Proceedings of the Global Conference on Global Warming 2011
11-14 July, 2011, Lisbon, Portugal

Exergoenvironmental Analysis of a Trigeneration System Based on Micro Gas Turbine and Organic Rankine Cycles

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Abstract — A comprehensive thermodynamic modelling is reported of a trigeneration system for cooling, heating, electricity generation and hot water production. This trigeneration system consists of a gas turbine cycle, an organic Rankine cycle (ORC), a single-effect absorption chiller and a domestic water heater. Energy and exergy analyses, environmental impact assessments and related parametric studies are carried out, and parameters that measure environmental impact and sustainability are evaluated. The exergy efficiency of the trigeneration system is found to be higher than that of typical combined heat and power systems or gas turbine cycles. The results also indicate that carbon dioxide emissions for the trigeneration system are less than for the aforementioned systems. The exergy results show that combustion chamber has the largest exergy destruction of the cycle components, due to the irreversible nature of its chemical reactions and the high temperature difference between the working fluid and flame temperature. The parametric investigations show that the compressor pressure ratio, the gas turbine inlet temperature and the gas turbine isentropic efficiency significantly affect the exergy efficiency and environmental impact of the trigeneration system. Also, increasing the turbine inlet temperature decreases the cost of environmental impact, primarily by reducing the combustion chamber mass flow rate.

Keywords —Trigeneration, organic Rankine cycle, environmental impact, exergy, energy, efficiency

1 INTRODUCTION

Fossil fuel depletion and global warming are two important concerns for the sustainability of energy systems in the future. Demand for energy has been steadily rising despite limited availability of non-renewable fuel resources. Hence, efforts to develop more efficient energy systems are becoming increasingly significant. The efficiency of conventional power plants, which are usually based on single prime movers, is usually less than 40%. Thus, most of the input energy is lost, much as waste heat.

The integration of systems to provide cooling, heating and hot water with conventional plant can increase the overall plant efficiency to up to 70% [1,2]. Trigeneration is the simultaneous production of heating, cooling and electricity from a common energy source. Trigeneration utilizes the waste heat of a power plant to improve overall thermal performance, essentially utilizing the "free" energy available via the waste energy. In a trigeneration system, waste heat from the plant's prime mover (e.g., gas turbine or diesel engine or organic Rankine cycle [3]), sometimes with temperature enhancement, drives heating and cooling devices. The literature shows that most research on trigeneration has been conducted in the last few years, likely motivated by the advantages of trigeneration. Khaliq et al. [4] carried out an exergy analysis of a combined electrical power and refrigeration cycle, as well as a parametric study of the effects of exhaust gas inlet temperature, pinch-point and gas composition on energy and exergy efficiencies, electricity-to-cold ratio and exergy destruction for the cogeneration system and its components. Minciuc et al. [5] present a method for analyzing trigeneration systems and establish limits for the best performance of gas turbine trigeneration with absorption chilling from a thermodynamic point of view.

Recently, combined exergoeconomic and environmental (e.g., exergoenvironmental) assessments have received increasing attention. Ahmadi and Dincer [6] report an exergo-environmental optimization of a combined heat and power (CHP) system using a genetic algorithm, and a sensitivity analysis of how optimized design parameters vary with fuel cost. A thermodynamic analysis of post-combustion CO_2 capture in a natural gas-fired power plant has been reported by Amrolahi et al. [7]. Exergo-environmental analysis can provide insights for trigeneration but such analyses have not to date been reported, especially based on organic Rankine cycles.

The organic Rankine cycle (ORC) can be

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integrated into trigeneration plants as a power producer. The ORC is expected to play an important role in energy production in the near future [3], mainly due to its ability to integrated with thermal systems from which have low- or medium-temperature waste heat is available [3]. The primary objective of this research is to perform thermodynamic modeling and both exergy and environmental analyses of a trigeneration system with a gas turbine prime mover. The specific objectives follow:

- To model a trigeneration system based on a micro gas turbine prime mover, an organic Rankine cycle, a single-effect absorption chiller and a domestic water heater for heating, cooling, hot water production and electricity generation.
- To perform exergy and environmental analyses of the system, including determinations of the exergy destruction and CO_2 emission of each component, and parametric assessments of the effects of varying selected design parameters on overall exergy and energy efficiencies.
- To determine the sustainability index for the system and quantify its variation with exergy destruction, and to establish a relation between exergy efficiency, exergy destruction and sustainability index.

2 ANALYSIS

The thermodynamic modeling of the trigeneration system considered here (Fig. 1) is divided into three parts: topping cycle (Brayton cycle), bottoming cycle (Organic Rankine cycle and domestic water heater) and single-effect absorption chiller. Exergo-environmental analysis is used to determine the temperature profile in the trigeneration plant, input and output enthalpies, exergy flows, environmental impacts, exergy destructions and exergy efficiencies. Relevant energy balances and governing equations for the main sections of the trigeneration plant in Fig. 1 are described in the following subsections.

