Chapter 3

Thermodynamics Assessment of the Multi-Generation Energy Production Systems

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/51522

1. Introduction

The efficiency of the solar multi-generation energy production system has great significance due to the limited supply of available energy from solar radiation as well as impact on system production performance, operation cost and environmental concerns. Thus, a good understanding of the efficiency of the whole system and its components is necessary for the multi-functional system installation. In this regard, the First Law of Thermodynamics based efficiency also known as energy efficiency may lead to inadequate and also misleading consequences, since all energy transfers are taken to be equal and the ambient temperature is not taken into consideration. The Second Law of Thermodynamics defines the energy conversation limits of this available energy based on irregularities between different forms of energies. The quality of the available energy is highly connected with the reference environment, which is often modeled as the ambient environment, as well as the success level of this conversion capacity; and needs to be considered to prevent any incomplete and/or incorrect energy conversation results. Quality of the energy should be given as an examining the work potentials of the initial and final stages of an investigated system. Such analysis is called as exergy analysis, which gives the amount of an energy that may be totally converted into useful work. Exergy (also called as an available energy or availability) of an investigated system is defined using the thermodynamics principles as the maximum amount of work which can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment [1-3]. It is well known that one of the important uses of the exergy analysis in engineering processes is to determine the best theoretical performance of the system.

The useful work potential of the system is reduced by the irreversibilities and the corresponding amount of energy becomes unusable [4]. The entropy generation give the effects of these irreversibilties in the investigation system during a process and helps compare the each component in the system based on how much they contribute to the operation inefficiencies of the whole system. Thus, entropy generations of the system components needs to be evaluated to determine the whole system efficiency. Even though energy analysis of the system is the most commonly used method for examining energy conversation systems, its only concerned with the conservation of energy, which neither takes the corresponding environmental conditions into account, nor provides how, where and why the system performance degrades for the operated system. Also, the energy analysis of the system only measures the quantity of energy and does not reveal the full efficiencies of the process [5]. Thus, in this scientific study, the multi-generation system is examined with exergy analysis in order to give the true efficiency of the whole system and its components by determining the irreversibilities in the each process, and how nearly the respective performance approach ideal conditions. By using the energy and exergy analysis, magnitude of the losses, and their causes and locations are identified by investigating the sites of exergy destruction in order to make improvements to the whole system and its components [6].

2. System Description

The whole system and its components are given for the solar multi-generation energy production system. This system can be divided into four subsystems; i-) parabolic trough collector, ii-) organic Rankine cycle (ORC), iii-) electrolyzer and iv-) absorption cooling and heating. The schematic diagram of the multi-generation system is given in the Figure 1. The main outputs of the given system are electricity, hydrogen, oxygen, heating, cooling and hot water. Thermal energy of the solar radiation is collected and concentrated using a parabolic trough collector in order to produce electricity, heating-cooling and hot water from ORC, absorption system and hot water collection tank, respectively. Another important purpose of this solar multi-generation system is producing of hydrogen. Stored hydrogen can be used in a PEM fuel cell to produce power in the night time. Thus, electricity can be produced continuously for 24 hours. A part of produced electricity from the organic Rankine cycle is used to run the PEM (proton exchange membrane) electrolysis system, which requires heat at nearly 80 °C and electricity as an input. The thermal energy is used in the PEM electrolysis to decrease the electricity demand of the electrolysis system. Heat requirements of the PEM electrolyzer system are supplied from generator waste heat. The hydrogen separator separates hydrogen from the steam by using hydrogen separation membrane. The produced hydrogen stream is then cooled to 40°C with the help of the cooling water. The produced hydrogen is compressed in a four-stage compressor, through intercooling to 40°C. The product gases (which is 99.9 wt% H_2) exit from the store tank at 506.5 kPa and 85°C. When the weather conditions are not favorable or additional power is needed, the stored hydrogen can be used in order to generate power. In addition, the outputted oxygen from the high temperature electrolysis is stored in a separate storage tank. The produced oxygen from the high temperature electrolysis system is cooled to 45°C via the cooling water. Similarly, the cooling water used in the oxygen cooler has an exit temperature of 80°C,

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The by-product oxygen has relatively negligible energy and exergy content, and can be used for the other purposes or can be sold.

