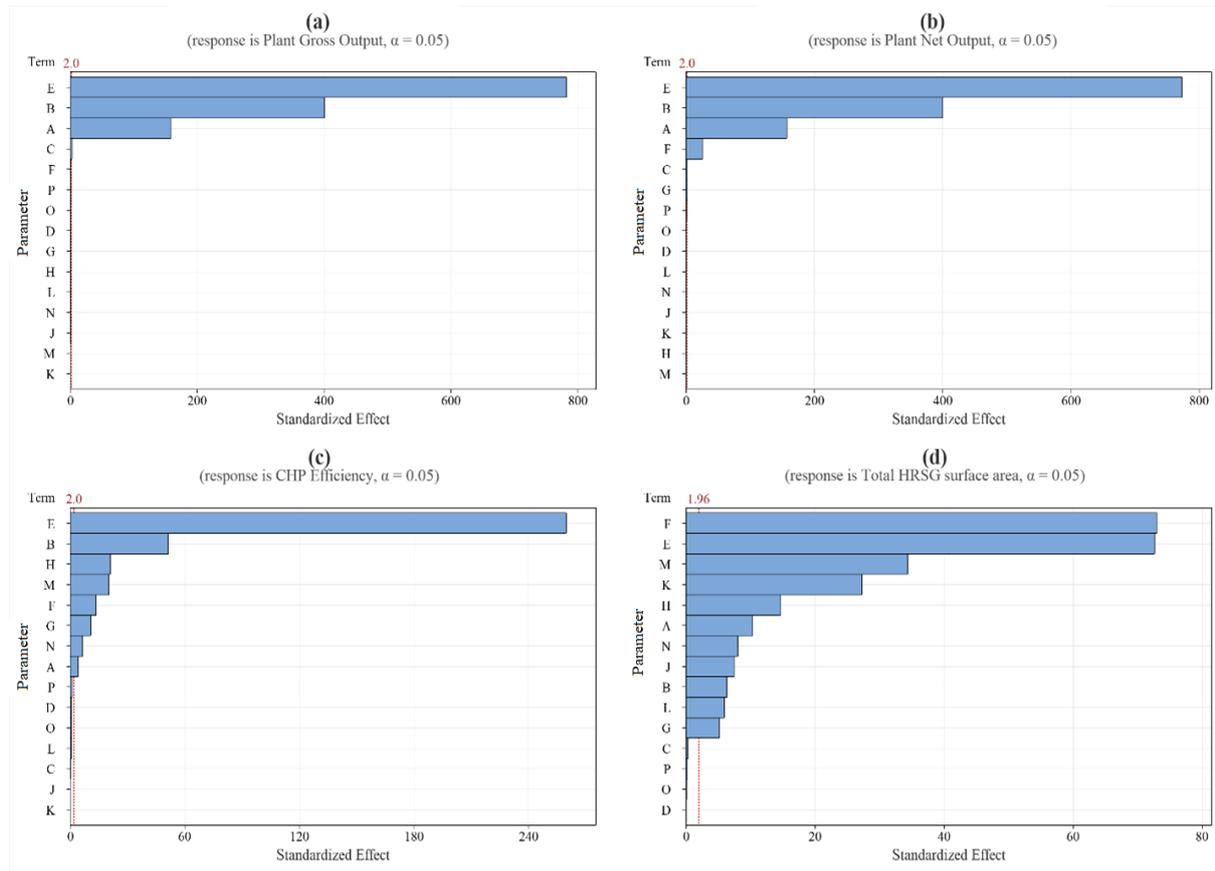
Factor	Name
A	Ambient Pressure
B	Ambient Temperature
C	Ambient Relative Humidity
D	Makeup Water Source Temp.
E	GT Power as % of Site Raiting
F	Main HP Process Prussure
G	Main HP Process Temp.
H	Main IP Process Prussure
J	Main IP Process Temp.
K	HPB Minimum Allowable Pinch
L	HP Feedwater Approach Subcoolin
M	IPB Minimum Allowable Pinch
N	IP Feedwater Approach Subcoolin
O	LPB Minimum Allowable Pinch
P	LPB Blowdown

Fig. 3. Pareto charts for (a) gross output power, (b) net output power, (c) CHP efficiency, and (d) total HRSG surface area.
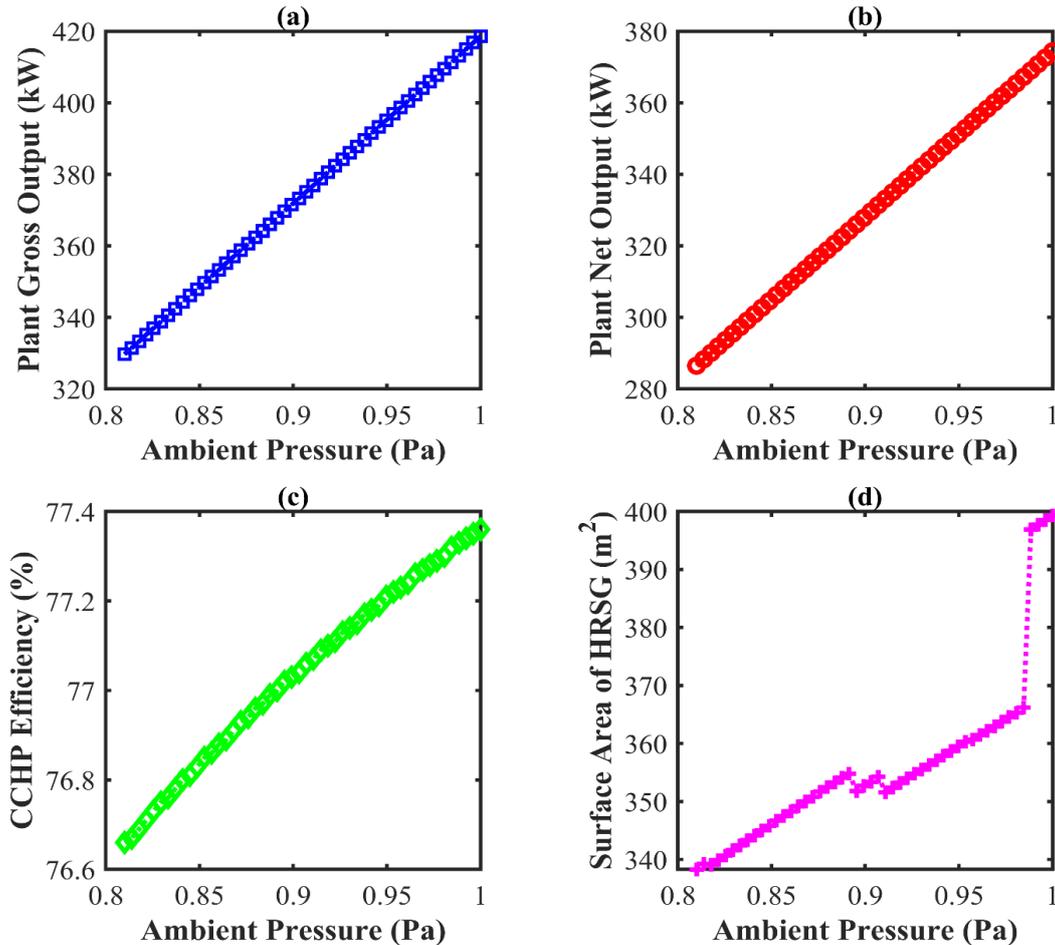
Fig. 4. Effects of ambient pressure on (a) gross output power, (b) net output power, (c) CHP efficiency, and (d) total HRSG surface area.

