



Exergoeconomic and exergoenvironmental analyses of an integrated solar combined cycle system



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ABSTRACT

The exergoeconomic and exergoenvironmental analysis of cogenerative system that combine a gas/steam turbine system and a solar field have been performed. The model is developed in order to produce around 400 MW of electrical power to investigate the effect of solar collector field in performance of each component. In addition, the exergy destruction, exergetic efficiency, cost rate and environmental impact per exergy unit, cost rate and environmental impact per exergy unit of product and fuel, cost rate and environmental impact rate associated with the exergy destruction, exergoeconomic and exergoenvironmental factor for each component are evaluated. The results reveal that the condenser needs to increase investment costs to increase the total thermodynamic efficiency and it needs to increase its exergetic efficiency to reduce the total environmental impact from an exergoeconomic and exergoenvironmental point of view. The exergoeconomic and exergoenvironmental analysis show that the effects of solar field leads to 4.2% increasing in the net produced electricity; 2.6% increasing in the average cost rate per exergy unit of electricity and –3.8% decreasing average environmental impact per exergy unit of electricity.

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1. Introduction

Electricity is one of the most important goods to ensure the country development. Several techniques try to improve his

efficiency with low cost. The cost analysis can be evaluated by Exergoeconomy which combines exergy and engineering economics principles. Researches of exergoeconomic analysis of power system for evaluate the cost rate per exergy unit have been carried out. Some values of electricity cost at simple, combined and trigeneration systems were summarized [1]. The electrical power of cost rate per exergy unit at combined system of gas turbine and steam turbine were accounted to be 13.96 \$/GJ and 37.69 \$/GJ respectively and its average cost rate was 18.89 \$/GJ, by Ref. [2]. In country with high solar irradiation, the solar collector is

Abbreviations: CEP, Condensate extraction pump; H/A, Hierarchist and average perspective according Eco-indicator 99 methodology; HRSG, Heat recovery steam generator; ISCCS, Integrated solar combined cycle system; LCA, Life Cycle Assessment; LHV, Lower heat value; NGCC, Natural gas combined cycle

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Nomenclature

A	area (m ²)
AC	air compressor
BFP	boiler feed Pump
\dot{B}	environmental impact rate (mPts/s)
b	environmental impact per exergy unit (mPts/GJ)
CC	combustor chamber
CCPP	Combined cycle power plant
CEP	Condensate extraction Pump
COLL	Collector
COND	condenser
D	diameter (m)
DEA	deaerator
\dot{E}	exergy (kW)
EI	environmental impact
EVA	evaporator
ECO	economizer
f	exergoeconomic factor
f_b	exergoenvironmental factor
FS	safety factor
HP	high pressure
GT	Gas turbine
LP	low pressure
\dot{m}	mass flow rate (kg/s)
OILP	oil Pump
p	pressure MPa
r_k	relative cost difference (%)

SH	super heater
SHE	solar Heat Exchanger
ST	steam Turbine
t	thickness (m)
vel	velocity (m/s)
\dot{Y}	component-related environmental impact (mPts/h)
Z_T	total cost rate of component (\$/h)

Greek letters

ε	exergetic efficiency %
ρ	specific mass kg/m ³
σ	rupturing stress MPa

Subscript

D	destruction
F	fuel
P	product

Superscript

CI	capital investment
CO	construction, including manufacturing, transport and installation
DI	disposal
OM	operation and maintenance

combined with turbine cycle to produce electricity. The parabolic trough solar is utilized at configuration called to integrated solar combined cycle system (ISCCS). An exergoeconomic analysis of ISCCS located in Yazd, Iran was performed [3]. The power plant contained two gas turbines, a steam turbine and solar field. The authors developed a multi-objective optimization in this system. The exergetic efficiency has increased in 3.2% and the product cost rate has decreased in 3.82%.

However, the electrical power should be produced with low cost and low environmental impact. The environmental aspect has started attracting attention due to problems as such as Global warming potential (GWP), ozone depletion potential (ODP) and environmental acidity. The combination of environmental assessment with exergy analysis has been first discussed in the late years 19 [4,5]. The components life cycle has been allocated in the environmental assessment [6,7]. The authors developed the exergoenvironmental analysis considering the materials used for manufacturing the components in LCA. In general, The Life Cycle Assessment (LCA) includes cradle to grave assessment of any process or product. The LCA of components should include the five phases [8]: materials, production processes, transport processes, energy generation processes and disposal scenarios. The exergoeconomics analysis may suggest modifications in the components design as such as to increase the heat exchanger area to increase the heat transfer or to use novel materials for allow higher temperature operation. However, the materials and energy needed for manufacturing a component consume natural resources. In addition, a component may consume energy and other resources and may generate additional pollutants during its operation. Furthermore, after the end of its life a component has to be disposed of, which may again require energy and emit part of its materials into the environment. These life-cycle-related effects of components and the resulting impact on the environment should be taken into account in the system analysis [6]. The authors developed of exergoenvironmental analysis and was conducted a