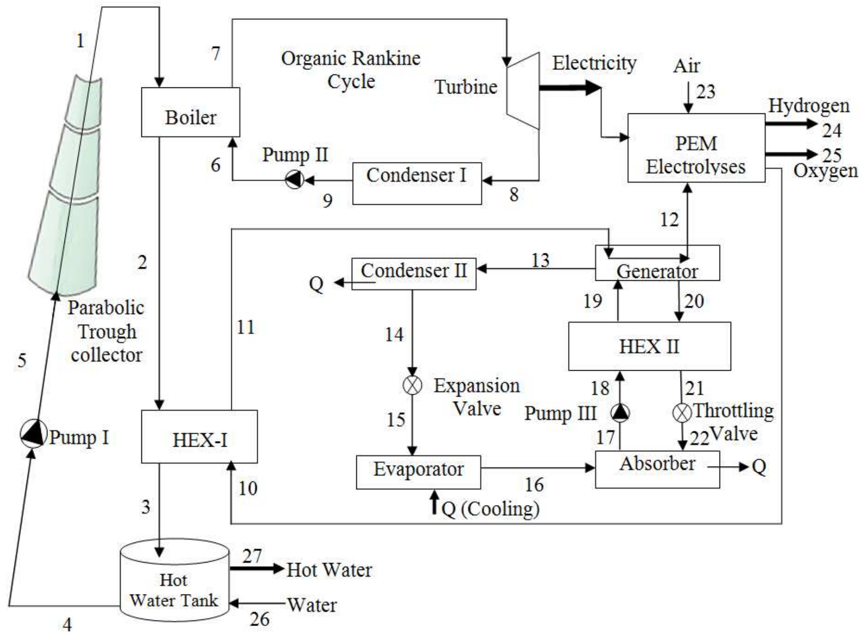

Figure 1. The Solar multi-generation energy production system

3. Thermodynamic Analysis

In this research, the general mass, energy and exergy balance equations to find the energy and exergy inputs and outputs, the rate of exergy decrease, the rate of irreversibility and the energy and exergy efficiencies for the solar multi-generation energy production system are given. In general, thermodynamic balance equation for a quantity in a process can be given as

$$Input + Generation - Output - Consumption = Accumulation \tag{1}$$

where input and output gives to quantities entering and exiting through the system boundary, respectively, generation and consumption gives to quantities produced or consumed within the system, respectively and accumulation gives to potential build-up of the quantity within the system [7]. The general mass balance equation can be given in the rate form.

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{2}$$

where $\dot{m}$ is the mass flow rate, and the subscripts in and out shows inlet and outlet flows, respectively. Assuming the absence kinetic, potential and chemical exergy terms, the general energy balance for the multi-generation system is formulated as follows;

$$\dot{Q} + \sum_i \dot{m}_{in,i}\left(h_i + \frac{V_i^2}{2} + gz_i\right) = \sum_e \dot{m}_{out,e}\left(h_e + \frac{V_e^2}{2} + gz_e\right) + \dot{W} \tag{3}$$

where $\dot{Q}$ and $\dot{W}$ represents the heat and work rates, respectively, and h is the specific enthalpy at the chosen state. Considering a system at rest relative to the environment, kinetic and potential terms can be ignored,

$$\dot{Q} + \sum_i \dot{m}_{in,i} h_i = \sum_e \dot{m}_{out,e} h_e + \dot{W} \tag{4}$$

The entropy balance can also be expressed on a time rate basis as

$$\dot{S}_{in} + \dot{S}_{gen} = \dot{S}_{out} \tag{5}$$

$$\dot{S}_{gen} = \dot{m}\Delta S \tag{6}$$

where $\dot{S}$ is the entropy flow or generation rate. The amount transferred out of the boundary must exceed the rate in which entropy enters, the difference being the rate of entropy generation within the boundary due to associated irreversibilities.

