Chapter 5
Exergetic Optimization of Two Renewable Energy Based Tri-generation Systems Using Genetic Algorithm

M. Malik, M. Al Ali, Ibrahim Dincer and S. Rahnamayan

Abstract In the present study, two renewable energy based tri-generation systems are considered. Optimization has been done using genetic algorithm in order to optimize the objective function, which is the maximization of overall exergy efficiency of system. Biomass and solar are the main sources of energy for both systems, respectively. Energy and exergy efficiencies are defined with or without considering tri-generation and the effect of tri-generation over single generation has been analyzed. The optimum value of objective function, which is the exergy efficiency of the system, is found to be equal to 36.18 % for biomass operated system and 70.68 % for solar operated system. Further, a parametric study has been conducted in order to observe the effect of variation in different parameters on the efficiency of the system.

Keywords Renewable energy · Exergy · Biomass · Solar · Trigeneration · Optimization

5.1 Introduction

Energy is the first and basic need of a developing country. A cursory look at the history of development of human civilization will make it abundantly clear that energy forms the backbone of the world's progress. With the increase of world population

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and the rise in living standards, world energy demands are also increasing steadily at a fast rate. Renewable energy can make a substantial contribution to overcome the energy crisis. It is in this context that the role of renewable energy needs to be seen. Also more attention has been given to improve the design of energy system in order to increase the efficiency of the system. Renewable energy is available in various forms in nature like solar, wind, geothermal, biomass, hydro, ocean current, tides and wave which can be utilized as primary sources of energy input to any system. These all renewable resources are important as they are non-exhaustible source of high quality energy and at the same time it is also important to utilize them with high energy efficiency.

A trigeneration system is a novel approach to increase the efficiency of any system by utilizing the waste energy. A trigeneration system is a thermal system that produces three different commodities from one or more primary energy sources. The products can be electrical power, heating, and cooling. The Organic Rankine Cycle (ORC) is a potential subsystem that can be used in trigeneration systems for electrical power production. ORC is suitable for a low- or medium-temperature energy source [1]. Moreover, when a high-temperature energy source is available a steam Rankine cycle can be integrated more efficiently.

A number of studies have been previously done by various researchers on trigeneration to improve the performance of the systems. Three trigeneration systems were presented by Al-Sulaiman et al. [2] using solar, biomass or SOFC as the primary energy source to produce electricity, heating and cooling. According to a study conducted by Zamfirescu et al. [3] energy efficiency of concentrated solar power (CSP) can be increased from 15–20 to 80 % through cogeneration by recovering the heat which is normally rejected by heat engine. Granovskii et al. [4] studied the exergetic performance of a cogeneration system that integrates a gas turbine with a SOFC and its found that efficiency can be raised up to 66 % by cogeneration. The efficiency of a system is greatly depends on the input and output parameters. In order to enhance the performance of a system, these parameters should be carefully selected to find the optimum value.

Optimization is a reasonable solution, in order to find out the optimum value of parameter for maximizing the system's performance. Many researchers use optimization techniques to enhance the performance of their system. Ahmadi and Dincer [5] have performed an exergoenvironmental analysis and optimization of a cogeneration plant system using Multimodal Genetic Algorithm (MGA) in order to minimize the running cost of a project and found 9.80 % improvement in objective function. While Ahmadi et al. [6] have done a multi-objective optimization of combined cycle power plants using an evolutionary algorithm. In another study, Dincer et al. [7] have conducted performance assessment and optimization of a novel integrated multigeneration system for residential buildings and concluded that there is 60 % increase in system efficiency with optimization and multigeneration. All these studies show that optimization techniques and cogeneration systems are very effective in improving the performance of a complicated system.

In the present paper, two renewable energy based systems are selected for optimization. The primary energy inputs to both these systems are biomass and solar radiations, respectively. The main objective of this study is to optimize the solar and biomass systems exergetically using genetic algorithm and to find the effect

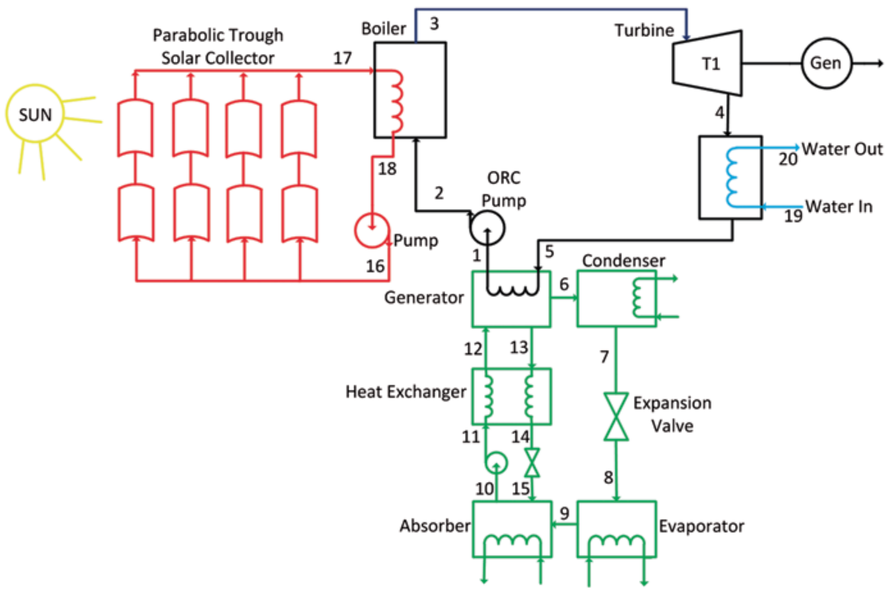

Fig. 5.1 A complete layout of the integrated solar system

of trigeneration and variation in variant parameters over objective function, which results maximization of the overall exergy efficiency.

5.2 Systems Description

In the current study, two trigeneration systems are studied and assessed in terms of energy and exergy efficiencies. Both systems are similar in term of the output but different in terms of energy input (energy source). In one system, the primary energy source is solar energy, where the energy from sun is collected by using concentrated parabolic trough solar collector, whereas in the other system the primary energy source is pine sawdust type biomass having 10 % moisture content. These systems are combined with the ORC and single effect absorption chiller system separately as shown in Figs. 5.1 and 5.2, respectively. Recent research efforts have been made to examine the feasibility of these two renewable energy sources and they are still ongoing. The systems considered consist of an ORC as a prime mover to produce the electrical power, a heat exchanger to supply the heating load, and single effect absorption chiller to supply the cooling load. In both systems, there are two common cycles [2]: ORC and single effect absorption chiller cycle.