2.1. Energy Analysis

2.1.1 Topping Cycle

We model a topping cycle, which consists of a micro gas turbine cycle using the first law of thermodynamics. As seen in Fig. 1, air at ambient conditions enters the air compressor at point 1 and, after compression (point 2), is supplied to the recuperator. Then the hot air enters the combustion chamber (CC). Fuel is injected in the combustion chamber and hot combustion gases exit (point 4) pass through a gas turbine to produce shaft power. The hot gas expands in the gas turbine to point 5, after which it passes through the recuperator to warm air. These hot gases leave the recuperator at point 6 and then enter the heat exchanger linked to the bottoming cycle. Details about thermodynamic relations of each part of the gas turbine cycle are given elsewhere [8].

2.1.2 Bottoming Cycle

Energy balances and governing equations for the components of the bottoming cycle (organic Rankine cycle and domestic water heater) are provided here.

2.1.3 Organic Rankine Cycle

The waste heat from the micro gas turbine is used to heat the organic fluid in the ORC, for the provision of heating and cooling. The waste heat from the ORC is used to produce steam in the heating process, using a heat exchanger, and to produce cooling using the single-effect absorption chiller. To have an efficient ORC, the working fluid in the ORC should have a high critical temperature so that the waste heat can be used more efficiently [3]. A typical organic fluid type used in ORCs is n-octane, which has a relatively high critical temperature, 569 K [3]. This organic fluid is selected as the working fluid of the ORC here. The thermodynamic properties of n-octane are obtained from the EES software, which is coupled with Matlab software for modelling. Energy balances for the key components in the ORC follow:

- **Heat exchanger**

$$\dot{m}_g C_{pg}(T_6 - T_{21}) = \dot{m}_{ORC}(h_{17} - h_{16}) \qquad (1)$$

- **Turbine**

$$\dot{m}_{ORC}(h_{17} - h_{18}) = \dot{W}_{ORC} \qquad (2)$$

- **Heating process**

$$\dot{m}_{ORC}(h_{18} - h_{19}) = \dot{Q}_{Heating} \qquad (3)$$

- **ORC pump**

$$\dot{m}_{ORC}(h_{15} - h_{16}) = \dot{W}_{ORC,Pump} \qquad (4)$$

2.1.4 Domestic Water Heater

The hot gases leaving the heat recovery heat exchanger enter the water heater to warm domestic hot water to 60 °C. Water enters this heater at a pressure and a temperature of 3 bar and 15 °C, respectively. The energy balance for this component is given as follows:

$$\dot{m}_g C_{pg}(T_{21} - T_{24}) = \dot{m}_w(h_{23} - h_{22}) \qquad (5)$$

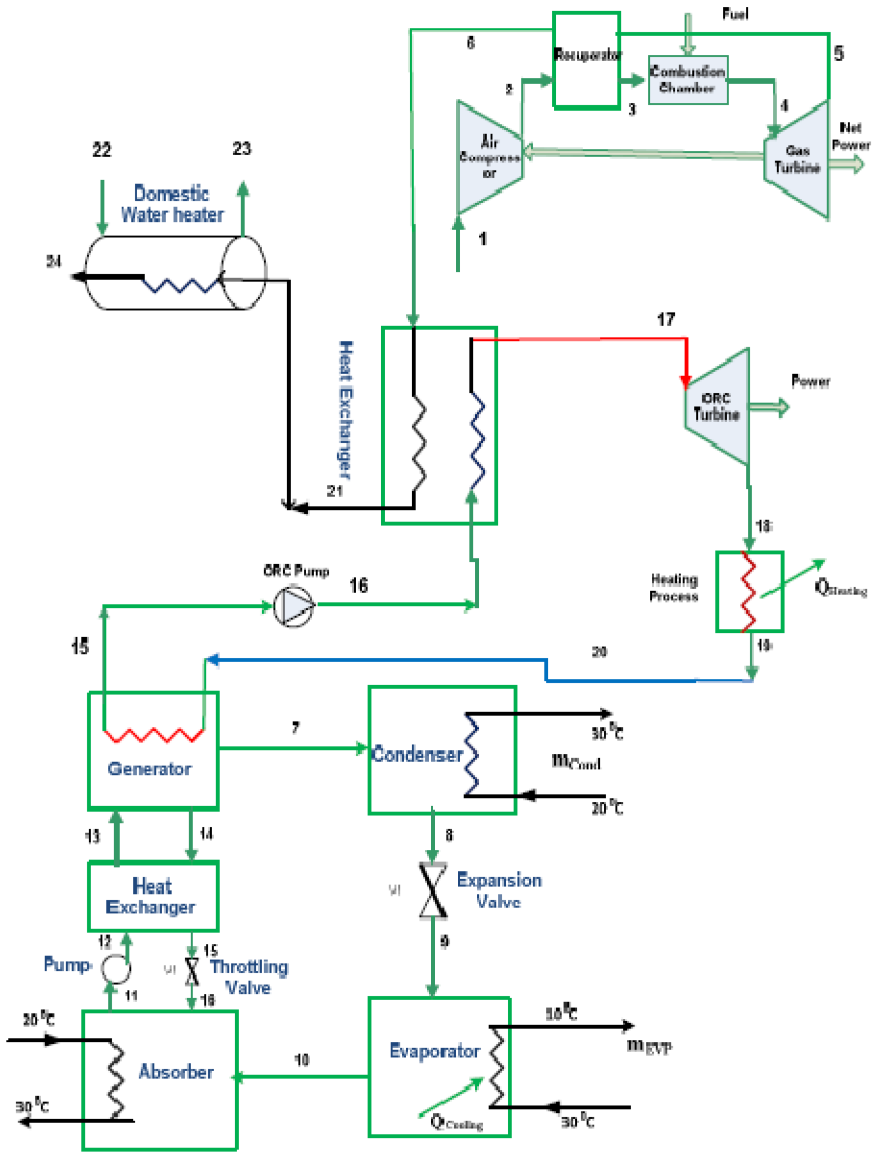

Fig. 1. Schematic of the trigeneration system for heating, cooling and electricity generation.

2.1.5 Absorption Chiller

The principle of mass conservation and the first and second laws of thermodynamics are applied to each component of the single-effect absorption chiller. In our analysis, each component is considered as a control volume with inlet and outlet streams, and heat and work interactions are considered. Mass balances are applied for the total mass and each material of the working fluid solution. The governing and conservation equations for total mass and each material of the solution for a steady state and steady flow process are detailed in reference [9]. The following simplifying assumptions are made here to render the analysis more tractable, while retaining adequate accuracy to illustrate the principal points of this study:

- All processes are operating at steady state.
- Air and combustion products are ideal-gas mixtures.
- The fuel injected to the combustion chamber is natural gas.
- Heat loss from the combustion chamber is 2% of the fuel lower heating value, and all other components are adiabatic.
- The ORC turbine and pump isentropic efficiencies are 80%.
- The ORC pump pressure ratio is 100.
- The ORC pump temperature is 72 °C.
- The organic fluid enters the turbine at 400 °C.
- The dead state is at a pressure of P_0 = 1.01 bar

and a temperature of $T_0 = 293.15$ K.

2.2 Exergy Analysis

Exergy analysis can help to develop strategies and guidelines for more effective use of energy, and has been applied to various thermal processes, including power generation, CHP and trigeneration. Exergy can be divided into four components: physical, chemical, kinetic and potential. In this study, the latter two are neglected since changes in elevation and speed are negligible [3, 6, 8, 10]. Physical exergy is defined as the maximum work obtainable as a system interacts with an equilibrium state [4]. Chemical exergy is associated with the departure of the chemical composition of a system from the chemical equilibrium of a a reference environment. Chemical exergy is important in combustion evaluation [10]. Applying the first and the second laws of thermodynamics, the following exergy balance for each component is obtained:

$$\dot{E}x_Q + \sum_i \dot{m}_i\, ex_i = \sum_e \dot{m}_e\, ex_e + \dot{E}x_W + \dot{E}x_D \qquad (6)$$

Details about each term in this equation are given in references [8, 9, 10].

2.3 Exergy Efficiency

The exergy efficiency, defined as the product exergy output divided by the exergy input, for the micro gas turbine, CHP and overall trigeneration systems, can be expressed as follows:

$$\psi_{GT} = \frac{\dot{W}_{GT}}{\dot{E}x_f} \qquad (7)$$

$$\psi_{CHP} = \frac{\dot{W}_{GT} + \dot{E}x_{Heating}}{\dot{E}x_f} \qquad (8)$$

$$\psi_{Tri} = \frac{\dot{W}_{net} + \dot{E}x_{Heating} + \dot{E}x_{Cooling} + \dot{E}x_{Hot\ water}}{\dot{E}x_f} \qquad (9)$$

where $\dot{E}x_f$ is the fuel exergy flow rate, $\dot{E}x_Q$ is the exergy rate associated with heating and cooling, and $\dot{W}_{net}$is net output power of GT and ORC cycle.[4].