case study of energy conversion system, a high-temperature solid oxide fuel cell integrated with biomass gasification process [6]. This approach was investigated at combined power plant [7]. The environmental impact was splitted into avoidable and unavoidable parts, called advanced analysis. The combustion chamber caused the most of environmental impact within the plant. The environmental impact of plant is mainly influenced by the environmental impact of fuel. An exergoeconomic and exergoenvironmental evaluation of power plants were evaluated [9]. The oxy-fuel plants, a plant with chemical looping combustion (CLC) with near 100% CO₂ capture and two advanced zero emission plants (AZEPs) with 100% and 85% CO₂ capture were compared to a similarly structured reference plant without CO₂ capture. They concluded that the three oxy-fuel plants are significantly more expensive, when compared to the reference plant without CO₂ capture, resulting in almost double the investment cost. Moreover, they result in an increase in the cost of electricity by a minimum of 23%. However, the overall environmental impact of the oxy-fuel plants is lower by 19–27%. The choice of the best option depends on the results of both the exergoeconomic and the exergoenvironmental analyses. If the environmental impact or monetary cost is of greater importance for the decision-maker, then the evaluation result is different. There is other paper with application of fuel cell, as [10] which considering the stage of material extraction, manufacturing, use, and disposal/recycling at a SOFC (solid-oxide fuel-cell) to generate electricity. The energy mix of a country influences in the environmental impact associated with electricity generation and it varies in time. The energy mix is composed by coal, oil, natural gas, nuclear, hydro-power, wind energy, import and others. The results demonstrated that the more coal is used in a country, the greater the environmental impact for this country. Furthermore, the manufacturing stage and the disposal stage have relatively small contributions to the total environmental impact.

The exergoenvironmental analysis is recent, it useful to take decision in project at environmental point of view. The potential

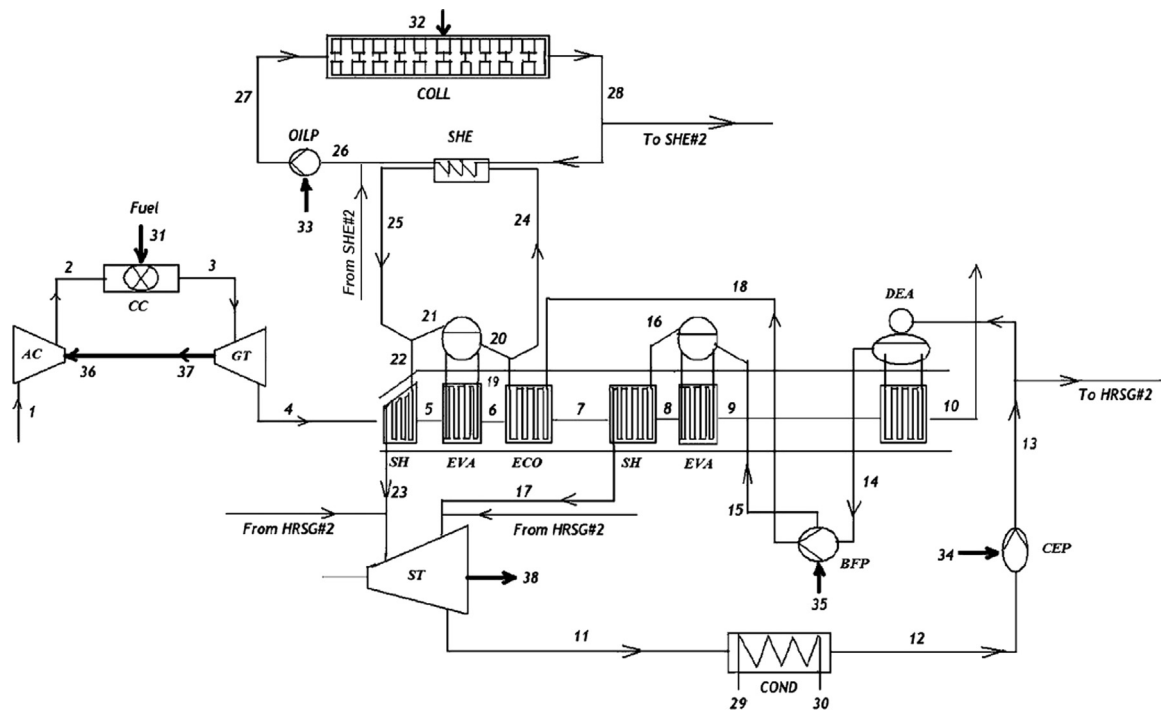


Fig. 1. Schematic diagram of the ISCCS. source [3].

issue is to choose the best decision at economic or environmental aspects. The reduction of electricity environmental impact would imply in increase of electricity monetary cost. These both approaches are useful for the decision-maker. However, there are not enough publications for power cycle and there is a lack of research about ISCCS to produce electricity. This study is unique for this application.