In case of solar operated system, a heat transfer fluid (HTF) is pumped to the parabolic trough solar collector at point 16, where it absorbs the concentrated solar energy from solar collector. This high temperature HTF enters to the boiler at point

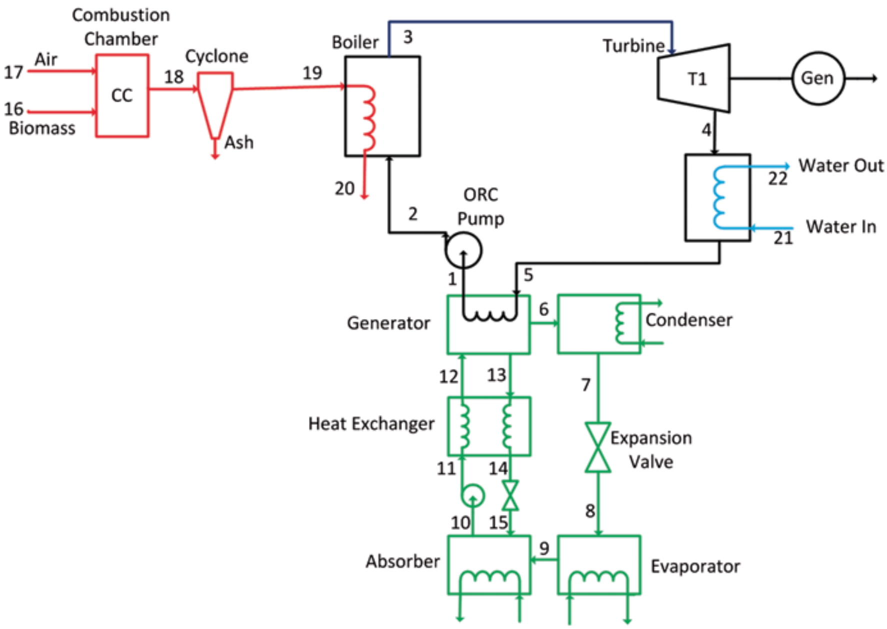

Fig. 5.2 A complete layout of the integrated biomass system

17, where it transfers the heat to the ORC working fluid and exits the boiler at point 18 and again pumps to solar collector.

The ORC working fluid exits the boiler at high temperature and pressure at point 3 and enters to ORC turbine and expands through the turbine to produce the mechanical power. This mechanical power is used to rotate the electrical generator which is connected to the turbine and converted into electrical power. Then, the working fluid exits the turbine at point 4 at low pressure and medium temperature and enters to the heat exchanger, where it supply the heat to the cold water entering to the heat exchanger at point 19 and hot water exit the heat exchanger at point 20. After that, the organic fluid enters the absorption chiller generator at point 5 as saturated vapor and transfers the remaining heat to the mixture of $LiBr-H_2O$ and leaves the absorption chiller generator as liquid at point 1. Then, the working fluid is transfer to the boiler at a high pressure through an ORC pump at point 2 and the cycle remains continuing. This ORC cycle is same for both the systems, there is only a few changes in state point, as in case of biomass operated system, point 19 and 20 are replace with point 21 and 22, and the process remains the same.

The heat rejected at absorption chiller generator from ORC working fluid is the input energy to the single- effect absorption chiller. The flow streams transport among the components of this chiller cycle as either water or a mixture of $LiBr-H_2O$. As a result of the input heat into the absorption chiller generator, water evaporates from the mixture of the $LiBr-H_2O$ and enters the condenser in vapor form at point

6. In the condenser, water vapor rejects the heat to a cooling source and exits the condenser in liquid form at point 7. After that, the water passes through an expansion valve and enters the evaporator at low temperature and pressure at point 8. In evaporator, heat from cooling load is absorbed by cold water and is converted into vapors. These water vapors exits from the evaporator and enters to the absorber at point 9, where it is mixed with strong solution of $LiBr-H_2O$ and is converted into weak solution of $LiBr-H_2O$.

This weak solution of $LiBr-H_2O$ exits the absorber at point 10 and is pumped to the heat exchanger at point 11, where it absorbs heat from strong solution of $LiBr-H_2O$ and enters to the absorption chiller generator at higher temperature. This mixture is heated in the absorption chiller generator and part of the water from the mixture evaporates and exits the absorption chiller generator in vapor form at point 6 leaving behind a strong solution of $LiBr-H_2O$. This strong solution of $LiBr-H_2O$ enters to the heat exchanger at point 13 and transfers the heat to the week solution of $LiBr-H_2O$ and exits the heat exchanger at point 14. Then passes through an expansion valve where its temperature and pressure drop and enters to the absorber at point 15 and is mixed with water vapor and this process remains continuing, which is the same for both systems.

In case of biomass operated system, air and pin saw dust type biomass enter to combustion chamber at point 16 and 17, respectively, as shown in Fig. 5.2. After combustion in combustion chamber (CC) air and biomass leaves the CC in form of high temperature gas at point 18 and enters to cyclone, where ash is removed from high temperature gas. This high temperature gas enters to the boiler at point 19 and transfers the energy to the ORC working fluid (n-octane) and exits to the atmosphere at a low temperature. Rest of the process and system is similar to solar operated system, which is discussed earlier.

5.3 Energy and Exergy Analyses

The thermodynamic modeling of biomass and solar systems were presented in [8, 9], respectively. The thermodynamic modeling applied to the single-effect absorption chiller is similar to the approach used by Refs. [10–12]. To carry out the analysis, some assumptions are made as follows:

- The systems operate at steady state flow process.
- The pressure changes are neglected except in the pumps, blowers, turbine and expansion valves.
- The ambient conditions T_0 and P_0 are assumed to be 298 K and 101.325 kPa, respectively.
- The efficiencies for all pump, compressor and turbine are taken as 85 % [13].
- The changes in kinetic and potential energies are negligible.
- No mass losses take place in the system.
- The incoming solar radiations are taken as constant.

In thermodynamics, it is important to write mass and energy balances under the first law of thermodynamics as follows:

$$\sum_{in} \dot{m} = \sum_{out} \dot{m} \tag{5.1}$$

$$\dot{Q} - \dot{W} = \sum_{out} \dot{m}\left(h + \frac{V^2}{2} + gz\right) - \sum_{in} \dot{m}\left(h + \frac{V^2}{2} + gz\right) \tag{5.2}$$

where, $\dot{m}$, $\dot{Q}$ and $\dot{W}$ are the mass flow rate, heat transfer to the system, and work done by the system, respectively.

Unlike energy, exergy is not conserved. The exergy balance of a control volume system is defined as

$$\sum_{k} \dot{Q}_k \left(1 - \frac{T_0}{T_k}\right) + \sum_{i} \dot{m}_i ex_i + \dot{W} + \sum_{e} \dot{m}_e ex_e + \dot{E}x_{Dest} \tag{5.3}$$

where T, ex and $\dot{E}x_{Dest}$ are temperature, specific exergy and exergy destruction rates, respectively. The subscript k is the property value at state k and the subscript 0 is the value of a property at the reference environment. The physical specific exergy, *ex*, at a given state is defined as:

$$ex = (h - h_0) - T_0(s - s_0) + \frac{V^2 - V_0^2}{2} + g(z - z_0) \tag{5.4}$$

The chemical exergy of ideal gas mixtures is defined as [14]

$$\overline{ex}_{ch} = \sum x_k \overline{ex}_{ch}^{k} + RT_0 \sum x_k ln(x_k) \tag{5.5}$$

where $\overline{ex}_{ch}^{k}$ is the standard chemical exergy for gas k.