The system components irreversibility and also recommended ways to improve the efficiencies of them can be evaluated by using exergy analysis. The exergy balance of the multi-generation system components is given as follows;

$$\sum \dot{E}x_{in} = \sum \dot{E}x_{out} + \dot{E}x_D \tag{7}$$

$$\sum_i \dot{m}_i ex_i + \dot{E}x_Q = \sum_e \dot{m}_e ex_e + \dot{E}x_W + \dot{E}x_D \tag{8}$$

where subscripts i and e are the specific exergy of the control volume inlet and outlet flow, $\dot{E}x$ is the exergy rate, $\dot{E}x_Q$and $\dot{E}x_W$ are the exergy flow rate associated with heat transfer and work, $ex$is the specific flow exergy of the process and $\dot{E}x_D$ is the exergy destruction rate.

$$\dot{E}x_Q = \left(1 - \frac{T_o}{T_i}\right)\dot{Q}_i \tag{9}$$

$$\dot{E}x_W = \dot{W} \tag{10}$$

$$ex = ex_{ke} + ex_{pe} + ex_{ph} + ex_{ch} \tag{11}$$

where ex_{ke} is the kinetic exergy, $ex_{pe}$is the potential exergy, ex_{ph} is the physical exergy and ex_{ch} is the chemical exergy. Since the variation of the kinetic, potential and chemical exergy is considered negligible in this study. The physical exergy

$$ex_{ph,i} = (h_i - h_o) - T_o(s_i - s_o) \tag{12}$$

The exergy rate of a material flow is given as follows.

$$\dot{E}x_i = \dot{m}ex_i \tag{13}$$

The difference being the rate of exergy destruction (or lost work) within the boundary due to associated irreverisibilities which can be calculated based on Gouy-Stodola theorem. The exergy destruction in the component i should be given as follows;

$$\dot{E}x_{D,i} = T_o \Delta S_{i,net} \tag{14}$$

where $\Delta S_{i,net}$ is the specific entropy change for the process. The exergy loss ratio of the system components is given as follows to compare of these components by using exergy analysis view point.

$$\dot{E}x_{LR} = \frac{\dot{E}x_{D,com}}{\dot{E}x_{D,sys}} \tag{15}$$

where $\dot{E}x_{D,com}$ is exergy destruction of the system components and $\dot{E}x_{D,sys}$ is the exergy destruction of the overall system. The exergy destruction rate for the each component and overall of the multi-generation system is given in the Table 1 according to given above procedure.