3.3.2. Effects of ambient temperature

The effects of ambient temperature on the output parameters of the cogeneration system can be seen in Fig.5. As is illustrated, increasing the ambient temperature significantly reduces the output power of the power plant non-linearly (Figs 5a & b). The net output power is halved as the temperature increases from -20°C to 50°C. As stated before, the gas turbine's performance is affected by changes to the mass flow or density of the intake air. The density of the air is influenced by ambient temperature, i.e., a reduction in temperature leads to an increase in air density [32]. This reduces the mass flow inlet to the gas turbine, leading to a decrease in production capacity.

As can be seen, increasing the ambient temperature leads to increasing the efficiency of the cogeneration system, i.e., in the temperature range studied in the present work, about an 8% increase in efficiency is observed

(Fig. 5c), which is a significant amount. Therefore, installing cogeneration systems in higher-temperature environments has higher economic efficiency. This indicates that despite the reduction in net output power, more heat output has been used in the recovery boiler system, which has increased the efficiency of the entire system.

Finally, the effect of ambient temperature on the total area of the heat recovery boiler is investigated (Fig. 5d). As can be seen, there is a somewhat erratic trend in the temperature level of the recovery boiler, especially near 0°C, where a sudden temperature rise is observed, and then a sharp decrease happens. Then, a slight increase in the boiler temperature is followed by a further rise in ambient temperature. It should be noted that the largest difference in the thermal level of the recovery boiler in this period is 30 square meters (less than 10%), which will not have much effect on the initial cost of the system and the recovery boiler.
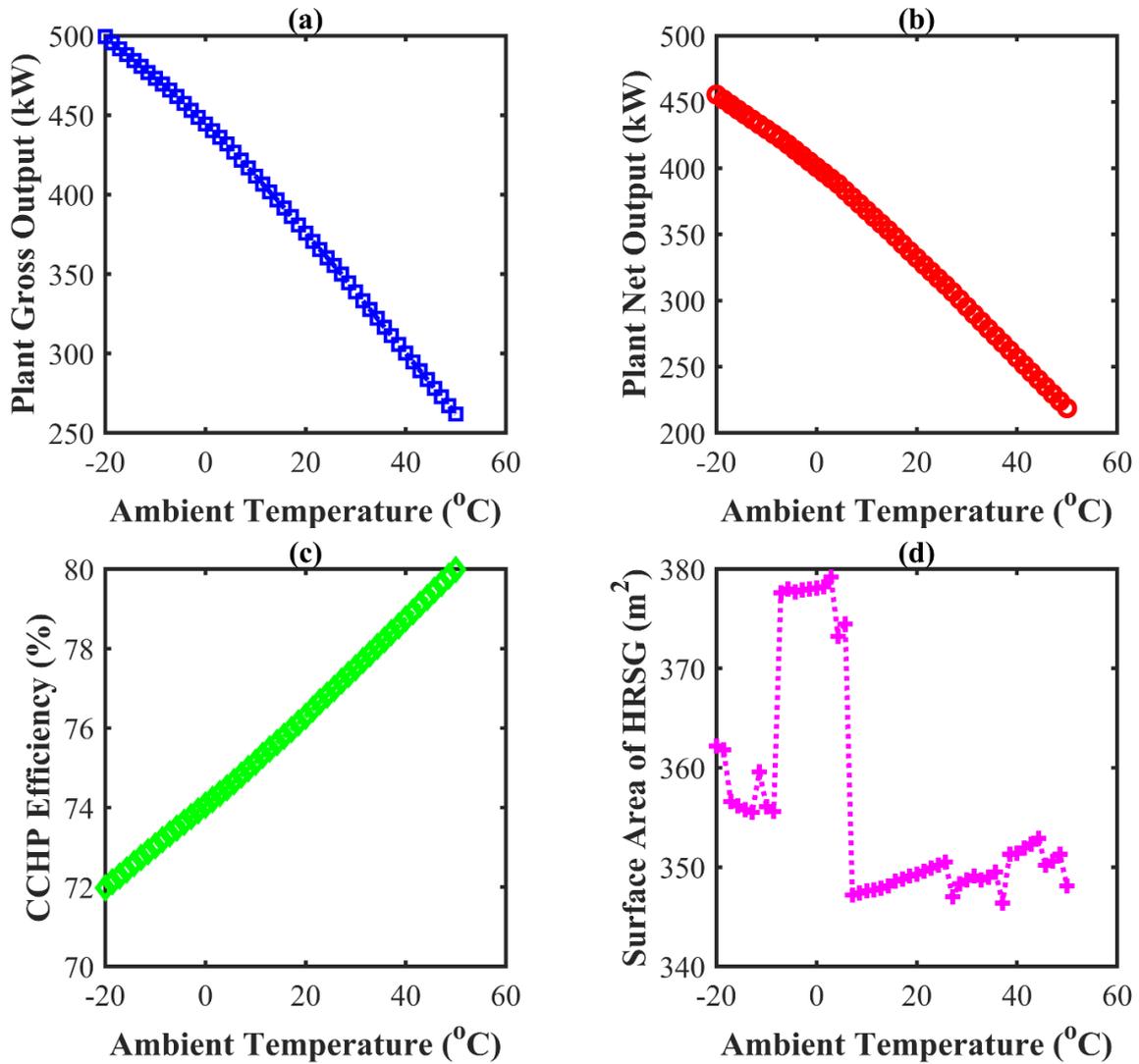
Fig. 5. Effects of ambient temperature on (a) gross output power, (b) net output power, (c) CHP efficiency, and (d) total HRSG surface area.