2.4 Exergoenvironmental Analysis

An important measure for reducing environmental impact, including emissions of carbon dioxide, a primary greenhouse gas, is increasing the efficiency of energy conversion processes and thereby decreasing fuel use. Although numerous exergy and exergoeconomic analyses have been reported for CHP and trigeneration systems, many do not address environmental impact. Rectifying this deficiency is one of the main objectives of the present work, in which emissions of CO, CO_2 and NO_x are considered.

The amount of CO and NO_x produced in a combustion chamber and combustion reaction depend on various combustion characteristics including the adiabatic flame temperature [11]. Here, the emissions for these species (in grams per kilogram of fuel) are determined as follows [12]:

$$m_{NO_x} = \frac{0.15E16\,\tau^{0.5}\exp(-71100/T_{pz})}{P_3^{0.05}(\Delta P_3/P_3)^{0.5}} \qquad (10)$$

$$m_{CO} = \frac{0.179E9\exp(7800/T_{pz})}{P_3^{2}\,\tau(\Delta P_3/P_3)^{0.5}} \qquad (11)$$

where τ is the residence time in the combustion zone (assumed constant here at 0.002 s), T_{pz} is the primary zone combustion temperature, P_3 is the combustor inlet pressure, and $\Delta P_3 / P_3$ is the non-dimensional pressure drop in the combustion chamber. In this analysis, we express the environmental impact as the total cost rate of pollution damage ($/s) due to CO, NO_x and CO_2 emissions by multiplying their respective flow rates by their corresponding unit damage costs (C_{CO}, C_{NOx} and C_{CO2}, which are taken to be equal to 0.02086 $/kg, 6.853 $/kg and 0.024 $/kg, respectively) [8]. The cost of pollution damage is assumed here to be added directly to other system costs.

To improve environmental sustainability, it is necessary not only to use sustainable or renewable sources of energy, but also to utilize non-renewable sources like natural gas fuel more efficiently, while minimizing environmental damage. In this way, society can reduce its use of limited resources and extend their lifetimes. Here, a sustainability index *SI* is used to relate exergy with environmental impact [13, 14]:

$$SI = \frac{1}{D_P} \qquad (12)$$

where D_P is the depletion number, defined as the ratio of exergy destruction to input exergy. This relation demonstrates how reducing a system's environmental impact can be achieved by reducing its exergy destruction.

3 RESULTS AND DISCUSSION

Results of the thermodynamic modeling and exergy and environmental analyses are presented here, including assessments of the effects of varying several design parameters on cycle performance. In these examinations, the molar composition of the inlet air is taken to be 0.7567 N_2, 0.2035 O_2, 0.003 CO_2 and 0.036 H_2O [15], and the fuel injected to the combustion chamber is natural gas, modeled as pure methane and with a *LHV* about 50,000 kJ/kg. Table 1 lists the thermodynamic specifications of the trigeneration system, including heating and cooling loads, electricity generated by the turbines, COP of the absorption chiller, and combustion chamber mass flow rates.

Table 1. Parameter values resulting from energy and exergy analyses of the system

Parameter		Value
Fuel mass flow rate	$\dot{m}_f$ (kg/s)	0.068
Heating load	$\dot{Q}_{Heating}$ (kW)	819.5
Cooling load	$\dot{Q}_{cooling}$ (kW)	199.8
Net output power	$\dot{W}_{net}$ (kW)	1500
Energy efficiency	η_{Tri}	0.89
Exergy efficiency	ψ_{Tri}	0.55
Total exergy destruction rate	$\dot{E}x_{D,Total}$ (kW)	2172
Specific CO_2 emission	CO_2 emission (kg/MWh)	88.2
Cost rate of environmental impacts	$\dot{C}_{env}$ ($/h)	7.54
Hot water mass flow rate	$\dot{m}_{hot,water}$	3.27
Absorption chiller COP	COP	0.44

3.1 Exergy Analysis Results

The exergy analysis results are summarized in Fig. 2, and they show that the highest exergy destruction occurs in the combustion chamber (CC), mainly due to the irreversibilities associated with combustion and the large temperature difference between the air entering the CC and the flame temperature. The heat exchanger exhibits the next largest exergy destruction, mainly due to the temperature difference between two fluid streams passing through it as well as to the pressure drop across the device.

Both exergy destruction and the dimensionless exergy destruction ratio are higher in the combustor than in other components, suggesting that it would likely be worthwhile to focus improvement efforts on this component. Moreover, the results show that the absorption cycle does not exhibit significant exergy destructions, mainly because it does not directly utilize fuel energy but instead uses steam produced by the ORC.