Components of the system	**Expression of exergy destruction rate**
Parabolic trough collector	$\dot{E}x_{D,PTC-I} = \dot{E}x_5 - \dot{E}x_1 + \dot{E}x^{Q}_{Solar}$
Boiler	$\dot{E}x_{D,Boil-I} = \dot{E}x_1 + \dot{E}x_6 - \dot{E}x_2 - \dot{E}x_7$
HEX I	$\dot{E}x_{D,HEX-I} = \dot{E}x_2 + \dot{E}x_{10} - \dot{E}x_3 - \dot{E}x_{11}$
Hot Water Tank	$\dot{E}x_{D,HWT} = \dot{E}x_3 + \dot{E}x_{26} - \dot{E}x_4 - \dot{E}x_{27}$
Pump I	$\dot{E}x_{D,P-I} = \dot{E}x_4 - \dot{E}x_5 + \dot{W}_{P-I}$
Turbine	$\dot{E}x_{D,HPT} = \dot{E}x_7 - \dot{E}x_8 - \dot{W}_{HPT}$
Condenser I	$\dot{E}x_{D,Con-I} = \dot{E}x_8 - \dot{E}x_9 - \dot{E}x^{Q}_{Con-I}$
Pump II	$\dot{E}x_{D,P-I} = \dot{E}x_9 - \dot{E}x_6 + \dot{W}_{P-II}$
PEM Electrolyses system	$\dot{E}x_{D,PEM} = \dot{E}x_{12} + \dot{E}x_{23} - \dot{E}x^{Q}_{PEM} + \dot{W}_{PEM} - \dot{E}x_{24,H_2} - \dot{E}x_{25,O_2}$
Generator	$\dot{E}x_{D,Gen} = \dot{E}x_{11} + \dot{E}x_{19} - \dot{E}x_{13} - \dot{E}x_{12} - \dot{E}x_{20}$
Condenser II	$\dot{E}x_{D,Con-II} = \dot{E}x_{13} - \dot{E}x_{14} - \dot{E}x^{Q}_{Con-II}$
Expansion valve	$\dot{E}x_{D,ExV} = \dot{E}x_{14} - \dot{E}x_{15}$
Evaporator	$\dot{E}x_{D,Ev} = \dot{E}x_{15} - \dot{E}x_{16} + \dot{E}x^{Q}_{Ev}$
Absorber	$\dot{E}x_{D,Ab} = \dot{E}x_{16} + \dot{E}x_{22} - \dot{E}x_{17} - \dot{E}x^{Q}_{Ab}$
Pump III	$\dot{E}x_{D,P-III} = \dot{E}x_{17} - \dot{E}x_{18} + \dot{W}_{P-III}$
Throttling valve	$\dot{E}x_{D,ThV} = \dot{E}x_{21} - \dot{E}x_{22}$
HEX II	$\dot{E}x_{D,HEX-II} = \dot{E}x_{18} + \dot{E}x_{20} - \dot{E}x_{19} - \dot{E}x_{21}$

Table 1. Exergy destruction rates for the multi-generation energy production system

3.1. Energy efficiency

The energy efficiency of the process is defined as the ratio of useful energy produced by the process to the total energy input. In this paper, energy efficiencies for five different systems are considered: parabolic trough collector, organic Rankine cycle, hydrogen production, absorption cooling and heating sub-system, overall multi-generation system as shown below

$$\eta_{PTC} = \frac{\dot{Q}_1 + \dot{Q}_5}{\dot{Q}_{solar}} \tag{16}$$

$$\eta_{org\text{-}Rankine} = \frac{\dot{W}_{net,org\text{-}Rankine}}{\dot{Q}_{boiler}} \tag{17}$$

$$\eta_{hydrogen} = \frac{\dot{m}_{H2} LHV\, H_2}{\dot{Q}_{Gen} + \dot{W}_{Turbine}} \tag{18}$$

$$\eta_{absorption} = \frac{\dot{Q}_{cooling} + \dot{Q}_{heating}}{\dot{Q}_{HEX\text{-}I} + \dot{W}_{P\text{-}III}} \tag{19}$$

$$\eta_{system} = \frac{\dot{W}_{org\text{-}Rankine} + \dot{m}_{H2} LHV\, H_2 + \dot{Q}_{cooling} + \dot{Q}_{heating} + \dot{Q}_{hotwater}}{\dot{Q}_{PTC}} \tag{20}$$

A coefficient of performance (COP) term can be used to expressing of the energetic performance of the absorption sub-system.

$$COP = \frac{\dot{Q}_{cooling}}{\dot{W}_{pump\text{-}III} + \dot{Q}_{gen}} \tag{21}$$

where $\dot{W}_p$ is the pumping power requirement, and it is usually neglected in the COP calculations and $\dot{Q}_{gen}$ is the rate of heat inputted to the generator.