Therefore, the purpose of this study is an application of exergoeconomic and exergoenvironmental analysis to an integrated solar combined cycle system. This research focused more on the effect of solar field in combined system and calculate the electrical power cost per unit of exergy, the electrical power environmental impact per unit of exergy.

2. Methodology

Fig. 1 shows a schematic diagram of the system assisted with solar field. This power plant has been studied according exergoeconomic point of view.

It contains two installed 125 MW model V94.2 gas turbine units with natural gas fuel, an installed 150-MW steam turbine, a 17-MW solar plant, which is not yet constructed and two HRSG with two pressure lines (84.8 bar, 506 °C and 9.1 bar, 231.6 °C). The exhaust gases temperature leaves at 113 °C to recover as much energy as possible. In this study, numerical results are based on site design condition with ambient temperature of 19 °C on 21 June in Yazd, IRAN at 12:00 noon. At this hour, solar radiation intensity is about 800 W/m² with annual thermal efficiency of 53%. The solar field is composed by aperture area per solar collector assembly of 545 m² with 224 mirror segments. The solar collector assembly has 99 m of length. The parabolic-trough technology utilized was described by the U.S. Department of Energy's Office of Power Technologies Concentrating Solar Power Program [11]. The heat transfer fluid used in the solar field is Therminol VP-1 [12]. The fluid propriety is available [13]. Table 1 shows the natural gas composition.

The Exergoenvironmental analysis is composed by environmental impact balance at all input streams to the overall system and each system component. Furthermore, the environmental impact obtained from the LCA of components is assigned to component balance. The exergoenvironmental variables are calculated.

The auxiliary equations at cost balance are assumed according to [14]. The principle is according to their approach, fuels and products. The costs are defined by systematically registering exergy and cost additions to and removals from each material and energy stream.

2.1. Input streams to the system

A quantitative environmental impact assessment is performed using an indicator. Here the Eco-indicator 99 life cycle impact assessment method is used as an example. It is especially developed as impact assessment method to support decision-making in a design for the environment.

An environmental impact rate B and an environmental impact per exergy unit b are defined as follows:

$$\dot{B} = b \cdot \dot{E} \quad (1)$$

The environmental impact rate B is the environmental impact expressed in Eco-indicator points per time unit (Pts/s or mPts/s). The environmental impact per exergy unit b is the average environmental impact associated with the production of the stream per exergy unit of the same stream [Pts/GJ or mPts/GJ].

The unit of environmental indicator 99 is called Eco-indicator point (Pt) or milli-point (mPts). The absolute value of the points is not very relevant as the main purpose is to compare relative differences between products or components. The scale is chosen in such a way that the value of 1 Pt is representative for one thousandth of the yearly environmental load of one average European inhabitant.

An inventory of fuels, life cycle and emissions (CO₂) was made. The CO₂ is a greenhouse gases and its effect is climate change. The