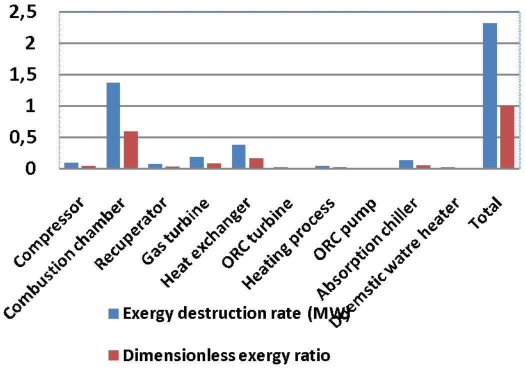

Fig. 2. Exergy destruction rate and dimensionless exergy efficiency for the trigeneration system and each of its components.

3.2 Parametric Study

The effect of variations of design parameters on the thermodynamic performance of the trigeneration system is assessed. Since compressor pressure ratio, gas turbine inlet temperature, gas turbine isentropic efficiency and organic fluid turbine inlet temperature significantly affect system performance parameters (e.g., energy and exergy efficiencies), we focus on them here.

Fig. 3 shows the variation with compressor pressure ratio of both exergy efficiency and exergy destruction for the system. It is observed that fuel consumption decreases as the compressor pressure ratio increases, mainly due to the increase of the air temperature entering the combustion chamber and the corresponding reduction in fuel consumption. In addition, it can be seen that there is an optimum value for air compressor pressure ratio. The reason is that, at lower pressure ratios, increasing the pressure ratio increases the outlet temperature of the compressor and decreases the fuel mass flow rate injected to the combustion chamber, increasing the efficiency. However, at a certain air compressor pressure ratio increasing R_{AC} increases the compressor work more than it decreases the fuel mass flow rate. This effect leads to a decrease in the output power. Consequently, the net work output first increases and then decreases as compressor pressure ratio increases.

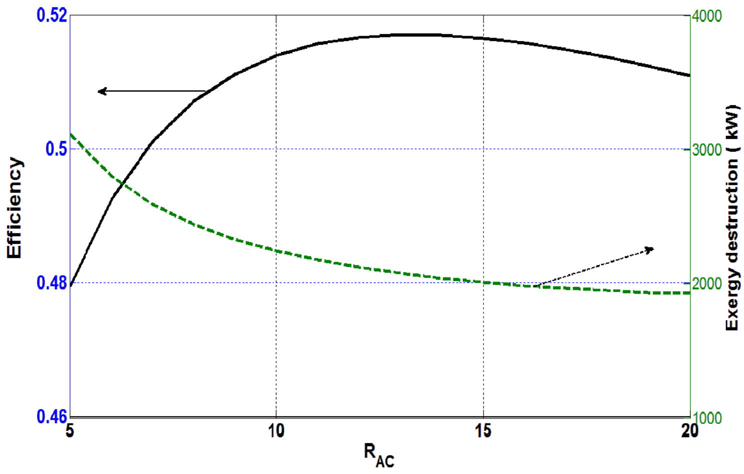

Fig. 3. Variation with compressor pressure ratio of exergy efficiency and exergy destruction rate for the trigeneration system.

To provide environmental insights, the environmental impact of the gas turbine cycle is compared to that of the trigeneration in Fig. 4. It is seen that the trigeneration cycle has less CO_2 emissions than the GT and CHP cycles, providing a significant motivation for the use of trigeneration cycles. It is also observed that trigeneration has a higher exergy efficiency than other cycles.

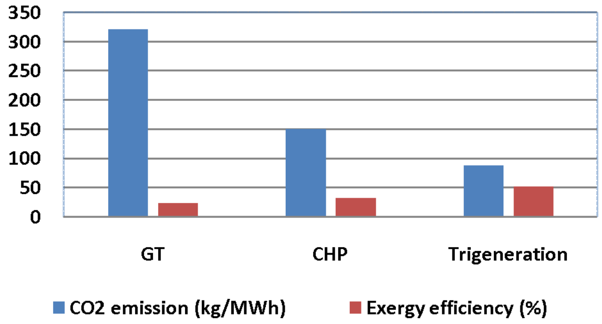

Fig. 4. Comparison of exergy efficiency and environmental impact of different types of plants.

The variation of CO_2 emission and sustainability index with compressor pressure ratio is shown in Fig. 5. Increasing the compressor pressure ratio is seen to decrease CO_2 emissions for the trigeneration cycle, but results in an increase in the sustainability index, due to the reduction of the mass flow rate injected to the combustion chamber. This is a direct result of the increase in air temperature entering the combustion chamber.