3.3.3. Effects of turbine load

Figure 6 shows the effects of turbine load percentage on output parameters. As mentioned before, the gas turbine load has the greatest impact among the studied parameters. Obviously, when the gas turbine operates at half or a quarter of its maximum power, the total and net output power of the power plant is greatly reduced; this reduction also occurs linearly (Figs 6a & b). Practically, partial load in gas turbines occurs when the system requires less production capacity, e.g., in residential areas at night.

It is also observed that the partial load changes of the gas turbine generator significantly affect the efficiency of the cogeneration system (Fig. 6c). So the efficiency of the system increases from about 50% to 80% with increasing partial load to full load. Hence, it is strongly recommended to avoid operating at partial loads. Also, increasing the partial load increases the surface area of the recovery boiler (Fig. 6d). This is obvious because increasing the partial load of the turbine increases the discharge of hot gases from the gas turbine. To provide sufficient heat from this amount of gas output, the heat level of the recovery boiler must be increased.
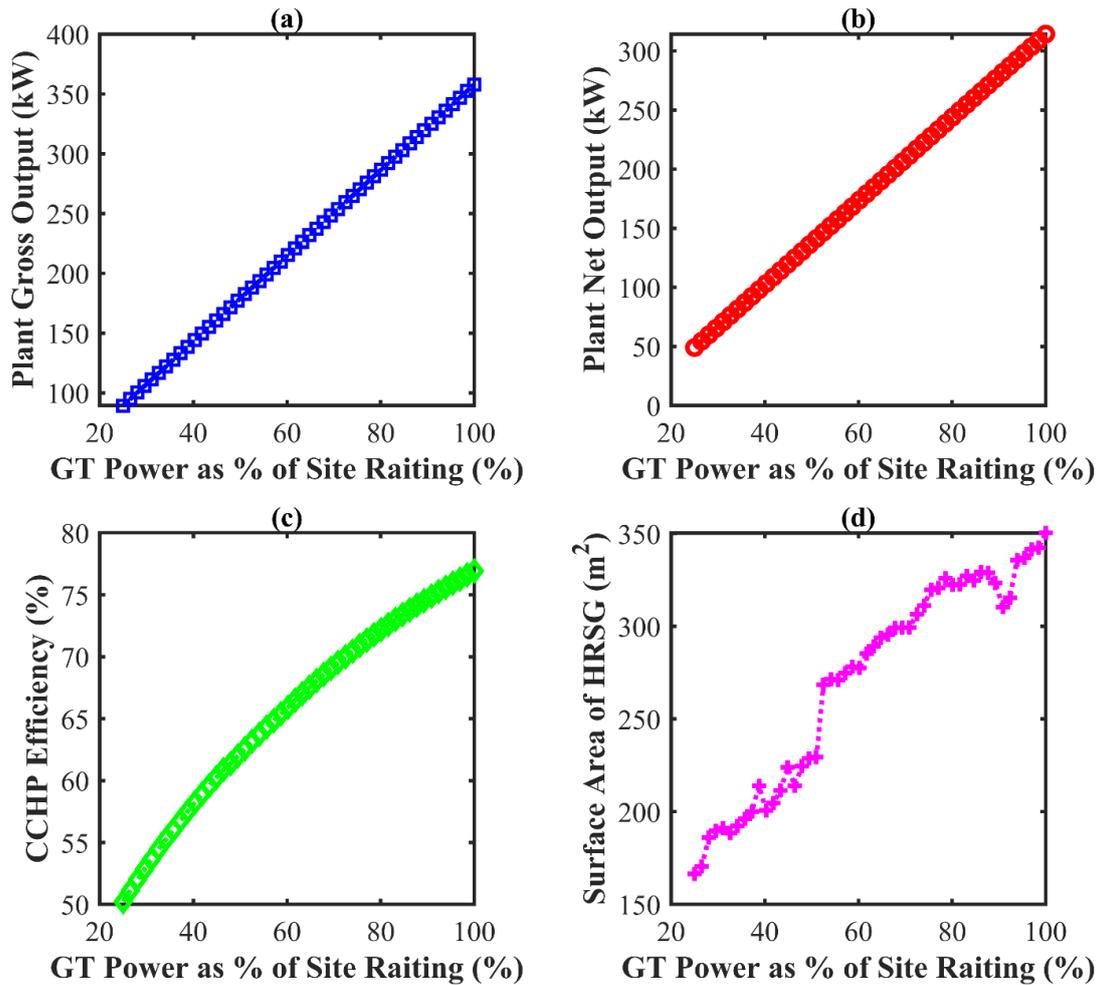
Fig. 6. Effects of turbine load on (a) gross output power, (b) net output power, (c) CHP efficiency, and (d) total HRSG surface area.

3.3.4. Effects of Main HP Process Pressure

Figure 7 shows the pressure effects of the high-pressure section of the recovery boiler on the output parameters. This pressure has very little impact on the total output power of the power plant, and the minor changes seen in the first figure are most likely due to computational errors (Fig. 7a). However, the effect of this parameter on the net output power of the power plant is more significant (Fig. 7b), although these changes can also be ignored. This means that the power consumption of components inside the power plant, such as pumps and other components, has increased with the increasing pressure of the high-pressure recovery boiler, which in constant output power of the gas turbine, has led to a decrease in net output power.