3.2. Exergy Efficiency

The exergy efficiency of the process is the produced exergy from the system output that is divided by the exergy system input and it can also be expressed by the aforementioned subsystems as follows;

$$\psi_{PTC} = \frac{\dot{E}x_1^Q + \dot{E}x_2^Q}{\dot{E}x_{solar}^Q} \tag{22}$$

$$\psi_{org\text{-}Rankine} = \frac{\dot{W}_{org\text{-}Rankine}}{\dot{E}x_{boiler}^Q} \tag{23}$$

$$\psi_{hydrogen} = \frac{\dot{E}x_{H2}}{\dot{E}x_{Gen}^Q + \dot{W}_{Turbine}} \tag{24}$$

$$\psi_{absorption} = \frac{\dot{E}x^{Q}_{cooling} + \dot{E}x^{Q}_{heating}}{\dot{E}x^{Q}_{HEX\text{-}I} + \dot{W}_{P\text{-}III}} \tag{25}$$

$$\psi_{system} = \frac{\dot{W}_{org,Rankine} + \dot{E}x_{H2} + \dot{E}x^{Q}_{cooling} + \dot{E}x^{Q}_{heating} + \dot{E}x^{Q}_{hotwater}}{\dot{E}x^{Q}_{PTC}} \tag{26}$$

The exergy efficiency equations for the solar-based multi-generation energy production system components are given in the Table 2. The exergetic performance of the absorption subsystem should be formulated in forms of the exergetic COP.

$$COP_{ex} = \frac{\dot{E}x^{Q}_{cooling}}{\dot{W}_{pump\text{-}III} + \dot{E}x^{Q}_{gen}} \tag{27}$$

Components of the system	Exergy efficiency
Parabolic trough collector	$\psi_{PDC-I} = \frac{\dot{E}x_1 - \dot{E}x_5}{\dot{E}x^{Q}_{solar}}$
Boiler	$\psi_{HEX-I} = \frac{\dot{E}x_7 - \dot{E}x_6}{\dot{E}x_1 - \dot{E}x_2}$
HEX I	$\psi_{HEX-III} = \frac{\dot{E}x_{11} - \dot{E}x_{10}}{\dot{E}x_2 - \dot{E}x_3}$
Hot Water Tank	$\psi_{HWT} = \frac{\dot{E}x_{27} - \dot{E}x_{26}}{\dot{E}x_3 - \dot{E}x_4}$
Pump I	$\psi_{Pump-I} = \frac{\dot{E}x_5 - \dot{E}x_4}{\dot{W}_{Pump-I}}$
Turbine	$\psi_{HPT} = \frac{\dot{W}_{HPT}}{\dot{E}x_7 - \dot{E}x_8}$
Condenser I	$\psi_{Con-I} = \frac{\dot{E}x^{Q}_{Con-I}}{\dot{E}x_8 - \dot{E}x_9}$
Pump II	$\psi_{Pump-I} = \frac{\dot{E}x_6 - \dot{E}x_9}{\dot{W}_{Pump-II}}$
PEM Electrolyses system	$\psi_{HTSE} = \frac{\dot{m}_{H_2} LHV_{H_2}}{\dot{E}x_{12} + \dot{W}_{Electricity}}$
Generator	$\psi_{Gen} = \frac{\dot{E}x_{13} + \dot{E}x_{20} - \dot{E}x_{19}}{\dot{E}x_{11} - \dot{E}x_{12}}$
Condenser II	$\psi_{Con-II} = \frac{\dot{E}x^{Q}_{Con-III}}{\dot{E}x_{13} - \dot{E}x_{14}}$
Expansion valve	$\psi_{ExV} = \frac{\dot{E}x_{13}}{\dot{E}x_{12}}$
Evaporator	$\psi_{Eva} = \frac{\dot{E}x^{Q}_{col}}{\dot{E}x_{16} - \dot{E}x_{15}}$
Absorber	$\psi_{Ab} = \frac{\dot{E}x^{Q}_{Ab}}{\dot{E}x_{16} + \dot{E}x_{22} - \dot{E}x_{17}}$
Pump III	$\psi_{Pump-III} = \frac{\dot{E}x_{18} - \dot{E}x_{17}}{\dot{W}_{Pump-III}}$
Throttling valve	$\psi_{ThV} = \frac{\dot{E}x_{22}}{\dot{E}x_{21}}$
HEX II	$\psi_{HEX-II} = \frac{\dot{E}x_{19} - \dot{E}x_{18}}{\dot{E}x_{20} - \dot{E}x_{21}}$