For the biomass system, the following composition has been used as fuel at combustion chamber:

$$C_xH_yO_z + \omega H_2O + \lambda(O_2 + 3.76N_2) \rightarrow aCO_2 + bH_2O + cN_2 \tag{5.6}$$

Chemical composition of biomass is calculated from the method specified by Ahmadi et al. [15]. To find out the physical exergy of fuel, lower heating value (LHV) of fuel is needed to be calculated, which is define as:

$$\overline{LHV}_{dry} = \frac{400,000 + 100,600y - \frac{z}{1 + 0.5y}(117,600 + 100,600y)}{12 + y + 16z} \tag{5.7}$$

It is assumed that biomass contain some moisture content which affects the LHV value of the fuel

$$\overline{LHV}_{Mois} = (1 - \mu_m - H_u) \times \overline{LHV}_{dry} - 2500 H_u \tag{5.8}$$

where μ_m and H_u are mineral matter and moisture contents in biomass, respectively. To assist in determining the chemical exergy of fuels, Szargut et al. [16] provided values of the exergy to energy ratio:

$$\phi = \frac{ex_f}{LHV} \tag{5.9}$$

For a chemical Formula $C_\alpha H_\beta N_\gamma O_\delta$ the value of ϕ can be calculated from given below relation [16]:

$$\phi = 1.0401 + 101728 \frac{\beta}{\alpha} + 0.0432 \frac{\delta}{\alpha} + 0.2169 \frac{\gamma}{\alpha}\left(1 - 2.062 \frac{\beta}{\alpha}\right) \tag{5.10}$$

The exergy destruction at combustion chamber can be calculated using the following equation.

$$\dot{m}_{16} ex_{16} + \dot{m}_{17} ex_{17} = \dot{m}_{18} ex_{18} + \dot{Q}_{L17}\left(1 - \frac{T_{s17}}{T_0}\right) + \dot{E}x_{cc}^{Dest} \tag{5.11}$$

The exergy destruction at the boiler:

$$\dot{m}_2 ex_2 + \dot{m}_{19} ex_{19} = \dot{m}_{20} ex_{20} + \dot{m}_3 ex_3 + \dot{Q}_{L20}\left(1 - \frac{T_{s20}}{T_0}\right) + \dot{E}x_{Boiler}^{Dest} \tag{5.12}$$

The exergy destruction at ORC heat exchanger:

$$\dot{m}_4 ex_4 + \dot{m}_{21} ex_{21} = \dot{m}_5 ex_5 + \dot{m}_{22} ex_{22} + \dot{Q}_{L21}\left(1 - \frac{T_{s21}}{T_0}\right) + \dot{E}x_{Boiler}^{HE_{ORC}} \tag{5.13}$$

In the absorption chiller cycle the exergetic COP is calculated as:

$$\dot{E}_{COP_{Chiller}} = \frac{\dot{m}_8 (h_9 - h_8)\left(1 - \frac{T_0}{T_{s_{eva}}}\right)}{\dot{m}_5 (h_5 - h_1)\left(1 - \frac{T_0}{T_{s_{gen}}}\right)} \tag{5.14}$$

The energy efficiency for the biomass operated trigeneration system is defined as

$$\eta = \frac{\dot{W}_{net} + \dot{Q}_{cool} + \dot{Q}_{heat}}{\dot{m}_{bio} \times LHV_{moist} + \dot{m}_{air} h_{air}} \tag{5.15}$$

Whereas the energy efficiency for the solar operated trigeneration system is defined as

$$\eta = \frac{\dot{W}_{net} + \dot{Q}_{cool} + \dot{Q}_{heat}}{\dot{Q}_{in}}, \tag{5.16}$$

where

$$\dot{Q}_{in} = \eta_{solar} \times A_p \times R_a \times Col_r \times Col_c \tag{5.17}$$

Whereas, in case of single generation, energy and exergy efficiency are calculated without considering $\dot{Q}_{cool}$ and $\dot{Q}_{heat}$ for both solar and biomass operated systems.

5.4 Optimization

Optimization is an essential tool for many engineering designs. Using that, one can find an optimum design without the need to examine all possible cases (i.e., exhaustive search). Several optimization methods have been proposed in the literature. Each method has own advantages and limitations. In Engineering Equations Solver (EES), genetic algorithm is one of the optimization methods which can be used. For the trigeneration systems considered in this study, the genetic algorithm is the appropriate one since it provides a good design solution for these complicated systems.

Optimization by Genetic Algorithm In last two decades, optimization algorithms have been improved significantly and have received increasing attention by the research communities as well as the industries. Genetic algorithm (GA) is an optimization technique based on natural genetics. GA was developed by Holland to understand the adaptive processes of natural systems [17]. GA proved to be a robust optimization technique to solve black-box non-convex and nonlinear problems efficiently. The term robust denotes the ability of the GA for finding the global optimum, or a near-optimal solution, for any optimization problem and keeping a good solution even if there is a small change (uncertainty) in the input parameters.

The basic steps for the GA are described as follow. An initial set of candidate solutions are created uniform randomly and each single candidate solution is converted into a string that is coded (chromosome). The size of the population may vary from tens to several hundreds. Increasing the population size does not necessarily result candidate solution improvement, a good number for population size can be determined after several trail runs. Then, each candidate solution is tested and evaluated on the objective function to show how good a solution is (fitness value). After that, the selection criterion is applied to conduct the crossover and mutation operations. Next, when a new population is created after applying the mentioned genetic operations; it replaces the old population. A stopping criterion is utilized for the algorithm to decide whether to continue with another iteration or stop. The number of generations is considered as the stopping criteria, a good number of generation is in

Table 5.1 Input data for solar and biomass operated systems

Input data for biomass	
Biomass type	Pine sawdust
Moisture content in the fuel (% wt)	10 %
Ultimate analysis (% wt dry basis)	
Carbon (C)	50.54 %
Hydrogen (H)	7.08 %
Oxygen(O)	41.11 %
Sulfur	0.57 %
Input data for solar	
Solar collector	Parabolic trough
Intensity of solar radiation (Ra)	800
Number of rows (Col_r)	7
Collector in each row (Col_c)	50
L	12.57 m
w	5.76 m
Overall efficiency of the solar system (η_{solar})	52.5 %

the range of 200–500 [17], depending on the dimension and complexity of problem to be solved. The candidate solutions should be coded when doing the operations, but decoded when evaluating the fitness values.

Objective Function The objective function in the current study is defined as the overall exergy efficiency of the trigeneration system. Trigeneration systems are well-connected systems and by changing one variable, the whole system is affected. Exergy efficiency is defined as the total useful exergy output over the exergy input supplied to the system. In these trigeneration systems, the useful outputs are power, heating and cooling, while the input for the biomass operated system is pine sawdust biomass and solar radiations in case of solar operated system. The generalized objective function (fitness function) for both systems can be defined as follows:

$$\psi = \frac{\dot{W}_{net} + \dot{E}x_c + \dot{E}x_h}{\dot{E}x_{in}} \tag{5.18}$$

where

$$\dot{W}_{net} = \dot{W}_T - \dot{W}_P \tag{5.19}$$

$$\dot{E}x_c = \dot{Q}_c \left(1 - \frac{T_0}{T_c}\right) \tag{5.20}$$

$$\dot{E}x_h = \dot{Q}_h \left(1 - \frac{T_0}{T_h}\right) \tag{5.21}$$

Table 5.2 Box constrains

Variables range
Overall efficiency of solar system ≤ 60 %
$0 < P_3 < 100$ MPa
260 °C < T_{HTF} < 593 °C
$COP_{chiller} \leq 0.9$
−56.77 °C < $T_{n-octane}$ < 477 °C
0.05 < MC < 0.4
Adiabatic flame temperature ≤ 2165 °C
6.02 ≤ Air fuel ratio ≤ 7

where $\dot{W}_{net}$, $\dot{Q}_c$, $\dot{Q}_h$, and $\dot{E}x_{in}$ are the net output power from the system, cooling load, heating load, and exergy input to the system, respectively. The exergy input depends on the energy source of the system, for the biomass trigeneration system, the exergy input is defined as

$$\dot{E}x_{in(bio)} = \dot{E}x_{biofuel} + \dot{E}x_{air} \tag{5.22}$$

where

$$\dot{E}x_{biofuel} = \dot{E}x_{ph} + \dot{E}x_{ch} \tag{5.23}$$

Whereas for the solar system the exergy input is defined as

$$\dot{E}x_{in(solar)} = \dot{Q}_{in}\left(1 - \frac{T_0}{T_{sun}}\right) \tag{5.24}$$