Increasing the pressure of the high-pressure recovery boiler leads to an increase in the efficiency of the entire cogeneration system (Fig. 7c), i.e., by changing the pressure from 50 to 150 times, the system's efficiency increases by about 2%. This was previously observed and analyzed utilizing exergy destruction by Hajabdollahi et al. [33], which found that whatever the pressure of the HP boiler increases, the energy destruction reduces, which leads to the increment in the efficiency of the cogeneration system. However, increasing the pressure of this boiler leads to a significant increase in the surface area of the recovery boiler, i.e., these changes can reach up to 50% (Fig. 7d). This is because as the pressure increases, there is more enthalpy in the hot gases, which means more thermal potential. Therefore, to use the energy of these hot exhaust gases, it is necessary to increase the surface area of the recovery boiler to have more time to be exposed to the hot gases.
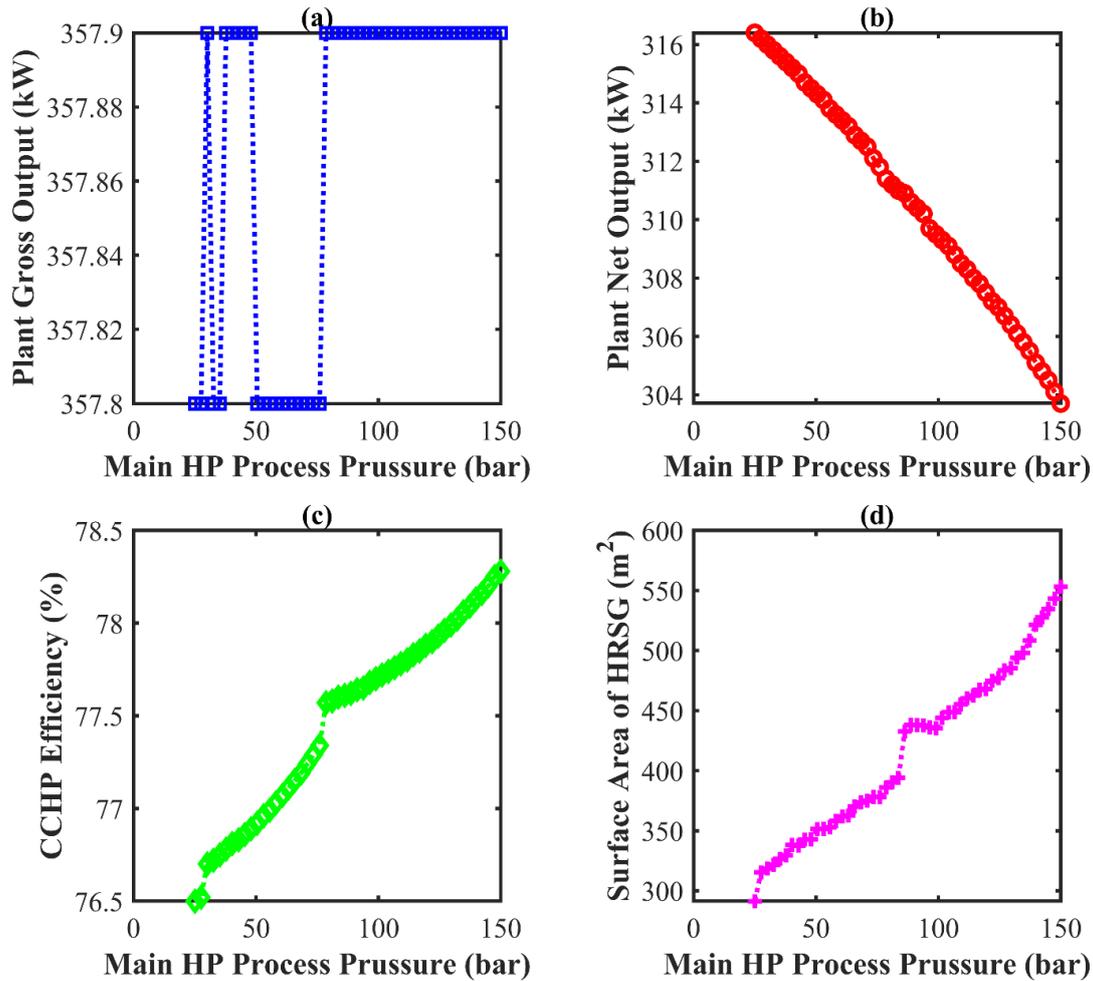
Fig. 7. Effects of main HP process pressure on (a) gross output power, (b) net output power, (c) CHP efficiency, and (d) total HRSG surface area.

3.3.5. Effects of Main HP Process Temperature

Figure 8 shows the effects of high-pressure recovery boiler temperature on the output parameters of the CHP system. As is illustrated, in this case, the effect of this parameter on the total power and net output power is very small (Figs. 8a & b). It only reduces the efficiency of the system by about 1.5 percent (Figure 8c). However, this generally leads to a relatively decreasing trend (up to about 10%) in the recovery boiler surface area (Fig.8d), which leads to a reduction in investment costs. Therefore, the use of higher temperatures in a high-pressure recovery boiler seems more desirable.

3.3.6. Effects of Main IP Process Pressure

Figure 9 demonstrates the effects of the intermediate pressure of the HRSG on the output parameters. In this case, the intermediate boiler pressure parameter does not have much impact on the output power (Figs 9a & b). While increasing this pressure leads to a reduction of up to 3% in the efficiency of the cogeneration system (Fig. 9c). On the other hand, the surface area of the HRSG is reduced by about 10% (Fig. 9d).

3.3.7. Effects of IPB Minimum Allowable Pinch

However, the minimum intermediate pressure pinch boiler temperature, although it has no effect on the output powers (Figs 10a & b), significantly reduces the efficiency of the cogeneration system. In fact, by changing this parameter from 10 to 30, a decrease in efficiency of about 4% is observed (Fig. 10c). As mentioned earlier, the pinch temperature is defined as the temperature difference between

the exhaust gas of the recovery boiler (at each stage) and the vapor saturation temperature. Therefore, the smaller the temperature difference, the longer the pipe length and, consequently, the higher the heat level for the recovery boiler to be able to create this temperature difference (Fig. 10d).