Table 2. Exergy efficiency equations for the system components

4. Result and Discussion

A software code in EES (Engineering Equation Solver) [8] is created to analyze a baseline model with respect to the balance equations given in Table 2. The ambient conditions are assumed to be 25 °C and 100 kPa for the analysis. A widely used refrigerant R134a is used in the absorption cooling system and water in the other sub-systems. The assumptions for the analysis are given as follow.

- Steady-state conditions with no chemical or nuclear reactions are assumed for all components in the cycle.
- Heat loss and pump work as well as kinetic and potential energies are considered negligible.
- Expansion valve and throttling valve are assumed to be isenthalpic and the heat transfer and pressure drops in the tubes connecting the components are neglected since there are short.

The values for the exergy destruction rates (kW), exergy destruction ratio (%), exergy efficiency (%) and the power or heat transfer rate of the solar multi-generation energy production system are given in the Table 3. Exergy destruction rate indicates the reduction in energy availability; however, it cannot be used to investigate the energy and exergy utilization performance of the system processes. The exergy efficiencies of the system components are more useful for determining exergy losses.

	Exergy destruction rate (kW)	Exergy destruction ratio (%)	Exergy efficiency (%)	Power or heat transfer rate (kW)
Parabolic trough collector	1892	46.89	34.21	18798
Boiler	564.1	13.98	90.92	18798
HEX-I	337.6	8.37	82.89	3351
Hot water tank	310.2	7.69	28.19	2593
Pump-I	45.11	1.12	56.03	74.37
Turbine	259.3	6.43	93.6	3792
Condenser-I	81.67	2.02	25.71	12734
Pump-II	114.7	2.84	58.77	175.5
PEM electrolysis system	202.4	5.02	37.03	781.5
Generator	37.03	0.92	75.42	750
Condenser-II	19.91	0.49	21.94	604.87
Expansion valve	0.15	0.00	97.36	1.69

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	Exergy destruction rate (kW)	Exergy destruction ratio (%)	Exergy efficiency (%)	Power or heat transfer rate (kW)
Evaporator	56.31	1.40	40.84	571.1
Absorber	98.25	2.43	21.42	696.2
Pump-III	8.24	0.20	34.41	12.92
Throttling valve	1.16	0.03	96.58	17.34
HEX-II	6.72	0.17	56.53	109.1

Table 3. Thermodynamic analysis data of the multi-generation energy production system devices

Based on the baseline analysis, the exergy efficiencies associated with the system and whole system are given in the Fig. 2. As seen in the Fig. 2, the solar parabolic trough collector and condenser are calculated to have the lowest exergy efficiency as 17 and 22%, respectively. This is associated with concentrating losses, high temperature differences and phase chance which results in more entropy generation between the inlet and outlet streams.