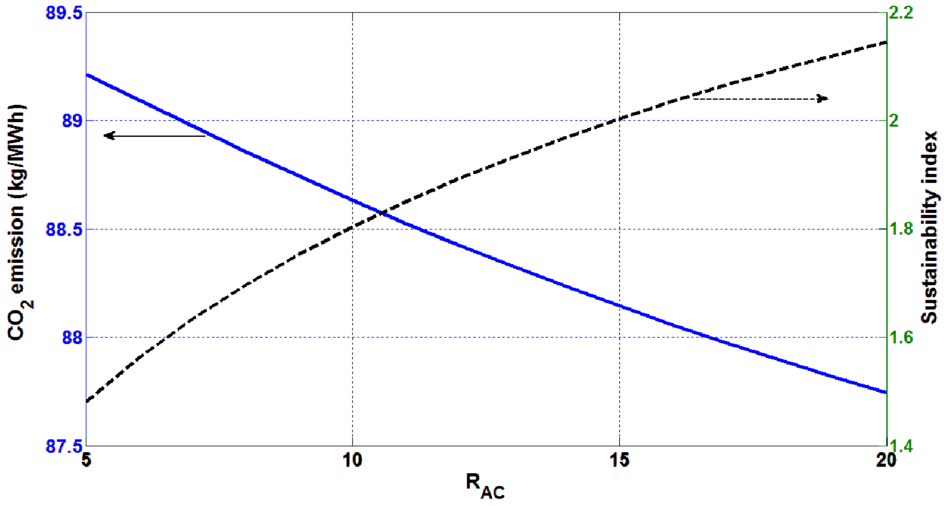

Fig. 5. Variation with compressor pressure ratio of sustainability index and CO_2 emission.

Expanding the results for CO_2 emissions, we investigate the effect of compressor pressure ratio on the cost of environmental impact and sustainability index. Fig. 6 shows that increasing the compressor pressure decreases the cost of environmental impact, due to the reduction of mass flow rate injected into the combustion chamber. Thus, the sustainability index increases.

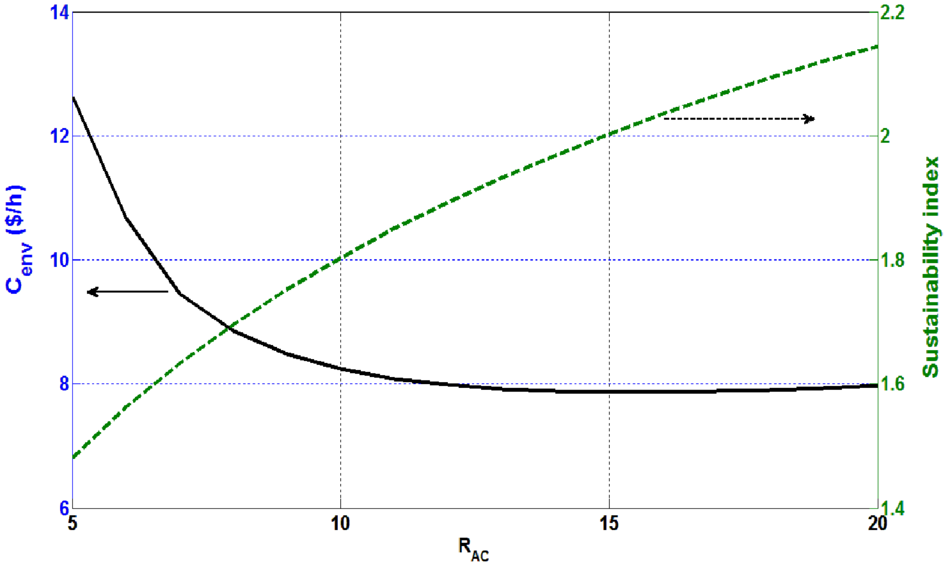

Fig. 6. Variation with compressor pressure ratio of sustainability index and cost rate of environmental impact.

Fig. 7 shows the effect of compressor pressure ratio on total exergy destruction rate of the cycle and sustainability index. It is observed that, the overall exergy destruction of the cycle decreases and the sustainability index increases with increasing compressor pressure ratio. Exergy efficiency, exergy destruction, environmental impact and sustainability are thus observed to be linked in such systems, supporting the utility of exergoenvironmental analyses.

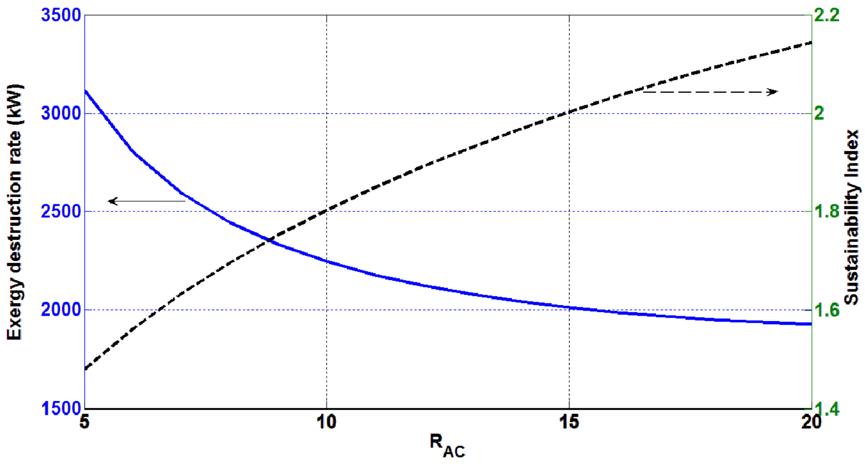

Fig. 7. Variation with compressor pressure ratio of total exergy destruction rate and sustainability index.