Decision Variables and Constrains There are many parameters which can affect the performance and efficiency of a trigeneration system. These parameters (decision variables) should be chosen carefully to save optimization time and to improve process to find the optimal design. To eliminate any thermodynamic or manufacturing problems, constrains must be specified accordingly. In this study some of the decision variables are selected based on Ref. [14]. The constrains and decision variables with their optimum values are given in Tables 5.2 and 5.3, respectively.

5.5 Results and Discussion

In the present study, two tri-generation systems which are different in terms of primary energy source are considered for optimization. Objective function which represents overall exergy efficiency is defined. Modeling of both systems has been done using engineering equation solver (ESS). The input data for the biomass and solar systems are listed in Table 5.1. Decision variables for each system have been

Table 5.3 Optimum values resulted by GA

Decision variable	Biomass	Solar
$\dot{m}_2$	2.002	5.061
$\dot{m}_{10}$	14.62	15.45
$\dot{m}_{21}$	1.509	–
P_2	2092	1965
P_4	47.02	47.12
T_0	30	27.76
T_3	439.5	453
T_4	152.6	105.8
T_{18}	1883	–
T_{22}	60.06	–
T_{13}	–	83.49
T_{16}	–	279.7
COP	0.7542	0.8848
η_{tri}	57.59 %	77.01 %
Objective unction (ψ_{tri})	36.18 %	70.42 %

carefully selected. Most of the decision variables are same in both systems except two or three, since primary energy source is different in both systems. To find the maximum exergy efficiency some constrains are defined and the range of the constraints are selected properly. Parameter studies are conducted to analyze the effects of the change in ambient temperature, ORC turbine input and output temperatures and mass flow rate, heat transfer fluid (HTP) temperature on energy and exergy efficiencies of the ORC cycle and the whole system. Also, calculations have been performed to find out the exergy destruction at major components. Furthermore,

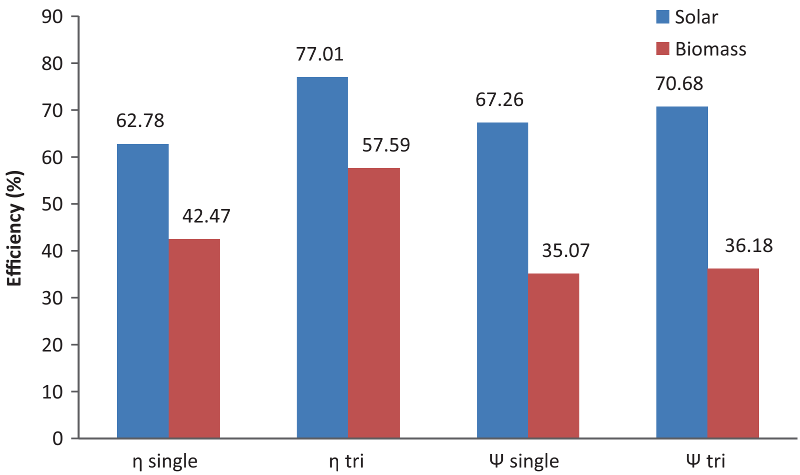

Fig. 5.3 Comparison of the energy and exergy efficiencies of biomass and solar systems

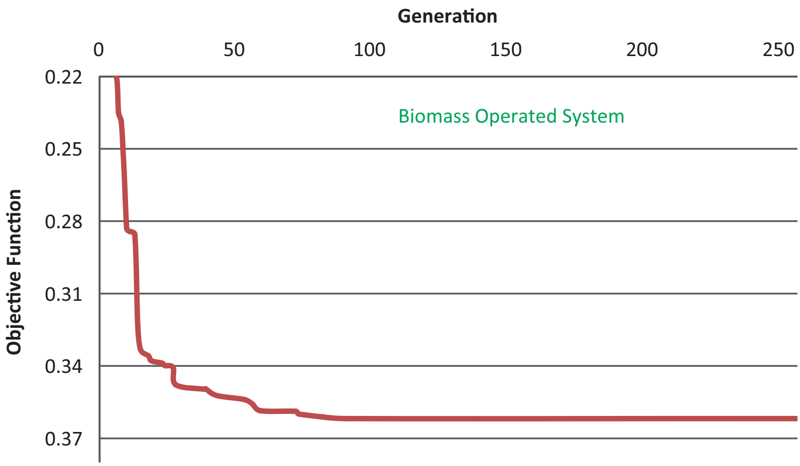

Fig. 5.4 Variation of the objective function with the number of generation for the biomass system

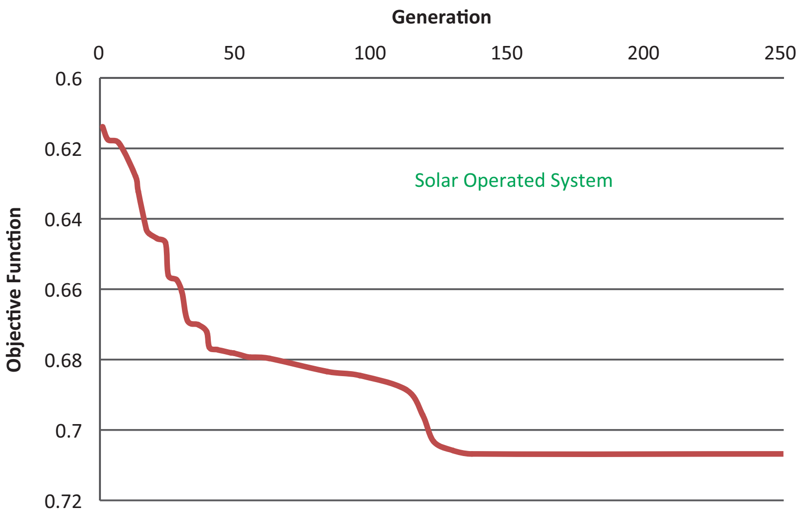

Fig. 5.5 Variation of the objective function with the number of generation for the solar system

the calculations have been done to obtain the properties like temperature, pressure, mass flow rate, enthalpy, entropy and exergy and to observe how the properties are varying at variant points in the system. These properties are given in Tables 5.5 and 5.6 for the biomass and solar system, respectively.