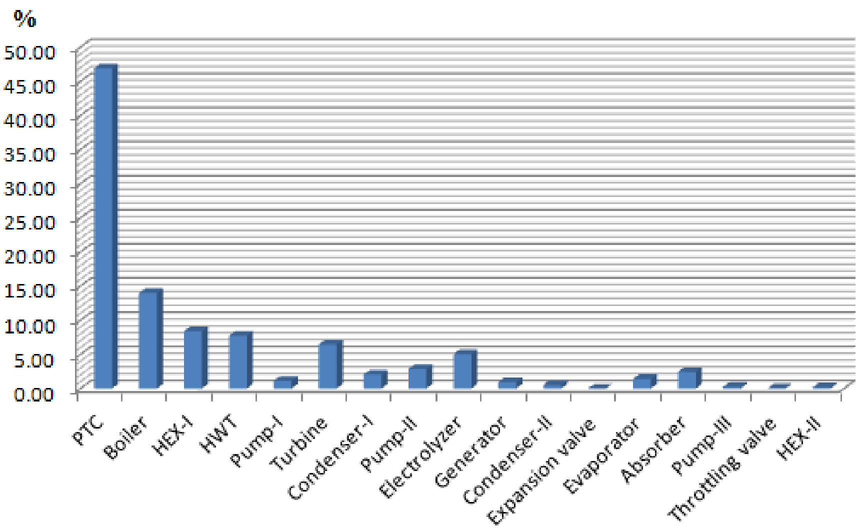

Figure 2. Exergy efficiencies of the multi-generation energy production system components

The COP and COPex of the single effect absorption refrigeration system are calculated as 0.7586 and 0.3321, respectively. The COPex is lower than COP, due to the considerable irreversibilities occurring in the absorption cycle. Energy and exergy efficiency results for the absorption system components are compared to the experimental studies [9-11] and a reasonably good agreement are found.

Parametric studies have also been conducted, by analyzing the changes in exergy efficiencies of the system components with respect to changes in the ambient temperature. The exergy efficiencies for the ambient temperature ranges of 10 °C to 30 °C can be seen in the Fig. 3 to 5 for the parabolic trough collector, organic Rankine cycle and absorption cooling-heating cycle, respectively.

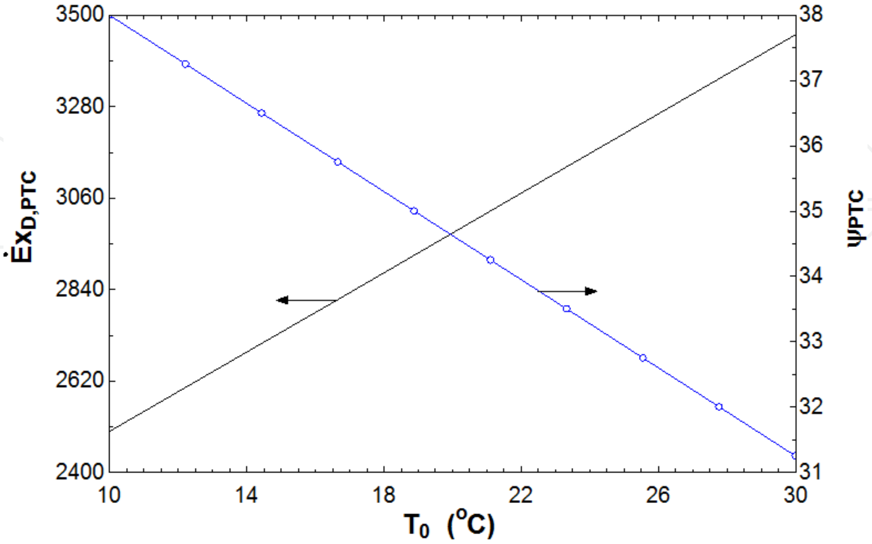

Figure 3. Exergy destruction rate and exergy efficiency of the parabolic trough collector (PTC) depending on ambient temperature changes