3.3.8. Effects of IP Feedwater Approach Subcooling

Figure 11 demonstrates the effects of intermediate pressure feedwater approach subcooling on the output parameters of the cogeneration system. As can be seen, the approach temperature of the intermediate pressure does not affect the output power of the cogeneration system (Figs 11a & b). However, increasing this parameter relatively reduces the system efficiency (Fig. 11c) and reduces the boiler's total surface area (Fig. 11d). In fact, the lower the approach, the larger the heating surface to transfer more heat from the hot gases to the steam to reduce the temperature difference of the approach. Hence, from an economic perspective, higher approach temperatures are desirable.
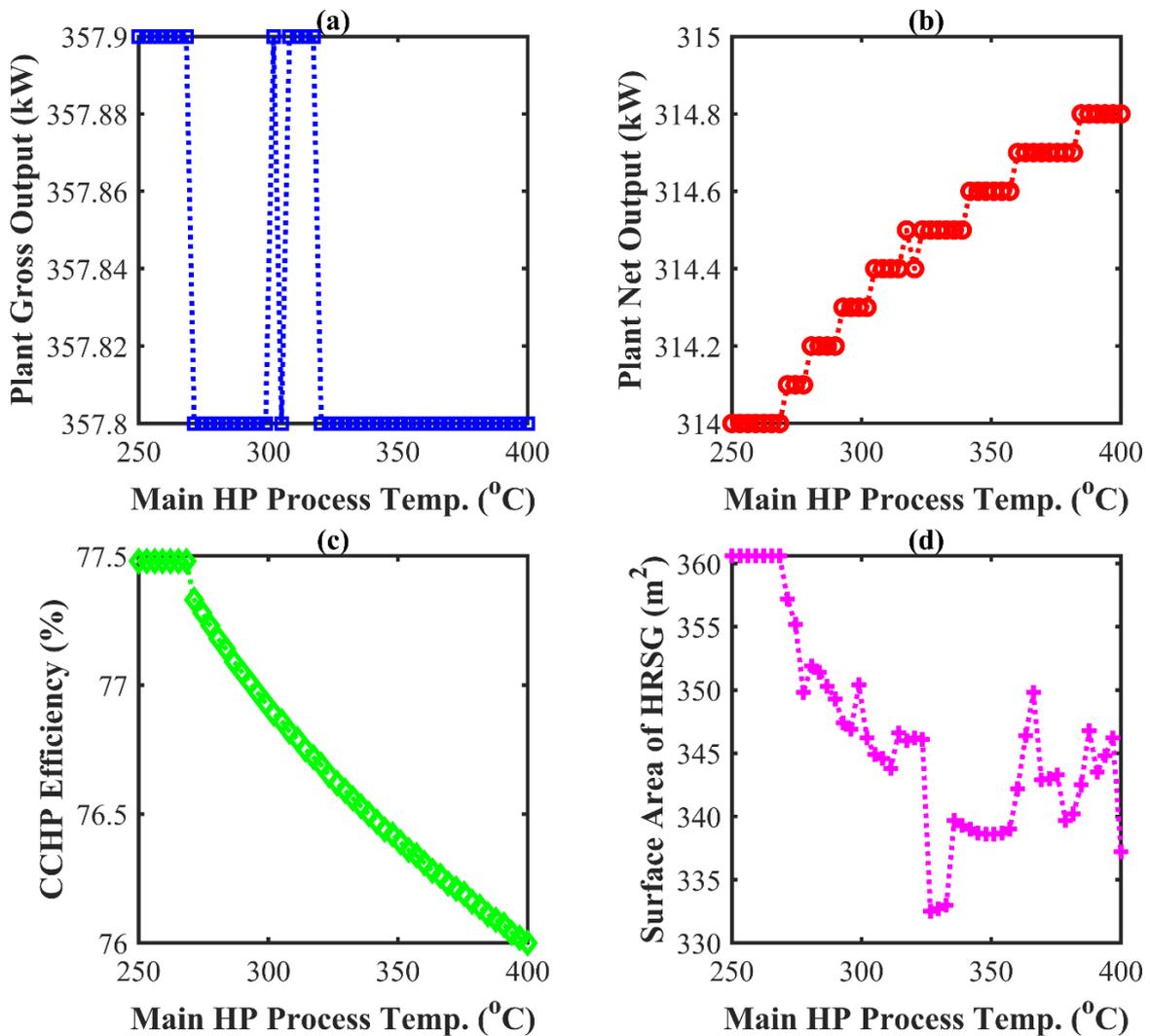