Optimization Results In this section, the optimization results for both systems have been discussed in detail. As it has been already explained, single objective optimization is applied on both systems in order to find out the maximum possible exergy efficiency using genetic algorithm. The objective function, maximization of exergy efficiency of each tri-generation system, has been modeled for the optimization. The optimization process has been done using genetic algorithm in EES software. For both systems, the number of generation has been set to 256 generations for each run and it is found that the optimum value of exergy efficiency for the biomass system is 36.18 % and found after 90 generations as shown in Fig. 5.4. On the other hand, in case of solar, the optimum value of exergy efficiency is 70.68 % and found after 136 generatiosn as shown in Fig. 5.5. The population size has been set to 32 with the maximum mutation rate of 0.0875. These parameters are set the same for both systems. The energy efficiency of tri-generation system in case of biomass is found to be equal to 57.59 %, whereas in case of solar, it is found to equal to 77.01 %. Energetic and exergetic values of COP for the absorption chiller cycle in case of biomass operated system with respect to the optimum value of the objective function is found to be equal to 0.7542 and 0.5097, respectively, whereas in case of solar system, it is found to be equal to 0.8848 and 0.5293, respectively.

The optimum values of the decision variables for both systems are given in Table 5.3. From these results, it is found that the value of the inlet pressure P_2 for both systems and outlet pressure P_3 for both systems at ORC turbine are very close. The inlet pressure P_2 at ORC turbine in the biomass is equal to 2092 kPa, whereas in the solar system it's equal to 1965 kPa. In the same manner, the outlet pressure P_3 is equal to 47.02 kPa and 47.12 kPa in biomass and solar operated system, respectively. The ORC turbines in both systems have different operating condition and input parameter, which lead to different power production. The power output from ORC turbine in the biomass operated system is equal to 2067 kW, whereas in case of solar it is equal to 6680 kW. One point should be accounted and taken care of that the objective of the current study is to optimize/maximize the exergy efficiencies of both systems, not getting the maximum power output from ORC turbine. Also, as the energy input to both ORC turbines are different, so it is worthless to compare their outputs, but the system having higher exergy efficiency is the best one.

Effect of Tri-Generation Over Single Generation By the definition of tri-generation systems, it is clear that in case of tri-generation, the system produces three outputs by using one or more primary energy inputs. The main reason for using a tri-generation system in place of a normal single generation system is to increase the overall efficiency of the given system. However, one point should be considered, converting a simple system into tri-generation is associated with a high initial cost, so before converting a simple system into tri-generation, calculation should be done in order to find out the effects of tri-generation over a simple system in terms of efficiency and initial cost.

In the current study, in order to see the effect of tri-generation over single generation, energy and exergy efficiency are calculated for a single generation system by neglecting the heating and cooling output and considering the same primary energy input for both systems. Results show that energy and exergy efficiencies

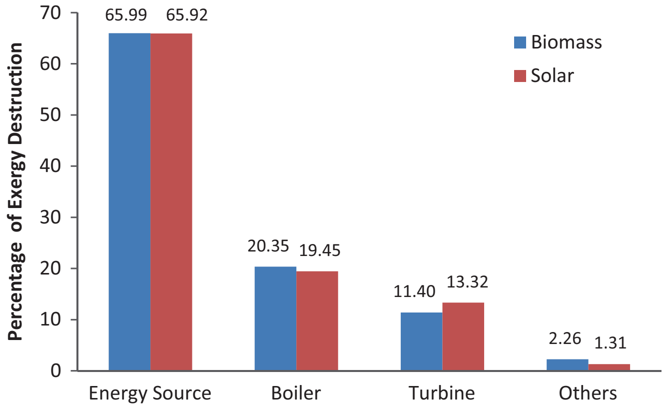

Fig. 5.6 Exergy destruction in major components of the systems

are decreased from 57.59 to 42.47 % and from 36.18 to 35.07 %, respectively, for the biomass system, whereas in the case of solar, energy and exergy efficiencies decrease from 77.01 to 62.78 % and from 70.68 to 67.26 %, respectively, as shown in Fig. 5.3. So, the results show that while using tri-generation system, the effect on energy efficiency is quite significant, while the effect on exergy efficiency is marginally good.

Comparison in Both Systems in Terms of Efficiency and Exergy Destruction The solar and biomass systems are same in terms of the type of outputs, but different in terms of their primary source of energy input. Both systems uses renewable energy sources and produce power output from ORC turbine, hot water from heat exchanger and chilling effect from absorption chiller system. So, it's important to compare the two systems in order to conclude about the more efficient system.

In Term of Efficiency From the results, it is found that, a system that have the solar as its primary energy source is more efficient as compared to a system that have the biomass as the primary energy source, both energetically and exergetically, whether its single generation or tri-generation. The energy and exergy efficiencies of the solar system are greater than biomass system's by 19.42 and 34.5 %, respectively, in case of tri-generation system, whereas in case of single generation system, energy and exergy efficiencies of solar operated system is more by 20.31 and 32.19 % respectively as shown in Fig. 5.3. So, from the results it can be concluded that solar system is more efficient in term of exergy as compared to energy generated by the biomass operated system.

In Term of Exergy Destruction As known, according to the 2nd law of thermodynamics there is no such a system that can convert 100 % of the heat into work; therefore, there are always some losses to the surrounding. In the current study, assumption has been taken that there is no heat loss to the surrounding from ORC turbine and pipes, but still there is exergy destruction at ORC turbine, combustion chamber, boiler, solar system and other parts in both systems. In order to compare

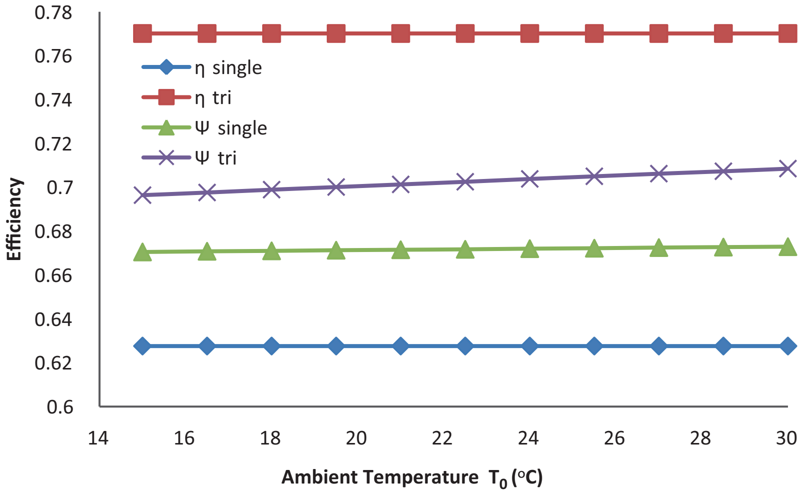

Fig. 5.7 Effect of the reference environment on the energy and exergy efficiencies of the solar system

the exergy losses in both systems, exergy destruction at all major components is calculated and their percentage values are plotted for both systems as shown in Fig. 5.6. From the calculations, it is found that the maximum exergy destruction is found to be at the energy sources, which is combustion chamber (i.e., 65.99 %) in case of biomass system and solar collector part (i.e., 65.92 %) in case solar operated system. After that, the maximum exergy destruction is found to be at the boiler with 20.35 and 19.45 % for the turbine, followed by 11.50 and 13.32 % at ORC turbine for the biomass and solar system, respectively, whereas negligible exergy destruction is found at other component, which is 1.31 and 2.26 % for solar and biomass operated system, respectively. While comparing the exergy destruction between both systems, it can be seen from Fig. 5.6 that percentage of exergy destruction is almost same at each component for both systems. So, both systems are almost the same in term of percentage of exergy destruction.