The gas turbine inlet temperature (GTIT) is a significant design parameter in a gas turbine cycle. Raising this parameter can increase gas turbine output power. But an energy balance of the combustion chamber indicates that the fuel mass input rate also increases as the GTIT rises. The increased fuel input is also reflective of the increase in turbine exhaust temperature. The exergy efficiency is observed to increase with increasing in turbine inlet temperature, because of the corresponding increase in net work output and relatively smaller increase in heat addition to the cycle. The same trend is observed for the exergy destruction rate which is shown in Fig. 8.

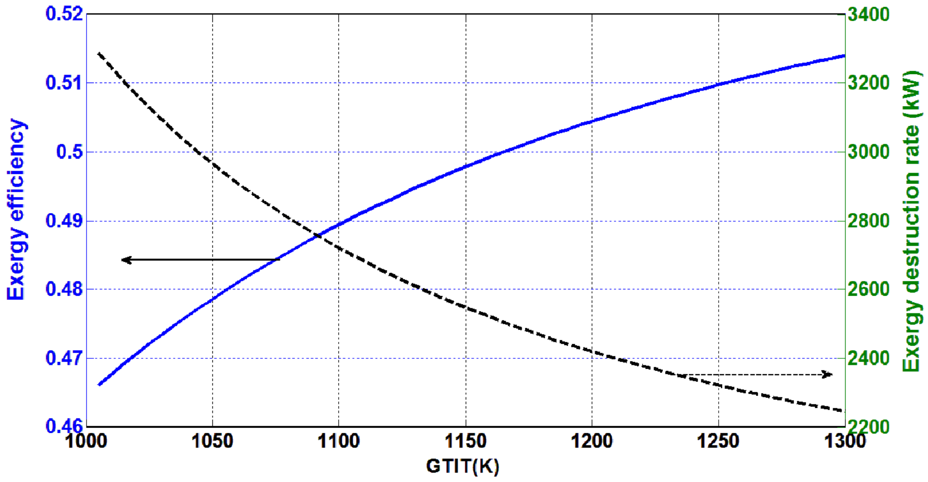

Fig. 8. Variation with gas turbine inlet temperature of total exergy destruction rate and exergy efficiency.

It is shown in Fig. 9 that the exergy efficiency for the GT, CHP and trigeneration cycles increases with turbine inlet temperature.

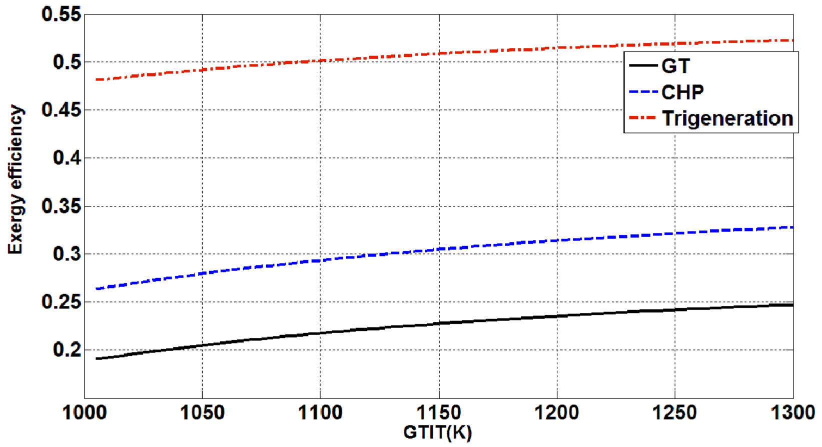

Fig. 9. Variation of gas turbine inlet temperature of exergy efficiency for several cycles.

Fig. 10 shows the effect of varying GTIT on the cycle's total exergy destruction rate and sustainability index. The sustainability index is seen to increase with gas turbine inlet temperature. Since the compressor pressure ratio is constant the exergy flow entering the combustion chamber is fixed. From the exergy balance for the combustion chamber, therefore, it is seen that increasing the GTIT increases the outlet exergy flow, reducing exergy destruction in the CC.