Fig. 8. Effects of main HP process temperature on (a) gross output power, (b) net output power, (c) CHP efficiency, and (d) total HRSG surface area.
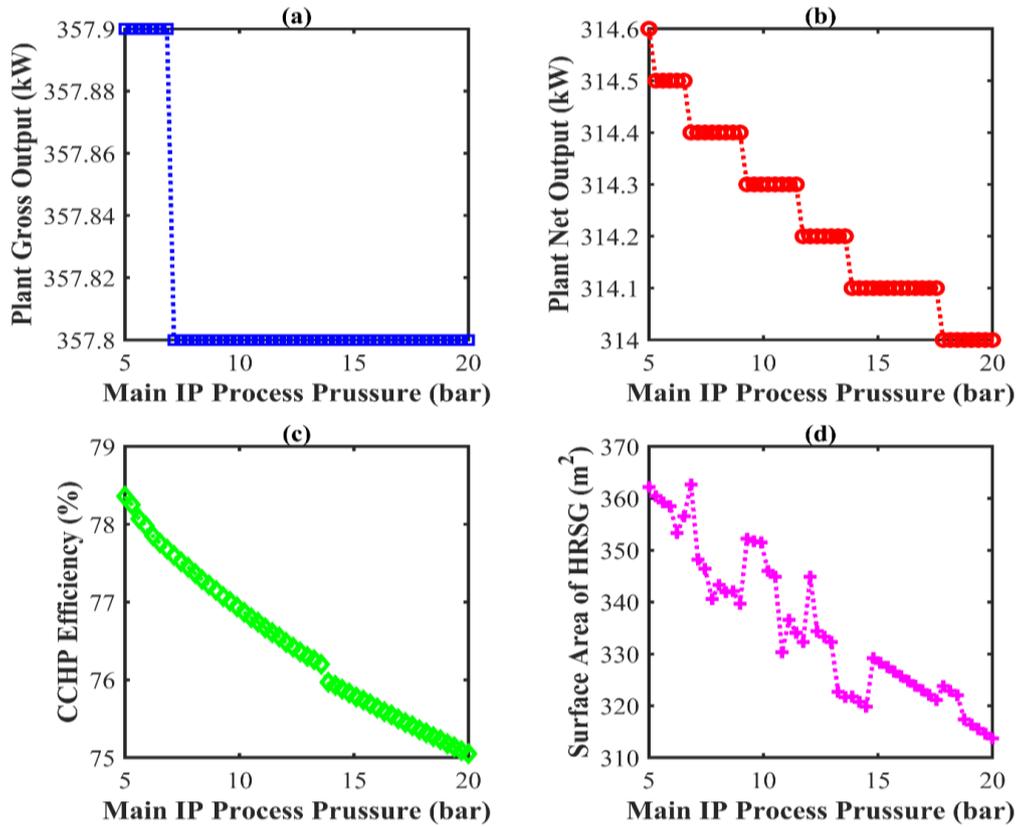
Fig. 9. Effects of main IP process pressure on (a) gross output power, (b) net output power, (c) CHP efficiency, and (d) total HRSG surface area.
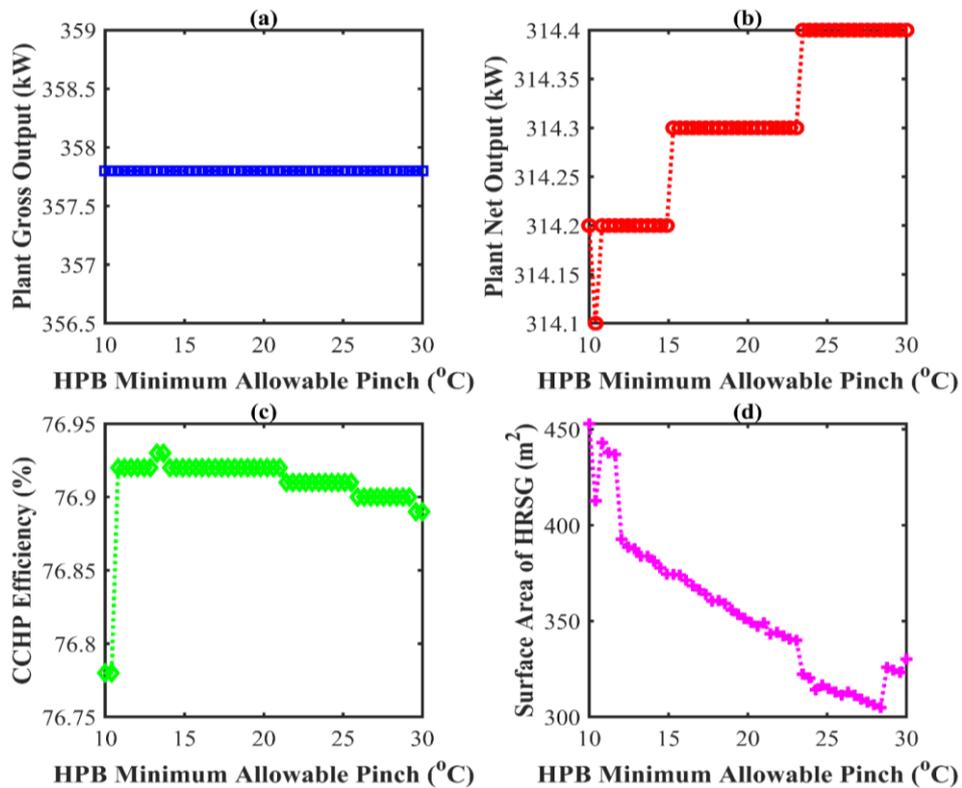

Fig. 10. Effects of IPB minimum allowable pinch on (a) gross output power, (b) net output power, (c) CHP efficiency, and (d) total HRSG surface area.
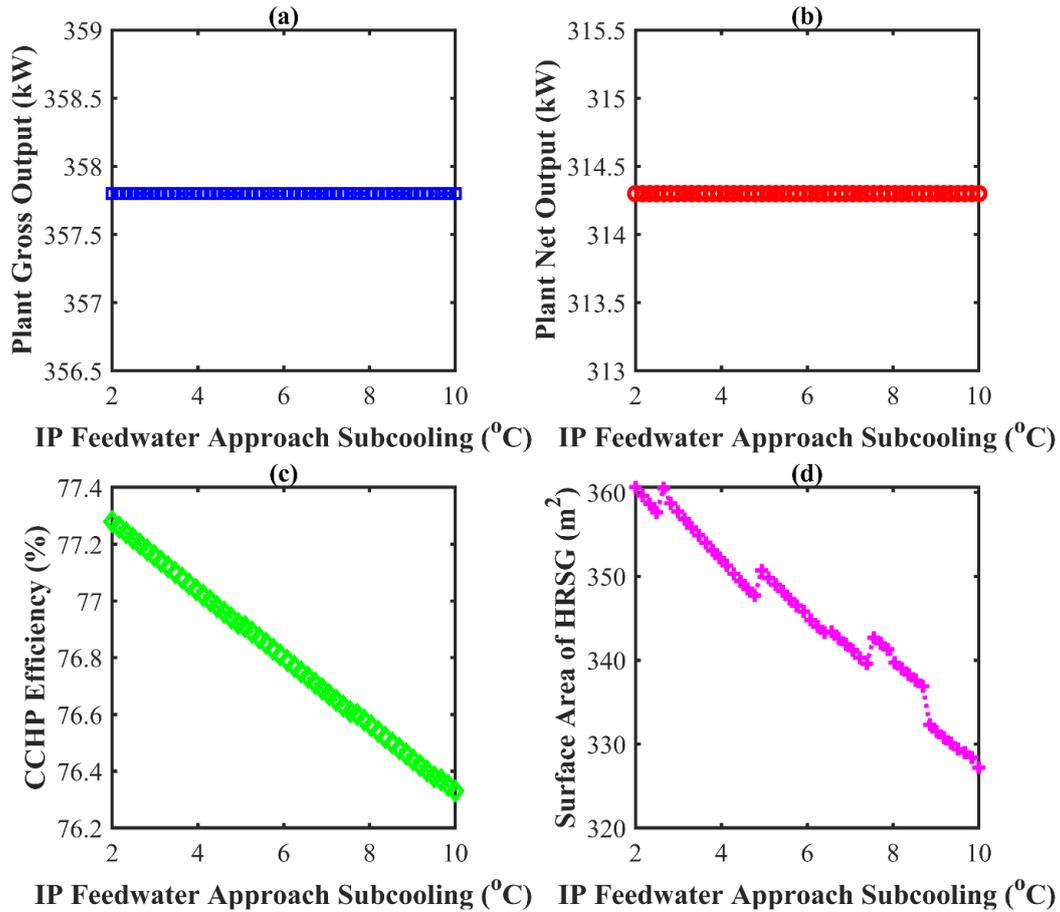
Fig. 11. Effects of IP feedwater approach subcooling on (a) gross output power, (b) net output power, (c) CHP efficiency, and (d) total HRSG surface area.