Parameter Analysis Parameter analysis of a system is very important, as the performance of any system is mainly dependent upon the various parameters. Any variation in a parameter will certainly change the outputs and efficiencies of a system. In the present study, a parameter study has been done for both systems in order to observe the effect of changes in various parameters like ambient temperature, input and output temperature and mass flow rate at ORC turbine, mass flow rate of biomass and air at CC and outlet temperature at CC, solar radiation and overall efficiency of solar system on exergetic and energetic efficiency of the system.

Effect of Ambient Temperature on System Ambient temperature plays an important role in determining the performance of any system. Any variations in the environmental conditions can increase or decrease the performance of a system. In the current study, the optimum value of the ambient temperature is equal to 27.76 °C

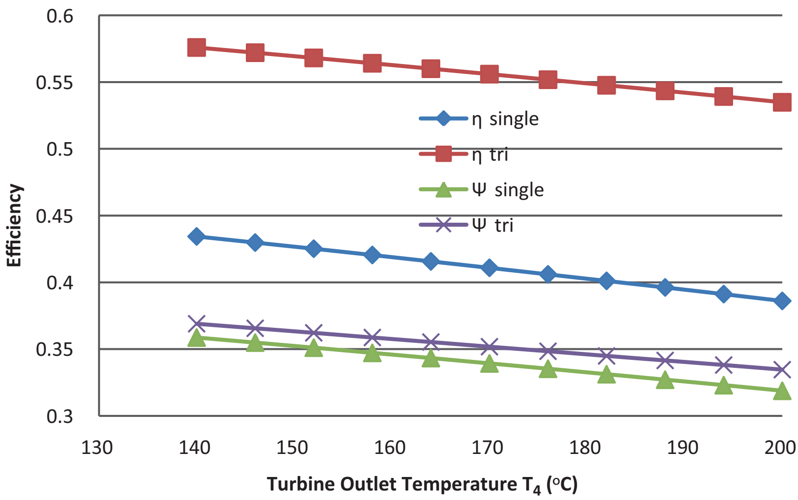

Fig. 5.8 Effect of ORC turbine outlet temperature on the energy and exergy for the biomass system

for the solar system and 30 °C for biomass system, while keeping the constant at 101.325 kpa for both systems. Calculations have been done to observe the effect of the change in ambient temperature on energy and exergy efficiencies of single and tri-generation system by varying ambient temperature from 15 °C to 30 °C. In case of solar operated system, the result shows that exergy efficiency is increasing from 69.64 to 70.85 % in case of tri-generation, whereas increasing from 67.05 to 67.29 % in case of single generation system, when the ambient temperature increase from 15 °C to 30 °C, while negligible effect is found on energy efficiency as shown in Fig. 5.7. The same pattern is found in case of biomass operated system for energy and exergy efficiencies with respect to the ambient temperature.

Effect of ORC Turbine Inlet and Outlet Temperature and Pressures on System Efficiency Output power from any turbine basically depends upon the inlet and outlet temperatures and pressure of turbine. From the calculation it has been observed that both exergy and energy efficiencies of the system increase with increase in inlet temperatures of ORC turbine temperature, while decrease with increase in turbine outlet temperatures. Fig. 5.8 shows that in case of biomass operated system, when turbine outlet temperature (TOT) increases from 140 to 200 °C, the energy efficiency of tri-generation system decreases from 57.59 to 53.48 %, whereas in single generation system it decrease from 43.44 to 38.61 %. Also, the exergy efficiency of tri-generation system decreases from 36.9 to 33.46 %, whereas in single generation system it decreases from 35.87 to 31.88 %. Same pattern is found in case of solar operated system. Furthermore, the calculation has been done by changing the turbine inlet and outlet pressures for both systems and it has been found that there is negligible effect of variation in inlet and outlet pressures on overall energy and exergy efficiency.

Table 5.4 Thermodynamic properties of n-octane

Substance name	n-octane
Mol. formula	C_8H_{18}
Mol. weight	114.231
Freeze point (°C)	−56.77
Boiling point (°C)	125.68
Crit. temp. (°C)	295.68
Crit. pressure (bar)	24.86
Crit. volume(cm^3/mol)	492.1
Crit. density(g/cm^3)	0.2322
Crit. compressibility	0.259
Acentric factor	0.396

Table 5.5 Optimum states for biomass resulted by GA

State No.	Temperature (C^o)	Pressure (kPa)	Mass flow (kg/s)	Enthalpy (kJ/kg.K)	Entropy (kJ/kg.K)	Exergy (kJ/kg)
0	29.8	101.3	–	10.74	0.03579	0
1	85	28.92	2.002	140.5	0.4346	8.992
2	85	1950	2.002	142.1	0.4252	13.42
3	438.5	1950	2.002	1824	2.755	990.1
4	153.9	28.92	2.002	612.2	1.709	94.87
5	85	28.92	2.002	469.2	1.346	61.57
6	78.2	7.424	0.2158	2646	8.471	80.96
7	40.11	7.424	0.2158	168	0.5737	−5.669
8	1.5	0.6812	0.2158	168	0.6116	−17.12
9	1.5	0.6812	0.2158	2503	9.114	−256.5
10	34	0.6812	14.84	90.43	0.1952	81.68
11	34	7.424	14.84	90.43	0.1952	81.68
12	71.64	7.424	14.84	166	0.4249	87.66
13	80	7.424	14.84	185.6	0.4665	94.71
14	41.36	7.424	14.84	109	0.2378	19585
15	36.06	0.6812	14.84	109	0.2048	0
16	29.8	101.3	0.3	–	–	2944
17	29.8	101.3	1.63	303.4	5.7	0
18	1882	101.3	1.93	2447	7.892	2944
19	1882	101.3	1.93	2447	7.892	2944
20	120	101.3	1.93	394.3	5.974	21.97
21	29.8	101.3	1.519	124.9	0.4338	0
22	60.21	101.3	1.519	285.2	0.8337	39.12

Effect of Mass Flow Rate in ORC on Efficiency In both systems, n-octane is used as working fluid in organic Rankine cycle. Properties of n-octane can be found in [18] and given in Table 5.4. The calculation has been done in order to see the effect of mass flow rate of n-octane on overall efficiencies of both systems and results show that overall efficiency of both the system decrease with increase in mass flow rate for same energy input. Fig. 5.10 shows that, in case of biomass operated system, when mass flow rate increases from 0.5 to 3.5 kg/s, the tri-generation energy and exergy efficiencies decrease from 66.29 to 48.91 % and from 46.18