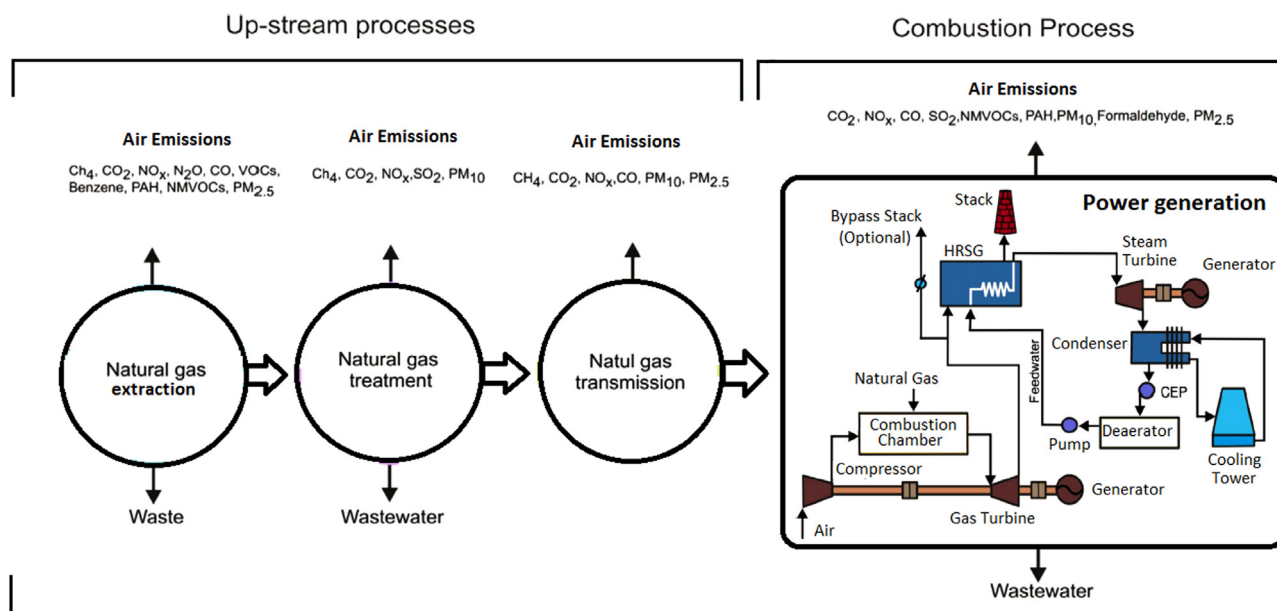


Fig. 2. Boundary condition used during electricity generation from NGCC, Adapted [15].

effect and damage can be at level local, land and global. The damages are distributed in three damage categories: Human health, Ecosystem quality and Resources. After the classification for each types of three damage categories, the damages are normalized, weighted and the result is expressed as Eco-indicator points (Pts or mPts).

The fuel is natural gas composed by a mixture of gases with higher concentration of methane. The value the environmental impact associated with the fuel (Natural gas) changes according to each processes, authors and country. Most of studies carried out at international level, therefore the authors try to develop the environmental impact of natural gas more specific to its country. The values of natural gas environmental impact at natural gas combined power plant at up-stream processes and combustion process were accounted [15]. Fig. 2 presents the up-stream and combustion processes at combined power cycle.

The upstream processes include extraction, treatment and transportation of natural gas from the extraction site to the power plant (253 km). Data related to air emissions, wastewater, fuel used, plant data was collected from combined power plant. The heat rate and lower heating value (LHV) are 2025 kcal/kW h and 11,728 kcal/kg. The data of impact damage category associated with natural gas during the upstream as extraction, treatment, transportation of natural gas and combustion process of natural gas were assembled at first column according [15]. The data damage to resource caused by natural gas extraction has been adopted from [16]. The data were converted from kWh (1st column) to kg fuel (2nd column) multiplying by LHV and dividing to heat rate. The three damage categories all have different units. In order to use a set of dimensionless factors, a normalisation is carried out dividing by the European normalizations values as such as $1.54\text{E}-2$ for human health (HH), $5.13\text{E}+3$ for ecosystem quality (EQ). The data were normalized and weighted for hierarchist (H) perspective according Eco-indicator 99 methodology [16]. The default weighting values (average - A) are 400 for HH and EQ and 200 for Resources. The data of environmental impact associated with Natural gas during the upstream processes, combustion process of natural gas and damage to resource (H/A) have shown at Table 2.

The damage to resource represents 75% of total environmental impact and global warming and climate change potential

Table 1
Natural gas composition.

Component	% volume
CH_4	89.35%
C_2H_6	8.03%
C_3H_8	0.78%
C_4H_{10}	0.08%
CO_2	0.48%
N_2	1.28%
LHV	47.997 MJ/kg

represents 12.5%. The damage to resource means more effort to extract the remaining resource due to the reduction of quality or the decline of easily extractable fossil fuels. Its unit is extra effort as "surplus energy" [8,17]. The global warming and climate change potential occurs mainly due to CO_2 emissions during the extraction, treatment, transmission and combustion of natural gas.

2.2. Life Cycle Assessment

The LCA is used to assess the environmental impact (EI) of product over its lifetime. This method follows the guidelines of international standard approaches (ISO 14004). The eco-indicator can be evaluated for materials, production processes, transport processes, energy generation processes and disposal scenarios. The higher values indicate the greater environmental impact. The LCA is made at all input streams to the overall system and at each system component. The most important components with the highest environmental impact can be identified. This evaluation assigns the results of environmental analysis to exergy streams.

The methodology of life cycle impact assessment is described at [8,16]. The five LCA phases of components were evaluated: (i) Materials - for production processes per kilo of material, (ii) Production processes of manufacturing - treatment and processing of various materials. Expressed for each treatment in the unit appropriate to the particular process (square meters of rolled sheet or kilo of extruded plastic), (iii) Transport processes of materials, components, fuels - per unit ton-kilometer, (iv) Energy generations processes utilized such as electricity and heat - to forming the components at units for electricity and heat, (v) disposal

Table 2

Environmental impact of Natural gas at up-stream and combustion processes.