3.4. Correlations were obtained to calculate output parameters in different working conditions

This section presents the results of the obtained relations regarding important input parameters on the output parameters. The relationships presented in this section can be easily used for different environmental and working conditions of cogeneration systems and are, in fact, a roadmap for the feasibility of using this type of system in various regions and working conditions.

First, the relationship between the three parameters affecting the total output power of the gas turbine is presented as follows:

$$P_{Gross} = -332.5 + 491.2\,P - 3.13240\,T + 3.5776\,G - 13.0\,P^2 - 0.010755\,T^2 + 0.000009\,G^2 \qquad (3)$$

, the relationship between the four parameters affecting the net output power of the gas turbine is as follows:

$$P_{Net} = -363.5 + 485.7\,P - 3.12400\,T + 3.5500\,G - 0.07444\,P_{HP} - 12.9\,P^2 - 0.010731\,T^2 - 0.000106\,G^2 - 0.000150\,P_{HP}^2 \qquad (4)$$

The following relationship is obtained between the eight parameters that affect the efficiency of the cogeneration system:

$$Eff. = 38.81 + 12.80\,P + 0.108406\,T + 0.61634\,G + 0.021462\,P_{HP} - 0.03045\,T_{HP} - 0.34762\,P_{IP} - 0.16676\,Pinch_{IP} - 0.1208\,App_{IP} - 5.04\,P^2 + 0.000213\,T^2 - 0.002132\,G^2 - 0.000042\,P_{HP}^2 + 0.000031\,T_{HP}^2 + 0.005331\,P_{IP}^2 - 0.000172\,Pinch_{IP}^2 + 0.00015\,App_{IP}^2 \qquad (5)$$

Finally, here is how the heat level of the recovery boiler relates to the parameters that affect it:

$$HRSG_{Area} = 1331 - 1900\ P - 0.552\ T + $$
$$4.821\ G + 1.283\ P_{HP} - 1.407\ T_{HP} - 2.13\ P_{IP}$$
$$- 20.00\ Pinch_{IP} - 4.21\ App_{IP} + 1161\ P^2 +$$
$$0.00644\ T^2 - 0.01855\ G^2 + 0.00323\ P_{HP}^2 \qquad (6)$$
$$+ 0.001952\ T_{HP}^2 - 0.0537\ P_{IP}^2 + 0.3137\ Pinch_{IP}^2$$
$$+ 0.038\ App_{IP}^2$$

4. Conclusion

In the present research, the effects of 15 basic parameters on the performance of the cogeneration system were examined. Environmental parameters included temperature, pressure, and ambient relative humidity, along with makeup water temperature. Besides, the percentage of gas turbine load and parameters related to the heat recovery boiler were considered non-environmental parameters. Total gross power, net output power, cogeneration system efficiency, and surface area of the recovery boiler were examined as output parameters.

The results showed that ambient temperature has the greatest effect on the net output power and efficiency of the cogeneration system among environmental conditions, i.e., increasing ambient temperature from -20 to 50 $^\circ$C leads to an 8% increase in the efficiency of the CHP system. The results also showed that the percentage of gas turbine load significantly affects the output parameters. Also, the sensitivity analysis results showed that only three parameters, including gas turbine load percentage, ambient temperature, and ambient pressure affect the output power of the CHP system. Other parameters can be ignored in comparison with these three parameters. However, in addition to the three parameters mentioned, the main line pressure of the high-pressure part of the recovery boiler is an effective parameter for the net output power. Additionally, the findings of the discovered relationships between significant input parameters and output parameters were provided. In reality, the correlations shown in this study constitute a road map for the viability of employing this sort of system in various locations and working situations. They may be utilized for varied environmental and working conditions of cogeneration systems.

The results obtained from this study can be easily generalized to all different working conditions and different environmental conditions. The sensitivity analysis gives insight into the design of a CHP system and the trade-off between various effective parameters. Besides, using the relationships presented here, the desired and important outputs of a cogeneration system can be easily achieved for various environmental and working conditions.

The most significant limitation of this study was the huge amounts of case studies. So, a single gas turbine as a prime mover was only investigated. Besides, some other minor parameters can be considered for the analysis of effective parameters, however, due to the limitations of case studies, these parameters were eliminated in this study.

In future research, we recommend performing a more comprehensive analysis of the effective parameters in a CHP system with various primary movers. Besides, analysis of effective parameters in CCHP systems is essential for the systems containing a cooling section.

Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

[1] Gani, A., Fossil fuel energy and environmental performance in an extended STIRPAT model. Journal of Cleaner Production, 2021. 297: p. 126526.