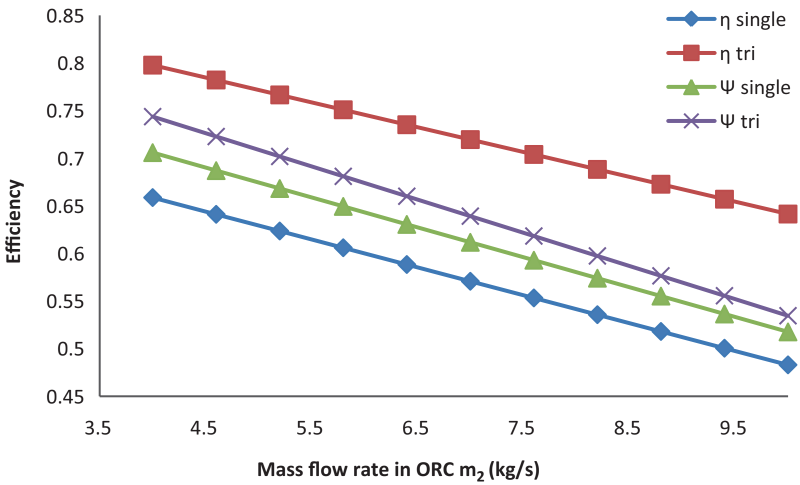

Fig. 5.9 Effect of mass flow rate in ORC on efficiency for solar system

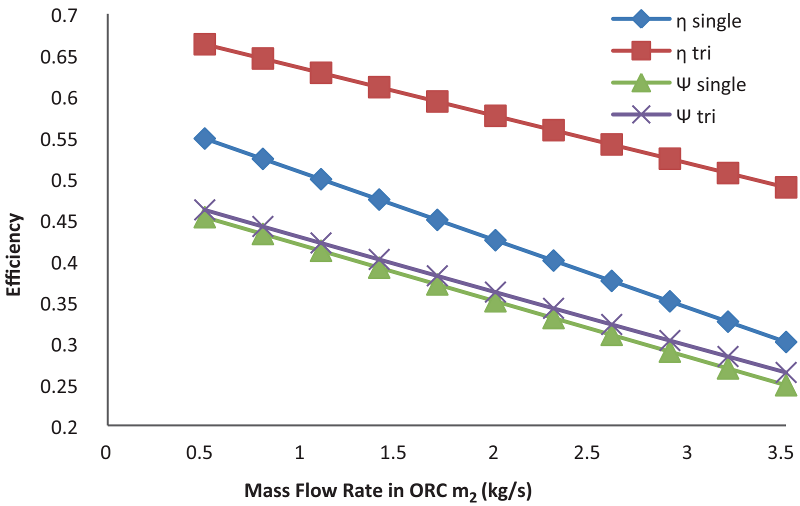

Fig. 5.10 Effect of mass flow rate in ORC on efficiency for biomass system

to 26.43 % respectively, while single generation energy and exergy efficiencies decrease from 54.84 to 30.13 % and from 45.29 to 24.88 % respectively. The reason behind is the same, as the mass flow rate increases, the temperature of working fluid decreases, which further decrease the specific enthalpy and entropy on which energy and exergy values are dependent. But the mass flow at which efficiency is the maximum which can't be used due to temperature limitation of working fluid.

Table 5.6 Optimum states for solar resulted by GA

State No.	Temperature (C^o)	Pressure (kPa)	Mass flow (kg/s)	Enthalpy (kJ/kg.K)	Entropy (kJ/kg.K)	Exergy (kJ/kg)
0	27.76	101.3	–	6.154	0.02062	0
1	80	47.12	5.061	140.5	0.5319	12.03
2	85	1965	5.061	142.1	0.4251	14.25
3	453	1965	5.061	1415	2.821	566.9
4	105.8	47.12	5.061	508.8	1.417	82.57
5	95	47.12	5.061	423.3	1.198	63.09
6	78.2	7.424	0.6303	2646	8.471	98.23
7	40.11	7.424	0.6303	168	0.5737	4.551
8	1.5	0.6812	0.6303	168	0.6116	-15.93
9	1.5	0.6812	0.6303	2503	9.114	-237.9
10	34	0.6812	15.45	90.43	0.1952	77.1
11	34.19	7.424	15.45	90.8	0.1964	77.12
12	72.55	7.424	15.45	167.8	0.4302	83.78
13	83	7.424	14.82	196.6	0.4729	99.88
14	42.08	7.424	14.82	118.2	0.2359	92.63
15	38.98	0.6812	14.82	118.2	0.2172	98.26
16	279.7	101.3	35	29.5	0.05385	45.7
17	483	101.3	35	337.1	0.5279	495.9
18	279.7	101.3	35	29.5	0.05385	45.7
19	27.7	101.3	3	116.1	0.4046	0
20	60	101.3	3	174.1	0.8311	70.32

On the same pattern, Fig. 5.9 shows that, in case of solar operated system, when mass flow rate increase from 4 to 10 kg/s, the tri-generation energy and exergy efficiency decrease from 79.78 to 64.14 % and from 74.37 to 53.46 % respectively and in the same pattern for single generation. The reason behind this is same as in case of biomass operated system. The optimum value of mass flow rate with respect to optimum value of objective function is found to be equal to 2.002 and 5.061 kg/s for biomass and solar operated system, respectively.

Effect of CC Outlet Temperature and Mass Flow Rate of Biomass on Efficiencies In case of biomass operated system, the outlet temperature of air at CC depends on the adiabatic flame temperature of the biomass, which is further dependent on the percentages of carbon, hydrogen and other molecules present in the biomass. In the present study, the adiabatic flame temperature is found to be equal to 2165 °C. For the current study the value of air and biomass ratio (air-fuel) is taken as 6.33. Figure 5.12 shows that the tri-generation energy and exergy efficiency are increase from 40.39 to 57.55 % and from 21.98 to 36.15 %, with increase in air temperature at outlet of CC from 1400 to 1880 °C while the single generation energy and exergy efficiencies are increased from 25.27 to 42.43 % and from 20.86 to 35.04 %. The optimum value of air temperature at outlet of CC is found 1881 °C. Figure 5.11 shows the effect of the mass flow rate of biomass over the energy and exergy efficiencies and results are very interesting. From results, it is found that energy and exergy efficiency are increasing drastically with the increase of mass flow rate

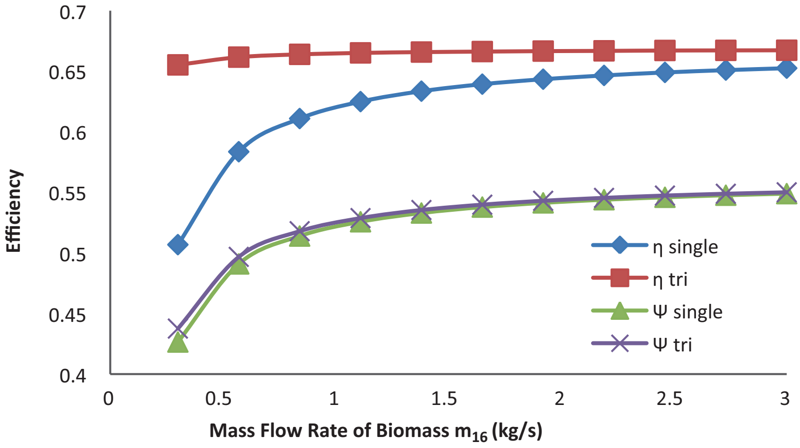

Fig. 5.11 Effect of mass flow rate of biomass on efficiencies

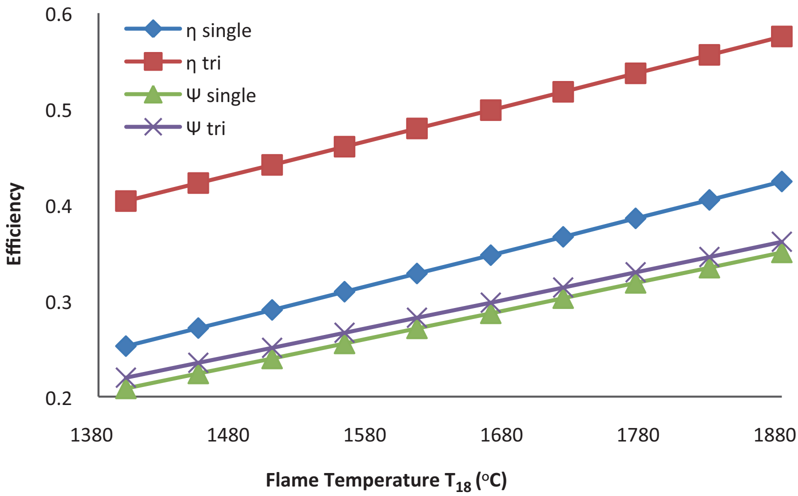

Fig. 5.12 Effect of CC outlet temperature on efficiencies

of the biomass up to a certain limit and then after that it is almost constant with increase in mass flow rate of biomass. Tri-generation energy and exergy efficiency are increasing from 74.49 to 78.25 % and from 51.29 to 64.69 % respectively; and the same pattern is found for single generation energy and exergy efficiencies.