Damage category	Unit per kW h	Unit per kg fuel	Normalized damage factor	Weight damage factor
Global warning and climate change potential	1.2×10^{-7} DALY/kW h	6.95×10^{-7} DALY/kg	4.51×10^{-6}	18.1 mPts/kg
Acidification and eutrophication potential	0.0024 PDF m ² yr/kW h	0.014 PDF m ² yr /kg	2.65×10^{-6}	1.1 mPts/kg
Human health damage carcinogens potential	3.3×10^{-9} DALY/kW h	1.91×10^{-8} DALY/kg	1.24×10^{-6}	0.5 mPts/kg
Human health damage respiratory inorganics	1.03×10^{-7} DALY/kWh	5.97×10^{-7} DALY/kg	3.87×10^{-5}	15.5 mPts/kg
Human health damage respiratory organics	4.0×10^{-10} DALY/kW h	2.32×10^{-9} DALY/kg	1.50×10^{-7}	0.1 mPts/kg
Ecotoxicity potential	0.0016 PAF m ² yr/kW h	0.00903 PAF m ² yr	1.76×10^{-6}	0.7 mPts/kg
Resource damage caused by natural gas extraction				108.0 mPts/kg
Total				143.9 mPts/kg fuel

scenarios for materials and waste - per kilo of material, subdivided into types of material and waste processing methods.

The factors such as available data, time restriction and available funds are the boundary of study. Due to lack of available data about the weight components, the weight of materials for air compressor, combustion chamber and gas turbine were evaluated by mass flow rate of fluid inside the components and the rupturing pressure in cylindrical steel shell using the following equations.

$$\dot{m} = \rho \cdot \text{vel} \cdot A \quad (2)$$

$$t = \frac{p \cdot D \cdot FS}{2 \cdot \sigma} \quad (3)$$

The values of air and combusted gases velocity (vel) were used according [18]. The property of rupturing stress (σ) was for steel ASTM A (2.1/4%Cr, 1% Mo) used in steam boilers. Its value was 21 MPa considering the creep effect with rupturing time of 100,000 h at 650 °C. The factor of safety (FS) were adjusted according data [19] and compared for steam-boilers as recommended by the A.S.M.E [20]. The weights of components were assumed as composed for pressure vessels shell and inside portion (vanes, blades, nozzle). The combustion section is made of eighteen combustors arranged in a can annular configuration. Into combustion chamber, 20% of the total air mass flow (primary air) enters the flame tubes. The remainder of air passes outside of the flame tube cooling it. The weight of materials for steam turbine, super heater, evaporator, economizer, deaerator, Pump, heat

exchanger and Motor/Generator were evaluated through design [18–22].

The purchase cost function of the component is determined by Refs. [3,23–25]. The solar field is comprised of collectors parabolic-trough from type of LS-3 which are single axis tracking and aligned on a north–south line, thus tracking the sun from east to west [11]. Appendix A shows the cost and weight functions for all components.

The composition of each component was obtained and its correspondent indicators Eco'99 were obtained from [8,19]. Table 3 shows the data.

The eco-indicator for production process and energy generation process for component were considered. The phase of production process may change for each manufacturer. The difficult is obtaining accurate data. The manufacturing process data is industrial secret and there are no studies concerning about the production process and energy generation processes applied to components of system. The manufacturing processes of heat exchanger were evaluated considering component design [11]. The manufacturing processes of motor/Generator were evaluated considering design of motor induction electric motor [22]. The production processes of solar collector were evaluated considering design of parabolic trough collector [11].

Table 4 shows the data of production process and energy generation process for manufacturing a component at its life cycle.

Appendix A are given the weight; environmental impact of material, process, disposal and total environmental impact of all components. The environmental impact of a component is converted into the EI rate considering the estimated equipment lifetime. It was considered 30 years and 7500 h per year for combined cycle and 2000 h per year for solar field.

Table 3

Eco-indicator for materials for system components. Source [19,22].