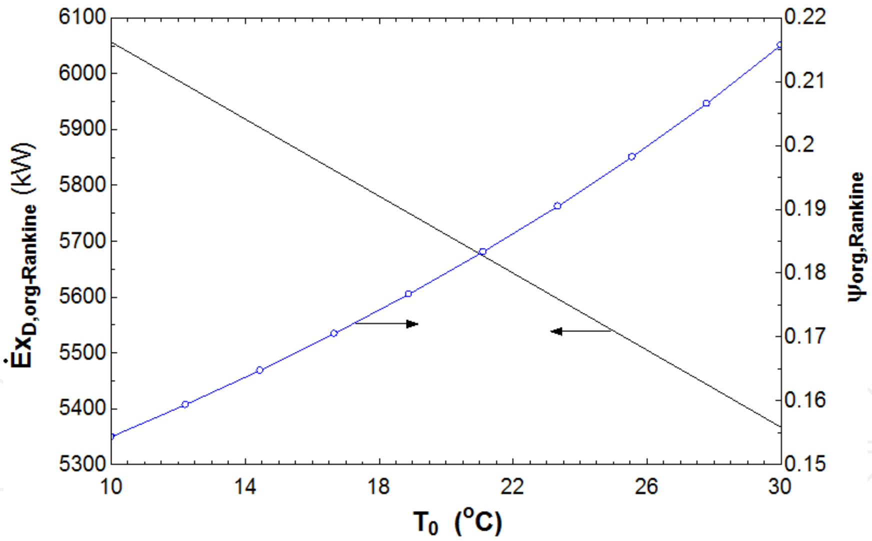

Figure 4. Exergy destruction rate and exergy efficiency of the organic Rankine cycle (ORC) depending on ambient temperature changes

Although ambient temperature increases, exergy destruction of the parabolic trough collector and absorption system are increases and exergy efficiencies of these components decreases. The variations of exergy destruction rate and exergy efficiency of these components according to the ambient temperature remain almost linear. These results are expected since the exergy destruction rate and exergy efficiency of the process are

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generally inversely proportional properties. The variations of the exergy destruction rate and also exergy efficiency in concern with the ambient temperature for the organic Rankine cycle are given in the Fig. 4.

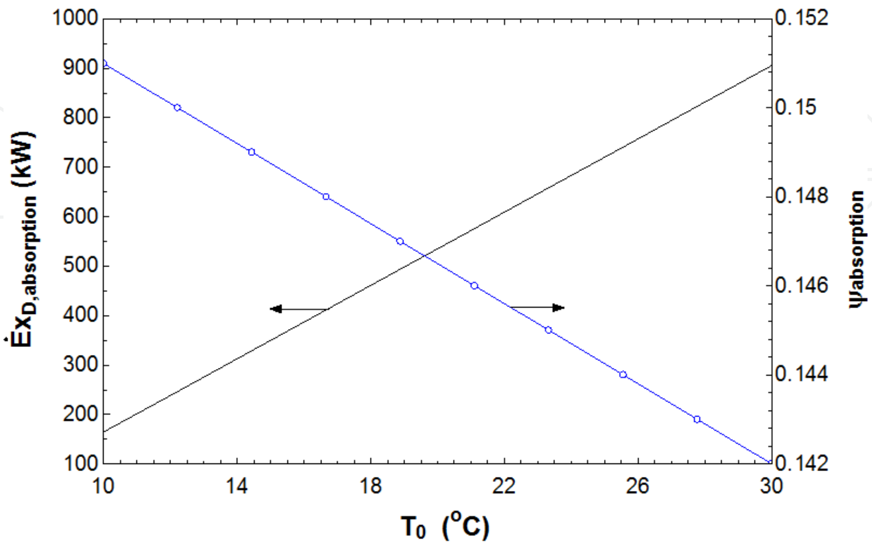

Figure 5. Exergy destruction rate and exergy efficiency of the absorption cooling and heating system depending on ambient temperature changes

5. Conclusions

In the present study, a solar multi-generation system for electricity, hydrogen, oxygen, heat water production and space heating and cooling is proposed and examined with respect to exergy analysis in order to determine the magnitude of losses, and their causes and locations by determining the irreversibility in each cycle and the whole system. In addition to that, exergy efficiency of the system components is evaluated to show how the system reaches a real operating condition. Some parametric studies are given in order to investigate the effects of varying operating conditions such as ambient temperature.

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