Effect of Change in Solar Radiation and Solar System Efficiency in Solar Operated System During the day time, the intensity of solar radiation constantly varies, depending on the weather conditions. So, in order to calculate the effect of the

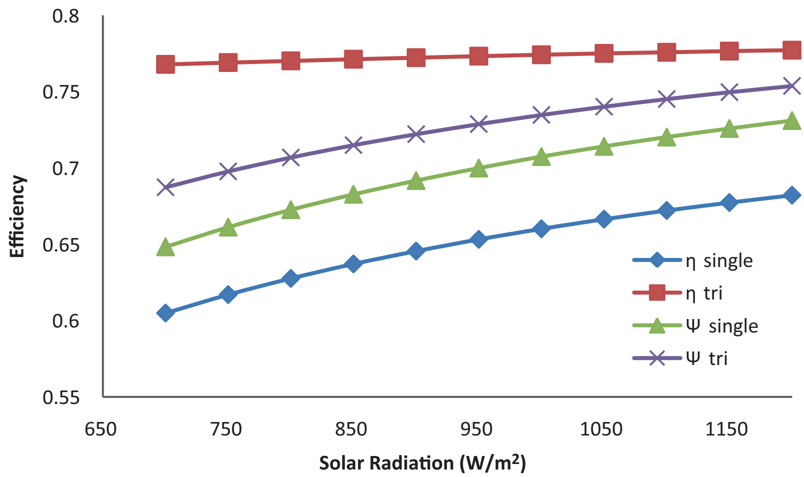

Fig. 5.13 Effect of change in solar radiation on energy and exergy efficiency in solar operated system

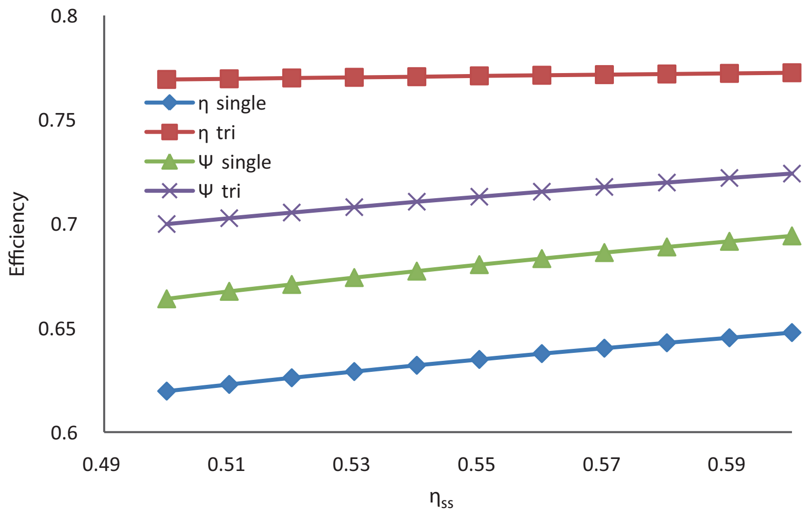

Fig. 5.14 Variation in energy and exergy efficiencies with respect to change in solar system efficiency

change in solar radiation on the efficiency of the system, calculation has been conducted by varying the intensity of the solar radiation from 700 to 1220 W/m^2. Figure 5.13 presents that tri-generation energy and exergy efficiency increase from 76.78 to 77.71 % and from 68.73 to 75.37 % respectively, with increase in intensity of solar radiation and the same pattern is found in case of single generation. For the simplicity, the overall efficiency of whole solar system has been selected (52.2 %)

and in order to see the effect of it on the overall energy and exergy efficiency, calculation has been done by varying the efficiency of solar system from 50 to 60 %. Fig. 5.14 shows that the tri-generation energy and exergy efficiencies increasing almost linearly from 76.93 to 77.25 % and from 69.99 to 72.41 % respectively with increasing in the efficiency of the solar system. Similarly, the single generation energy and exergy efficiencies increase from 76.73 to 77.25 % and from 66.4 to 69.42 %, respectively.

Conclusions

In the present study two tri-generation systems are considered for optimization and objective function which is the overall exergy efficiency is optimized using genetic algorithm. The optimum value of exergy efficiency in biomass operated system in found to be 36.18 %, while it is higher in solar operated system and equal to 70.68 %. By comparing single and tri-generation system, it is found that the exergy efficiency in biomass operated system is increased by 1.11 % and by 3.42 % in the solar operated system in tri-generation over single generation. From this study it has been observed that any change in the parameters can significantly affect the energy and exergy efficiencies of the system and also tri-generation and optimization approaches are novel way to enhance the efficiency of a system.

Nomenclature

A_p	aperture area of collector, m^2
Col_c	collector in each row
Col_r	number of rows
CoP	coefficient of performance
en	specific energy, kJ/kg
ex	specific exergy, kJ/kg
$\dot{Ex}$	exergy rate, kW
g	gravity of acceleration, m/s^2
h	specific enthalpy, kJ/kg
H_u	moisture content in biomass
L	length of collector, m
LHV	lower Heating value of fuel, kW
$\dot{m}$	mass flow rate, kg/s
P	pressure, kPa
$\dot{Q}$	heat transfer rate, kW
R_a	intensity of solar radiation, W/m^2
s	specific entropy, kJ/kg K.
T	temperature, K
ν	specific volume, m^3/kg
V	velocity, m/s
w	width of collector, m

w,a,b,c stoichiometric constant in biomass combustion reaction in Eq. (5.6) (moles)
$\dot{W}_P$ pump work Input, kW
$\dot{W}_T$ turbine work output, kW
x_k number of molecules of gas k (molecules)
y,z constant in Eq. (5.7) related to number of atoms of hydrogen and oxygen in biomass
z elevation difference, m

Greek Letters

α number of atoms of carbon,
β hydrogen,
δ nitrogen and
γ oxygen in biomass (atoms/mole)
η energy efficiency
Ψ exergy efficiency
μ_m mineral matter content in biomass
ϕ exergy to energy ration of fuel

Subscripts

bio biomass

Cc combustion
ch chemical
cool cooling
Dest destruction
e exit
eva evaporator
gen generator
heat heating
HE heat exchanger
HTF heat transfer fluid
i inlet
L loss
mois moisture
ORC organic Rankine cycle
ph physical
s source
ss solar system
single single generation
tri tri-generation
x,y,z number of atoms of carbon, hydrogen and oxygen in biomass(atoms/molecule)
1…22 state numbers
0 ambient or reference condition

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