Component	Material	Percent of material	Eco'99 indicator mPts/kg	Points mPts/kg
Air Compressor	Steel	33%	86	131
	Steel low alloy	45%	110	
	Cast iron	22%	240	
Combustion Chamber	Steel	33%	86	729
	Steel high alloy	77%	910	
Gas/steam turbine	Steel	25%	86	202
	Steel high alloy	75%	240	
Super heater	Steel	25%	86	704
	Steel low alloy	75%	910	
Evaporator Economizer Deaerator Pump	Steel	100%	86	86
	Steel	35%	86	
	Cast iron	65%	240	
Motor/Generator	Steel	20%	86	410
	Cast iron	60%	240	
	Copper	15%	1400	
	Aluminum - primary material	5%	780	

2.3. Exergoenvironmental evaluation

The environmental impact balances are written for the system component in the following form [6]:

$$\dot{B}_p = \dot{B}_F + \dot{Y} \quad (4)$$

$$b_p \dot{E}_p = b_F \dot{E}_F + \dot{Y} \quad (5)$$

where \dot{B}_p and \dot{B}_F are the environmental impact rates associated with product and fuel respectively, and b_p and b_F are the corresponding environmental impacts per unit of exergy for product and fuel.

The component-related environmental impact \dot{Y} , which considers the entire life cycle of the component, consists of the following contributions:

$$\dot{Y} = \dot{Y}^{CO} + \dot{Y}^{OM} + \dot{Y}^{DI} \quad (6)$$

Here \dot{Y}^{CO} is the environmental impact that is associated with construction, including manufacturing, transport and installation,

Table 4

Production process and energy generation process for manufacturing of component.

Component	Processing	Description	Eco'99 indicator mPts per kg, m ³ , MJ, mm ²	Points mPts/kg
Compressor	Cast 33% of weight	Forming: gas-fired heat with furnace Brazing	furnance efficiency 60%, melting heat 0.47 MJ/kg Percentage of weight of brazing in total weight 0.5%	5.3 mPts/MJ 4000 mPts/kg brazing
	Axis 22% of weight	Milling, turning, drilling	Percentage of removed material in weight 5%	0.8 mPts/m ³ removed material
	Vanes blades 45% of weight	Forming: gas-fired heat with furnace	furnance efficiency 60%, melting heat 0.47 MJ/kg	5.3 mPts/MJ
		40.5% Milling, turning, drilling:	Percentage of removed material in weight 5%	0.8 mPts/m ³ removed material
		4.5% Shearing/stamping-steel	1 mm thickness × perimeter	0.00006 mPts/mm ² cutting surface
Total				11.7
Combustion Chamber	Shearing/stamping-steel Brazing	1 mm thickness × perimeter	0.00006 mPts/mm ² cutting surface	8.5E–05
		Percentage of removed material in weight 0.5%	4000 mPts/kg brazing	20
Total				20
Turbine	Cast 33% of weight	Forming: gas-fired heat with furnace Brazing	furnance efficiency 60%, melting heat 0.47 MJ/kg Percentage of weight of brazing in weight 0.50%	5.3 mPts/MJ 4000 mPts/kg brazing
	Axis 22% of weight	Milling, turning, drilling:	Percentage of removed material in weight 5%	0.8 mPts/m ³ removed material
	Vanes blades 45% of weight	Forming: gas-fired heat with furnace	furnance efficiency 60%, melting heat 0.47 MJ/kg	5.3 mPts/MJ
		40.5% Milling, turning, drilling:	Percentage of removed material in weight 5%	0.8 mPts/m ³ removed material
		4.5% Shearing/stamping-steel	1 mm thickness × perimeter	0.00006 mPts/mm ² cutting surface
Total				11.7
Component	Processing	Description	Eco'99 indicator mPts per kg, m ³ , MJ, mm ²	Points mPts/kg
Heat Exchanger	Drilling:	Percentage of removed material in weight 0.05%	0.8 mPts/m ³ removed material	0.051
	Brazing:	Percentage of weight of brazing in weight 0.30%	4000 mPts/kg brazing	12
Total				12.1
Motor	Steel 20%, Shearing	1 mm thickness × perimeter	0.00006 mPts/mm ² cutting surface	8.5E–05
	Cast iron 60%, Forming: gas-fired heat with furnace	furnance efficiency 60%, melting heat 0.47 MJ/kg	5.3 mPts/MJ	2.49
	Copper 15%	Extrusion	72 mPts/kg	10.8
	Aluminum 5%, Forming: gas-fired heat with furnace	efficiency 60%, melting heat 0.60 MJ/kg	5.3 mPts/MJ	3.18
	Brazing:	Percentage of weight of brazing in 0.01%	4000 mPts/kg	0.4
Total				16.9
Collector	Brazing	Percentage of weight of brazing in weight 0.05%	4000 mPts/kg brazing	2.0
	Silver coating	0.099 m ² /kg surface per weight	49 mPts/m ²	4.9
	Glass 2%, Forming: gas-fired heat with furnace	efficiency 60%, melting heat 2.4 MJ/kg	5.3 mPts/MJ	0.42
Total				7.3

Table 5

Exergoeconomic and exergoenvironmental data of the combined cycle integrated.