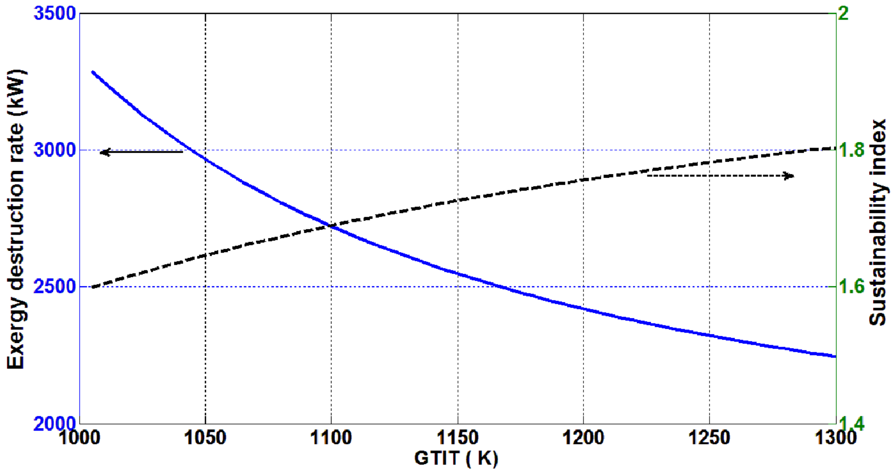

Fig. 10. Variation with GTIT of total exergy destruction rate and sustainability index.

Trigeneration is observed to be an advantageous option from an environmental point of view. The variations with GTIT of both cost of environmental impact and sustainability index are shown in Fig. 11, where the cost of environmental impact is seen to decrease with increasing GTIT.

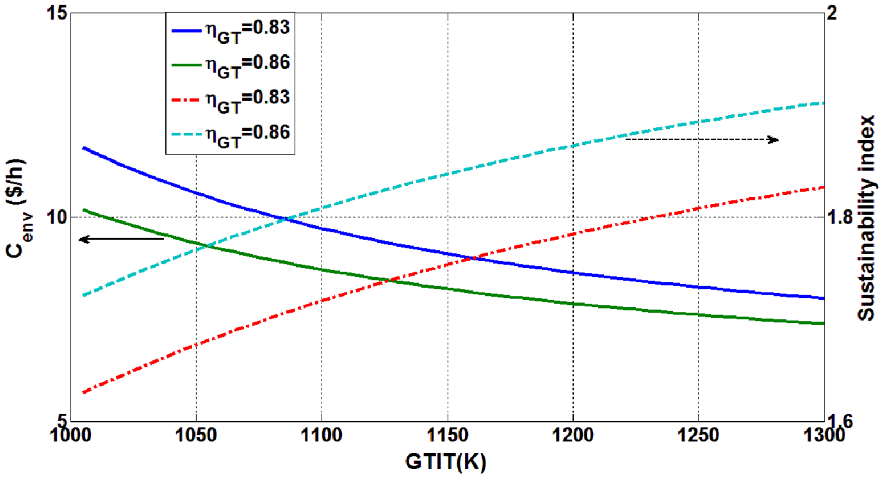

Fig. 11. Variation with GTIT of sustainability index and cost rate of environmental impact.

4 CONCLUSIONS

The comprehensive thermodynamic modeling and exergoenvironmental analysis of a trigeneration system for heating, cooling, electricity generation and hot water has provided useful insights. The exergy results show that combustion chamber and heat exchanger are the two main sources of irreversibility, with the high exergy destruction due to the high temperature difference for heat transfer in both devices and the combustion reaction in the combustion chamber. System performance is notably affected by the compressor pressure ratio, the gas turbine inlet temperature and the gas turbine isentropic efficiency. The exergy efficiency and sustainability index for the system increase with increasing compressor pressure ratio and turbine inlet temperature. In addition, the trigeneration cycle exhibits less CO_2 emissions than micro gas turbine and CHP cycles.

Nomenclature

C_p	Specific heat at constant pressure (kJ/kg K)
ex	Specific exergy flow (kJ/kg)
$\dot{E}x$	Exergy flow rate (kW)
$\dot{E}x_D$	Exergy destruction rate (kW)
h	Specific enthalpy (kJ/kg)
$\dot{m}$	Mass flow rate (kg/s)
P	Pressure (bar)
$\dot{Q}$	Heat rate (kW)
T	Temperature (K)
$\dot{W}$	Work rate (kW)

Greek symbols

η	Energy efficiency
Ψ	Exergy efficiency

Subscripts

AC	Air compressor
CHP	Combined heat and power
Cooling	Cooling load
D	Destruction
D_P	Depletion number
e	Exit condition
f	Fuel
g	Combustion gases
GT	Gas turbine
Heating	Heating load
i	Inlet condition
net	Net output power
SI	Sustainability index
Tri	Trigeneration

Superscript

·	Rate

ACKNOWLEDGMENT

The authors acknowledge the support provided by the Natural Sciences and Engineering Research Council.

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