[2] Kannan, N. and D. Vakeesan, Solar energy for future world:-A review. Renewable and sustainable energy reviews, 2016. 62: p. 1092-1105.

[3] Mago, P., L. Chamra, and A. Hueffed, A review on energy, economical, and environmental benefits of the use of CHP systems for small commercial buildings for the North American climate. International Journal of Energy Research, 2009. 33(14): p. 1252-1265.

[4] Barrager, S. and E. Cazalet, Transactive energy: a sustainable business and regulatory model for electricity. 2014: Baker Street Publishing, LLC.

[5] Marinakis, V., Big data for energy management and energy-efficient buildings. Energies, 2020. 13(7): p. 1555.

[6] Kheiri, F., A review on optimization methods applied in energy-efficient building geometry and envelope design. Renewable and Sustainable Energy Reviews, 2018. 92: p. 897-920.

[7] Ionescu, C., et al., The historical evolution of the energy efficient buildings. Renewable and Sustainable Energy Reviews, 2015. 49: p. 243-253.

[8] Hanafizadeh, P., et al., Evaluation and sizing of a CCHP system for a commercial and office buildings. Journal of Building Engineering, 2016. 5: p. 67-78.

[9] Rey, G., et al., Performance analysis, model development and validation with experimental data of an ICE-based micro-CCHP system. Applied Thermal Engineering, 2015. 76: p. 233-244.

[10] Ebrahimi-Moghadam, A., et al., Proposal and assessment of a novel combined heat and power system: Energy, exergy, environmental and economic analysis. Energy Conversion and Management, 2020. 204: p. 112307.

[11] Sukpancharoen, S. and B. Prasartkaew, Combined heat and power plant using a multi-objective Henry gas solubility optimization algorithm: A thermodynamic investigation of energy, exergy, and economic (3E) analysis. Heliyon, 2021. 7(9).

[12] Mahian, O., et al., Exergy analysis in combined heat and power systems: A review. Energy conversion and management, 2020. 226: p. 113467.

[13] Zhang, F.-y., et al., Thermo-economic optimization of biomass-fired organic Rankine cycles combined heat and power system coupled CO_2 capture with a rated power of 30 kW. Energy, 2022. 254: p. 124433.

[14] Oliveira, A., et al., A combined heat and power system for buildings driven by solar energy and gas. Applied Thermal Engineering, 2002. 22(6): p. 587-593.

[15] Bruno, J.C., A. Valero, and A. Coronas, Performance analysis of combined microgas turbines and gas fired water/LiBr absorption chillers with post-combustion. Applied Thermal Engineering, 2005. 25(1): p. 87-99.

[16] Cardona, E. and A. Piacentino, A methodology for sizing a trigeneration plant in Mediterranean areas. Applied thermal engineering, 2003. 23(13): p. 1665-1680.

[17] Foster-Pegg, R., Steam bottoming plants for combined cycles. J. Eng. Power;(United States), 1978. 100(2).

[18] Chin, W. and M. El-Masri, Exergy analysis of combined cycles: Part 2—analysis and optimization of two-pressure steam bottoming cycles. 1987.

[19] Karthikeyan, R., et al., Performance simulation of heat recovery steam generators in a cogeneration system. International Journal of Energy Research, 1998. 22(5): p. 399-410.

[20] Jarre, M., M. Noussan, and A. Poggio, Operational analysis of natural gas combined cycle CHP plants: Energy performance and pollutant emissions. Applied Thermal Engineering, 2016. 100: p. 304-314.

[21] De, S., et al., Development of an artificial neural network model for the steam process of a coal biomass cofired combined heat and power (CHP) plant in Sweden. Energy, 2007. 32(11): p. 2099-2109.

[22] Thomas, B., Benchmark testing of Micro-CHP units. Applied Thermal Engineering, 2008. 28(16): p. 2049-2054.

[23] Pilavachi, P., et al., Multi-criteria evaluation for CHP system options. Energy Conversion and Management, 2006. 47(20): p. 3519-3529.

[24] Anderson, M.J. and P.J. Whitcomb, Design of experiments. Kirk-Othmer Encyclopedia of Chemical Technology, 2000: p. 1-22.

[25] Rosa, P.A., A.M. Azevedo, and M.R. Aires-Barros, Application of central composite design to the optimisation of aqueous two-phase extraction of human antibodies. Journal of Chromatography A, 2007. 1141(1): p. 50-60.

[26] Sattari, A., et al., Numerical study of double emulsion droplet generation in a dual-coaxial microfluidic device using response surface methodology. Chemical Engineering and Processing-Process Intensification, 2021. 162: p. 108330.

[27] Ahmadi, M., et al., Application of the central composite design and response surface methodology to the advanced treatment of olive oil processing wastewater using Fenton's peroxidation. Journal of Hazardous Materials, 2005. 123(1-3): p. 187-195.

[28] Fard Masoumi, H.R., et al., Enhancement of encapsulation efficiency of nanoemulsion-containing aripiprazole for the treatment of schizophrenia using mixture experimental design. International journal of nanomedicine, 2015: p. 6469-6476.

[29] Christopher Frey, H. and S.R. Patil, Identification and review of sensitivity analysis methods. Risk analysis, 2002. 22(3): p. 553-578.

[30] The 2nd Law of Thermodynamics'.Page dated 2002-2-19. Retrieved on 2010-4-01.

[31] Sadeghi, S. and P. Ahmadi, Thermo-economic optimization of a high-performance CCHP system integrated with compressed air energy storage (CAES) and carbon dioxide ejector cooling system. Sustainable Energy Technologies and Assessments, 2021. 45: p. 101112.

[32] Baheta, A.T. and S.I.-U.-H. Gilani. The effect of ambient temperature on a gas turbine performance in part load operation. in AIP Conference Proceedings. 2012. American Institute of Physics.

[33] Hajabdollahi, H., P. Ahmadi, and I. Dincer, An exergy-based multi-objective optimization of a heat recovery steam generator (HRSG) in a combined cycle power plant (CCPP) using evolutionary algorithm. International Journal of Green Energy, 2011. 8(1): p. 44-64.