	\dot{m} [kg/s]	T [°C]	P [kPa]	Ex [MW]	\dot{C} [\$/h]	c [\$/GJ]	\dot{B} [mPt/s]	b [mPt/GJ]
1	421.8	19.0	101.3	0	0	0	0	0
2	421.8	358.0	1114.0	135.20	29,040	59.68	683.2	5054
3	430.5	1132.0	1058.0	436.80	79,167	50.35	1927.0	4412
4	430.5	615.8	107.0	149.50	27,107	50.35	659.9	4412
5	430.5	520.1	105.0	115.70	20,969	50.35	510.5	4412
6	430.5	304.1	104.0	49.91	9046	50.35	220.2	4412
7	430.5	240.0	104.0	34.14	6187	50.35	150.6	4412
8	430.5	236.1	102.0	32.54	5897	50.35	143.6	4412
9	430.5	167.0	102.0	18.45	3345	50.35	81.4	4412
10	430.5	113.0	101.3	9.83	1782	50.35	43.4	4412
11	171.9	48.0	11.2	34.28	8985	72.81	184.7	5389
12	171.9	48.0	11.2	1.40	368	72.81	7.6	5389
13	171.9	48.3	2550.0	1.85	536	80.29	11.0	5925
14	86.0	116.9	180.0	5.09	2030	110.60	43.6	8543
15	14.0	117.0	930.0	0.84	329	108.90	7.0	8348
16	14.0	176.8	930.0	11.86	3021	70.78	69.1	5833
17	14.0	231.5	910.0	12.52	3411	75.69	76.2	6089
18	72.0	118.6	11,900.0	5.22	2045	108.90	43.6	8348
19	72.0	215.0	11,800.0	15.26	5078	92.46	113.2	7418
20	57.9	215.0	11,800.0	12.28	4086	92.46	91.1	7418
21	57.9	305.6	9277.0	63.10	16,214	71.37	381.3	6043
22	72.0	305.6	9277.0	78.42	20,967	74.27	405.1	5166
23	72.0	506.0	8480.0	104.60	27,280	72.47	554.7	5305
24	14.1	215.0	11,800.0	2.98	992	92.46	22.1	7418
25	14.1	313.2	9277.0	15.63	4753	84.45	23.8	1522
26	222.5	298.0	1100.0	36.66	10,643	80.64	4.8	130
27	222.5	299.0	2600.0	36.90	10,800	81.31	8.0	216
28	222.5	393.3	1600.0	62.48	18,139	80.64	8.2	130
29	3084.0	19.0	101.3	8.01	0	0	0	0
30	3084.0	47.2	101.3	24.49	8631	97.91	177.2	7235
31	8.64	19.0	2000.0	429.90	50,101	32.37	1244.0	2893
32				91.07	0	0	0	0
33				0.51	157	84.62	3.2	6209
34				0.55	168	84.62	3.4	6209
35				1.13	344	84.62	7.0	6209
36				147.70	28,326	53.27	683.2	4626
37				274.00	52,545	53.27	1267.0	4626
38				173.50	52,860	84.62	1077.0	6209
39				422.80	100,286	65.89	2246.0	5312
40					112,480	73.90	2510.0	5936

\dot{Y}^{OM} is associated with operation and maintenance, and \dot{Y}^{DI} refers to the environmental impact associated with disposal [6].

Environmental impact rate associated with the exergy destruction within the component

$$\dot{B}_D = b_F \dot{E}_D \quad (7)$$

The total environmental impact associated with a component ($\dot{Y} + \dot{B}_D$) and the exergoenvironmental factor is calculated for correlation:

$$f_b = \frac{\dot{Y}}{\dot{Y} + \dot{B}_D} = \frac{\dot{Y}}{\dot{Y} + b_F \dot{E}_D} \quad (8)$$

3. Results and discussion

The exergoeconomic analysis of ISCCS is performed according the model described by [23] and the exergoenvironmental analysis of ISCCS is performed according the model described previously. The environmental impacts of all components were evaluated. Table 2 shows that the steel is material with lower environmental impacts and copper has the higher environmental impacts. The production process for manufacturing of component with lower and higher environmental impacts are shearing/stamping-steel and brazing, respectively.

The cycle is performed according the following parameters by Ref. [3]: Output exhaust gases temperature is 113 °C, solar radiation intensity is 800 W/m² with annual thermal efficiency of 53%. The pinch point at super heat low pressure is around 10 °C to calculate the water flow rate. The data of mass flow rate, temperature, pressure, exergy, cost rate and cost rate per exergy unit, environmental impact rate and environmental impact per exergy unit at each stream are given in Table 5. These data are relative to the combined cycle integrated solar field.

The net produced electricity is composed by exergy of gas turbine more steam turbine minus consumed pumps evaluated at point 39. Its value is 422.8 MW. The exergetic efficiency as found to be 49.17%. The cost rate of net electricity is 100,286 \$/h. The cost rate per exergy unit of electricity produced at gas turbine and steam turbine are calculated to be 53.27 \$/GJ and 84.62\$/GJ, respectively. Its average cost rate per exergy unit is 65.89 \$/GJ. The cost rate per exergy unit of electricity produced at gas turbine is lower due to lower ratio cost rate per power at gas turbine (969.5/(2 × 274)=1.77 \$(/h MW)) than steam turbine (464.3/173.5=2.68 \$(/h. MW). Similar result has been reported by Ref. [3], which the cost rate per exergy unit of electricity at gas turbine and steam turbine are 53.27 \$/GJ and 84.62\$/GJ, respectively. The total cost rate at point 40 is composed by the cost rate of net electricity more rejected cost at exhausted gases at point 10 and reject cost at hot water in condenser at point 30. The total cost rate is 112,480 \$/h. Its cost rate per exergy unit is the rate between total cost rate and

Table 6
Exergoeconomic and exergoenvironmental data of the combined cycle without solar field.

	\dot{m} [kg/s]	T [°C]	P [kPa]	Ex [MW]	\dot{C} [\$ /h]	c [\$ /GJ]	\dot{B} [mPt/s]	b [mPt/GJ]
1	421.8	19.0	101.3	0	0	0	0	0
2	421.8	358.0	1114.0	135.20	29,040	59.68	683.2	5054
3	430.5	1132.0	1058.0	436.80	79,167	50.35	1927.0	4412
4	430.5	615.8	107.0	149.50	27,107	50.35	659.9	4412
5	430.5	532.0	105.0	119.70	21,696	50.35	528.2	4412
6	430.5	296.7	104.0	48.00	8700	50.35	211.8	4412
7	430.5	240.5	104.0	34.25	6209	50.35	151.1	4412
8	430.5	236.3	102.0	32.59	5907	50.35	143.8	4412
9	430.5	162.1	102.0	17.59	3188	50.35	77.6	4412
10	430.5	113.0	101.3	9.83	1782	50.35	43.4	4412
11	156.3	48.0	11.2	31.12	7940	70.87	186.2	5985
12	156.3	48.0	11.2	1.28	326	70.87	7.6	5985
13	156.3	48.3	2550.0	1.69	474	78.13	11.1	6577
14	78.1	116.9	180.0	4.63	1833	109.90	39.8	8586
15	15.0	117.0	930.0	0.90	350	107.90	7.7	8586
16	15.0	176.8	930.0	12.73	3215	70.14	73.9	5803
17	15.0	231.5	910.0	13.44	3617	74.76	81.2	6044
18	63.1	118.6	11,900.0	4.57	1777	107.90	38.9	8512
19	63.1	215.0	11,800.0	13.38	4432	92.04	99.6	7446
20	63.1	215.0	11,800.0	13.38	4432	92.04	99.6	7446
21	63.1	305.6	9277.0	68.75	17,629	71.22	416.0	6050
22	63.1	305.6	9277.0	68.75	17,629	71.22	416.0	6050
23	63.1	506.0	8480.0	91.68	23,203	70.30	547.9	5976
24								
25								
26								
27								
28								
29	2800.0	19.0	101.3	7.27	0	0	0	0
30	2800.0	47.2	101.3	22.23	7627	95.30	178.6	8034
31	8.6	19.0	2000.0	429.90	50,101	32.37	1244.0	2893
32								
33								
34				0.50	149	82.29	3.5	6885
35				0.99	294	82.29	6.8	6885
36				147.70	28,326	53.27	683.2	4626
37				274.00	52,545	53.27	1267.0	4626
38				155.70	46,131	82.29	1072.0	6885
39				405.80	93,833	64.23	2241.0	5521
40					105,023	71.89	2506.0	6175

net produced electricity. Its value is 73.90 \$/GJ which is higher due to rejected cost rate.

The environmental impact of atmospheric air, solar radiation and water are null. The environmental impact of natural gas is 143.9 mPts/kg. By analogy to exergoeconomic analysis, the fuel fluid rejects an environmental impact rate and the product fluid receives an environmental impact rate. Components which receive heat, work or fuel increase its environmental impact rate at output streams. The environmental impact at output of combustion chamber at point 3 is higher due to the environmental impact of plant is mainly influenced by the environmental impact of fuel. The same result has been concluded in environmental evaluation of power plant by [7].

The effect of environmental impact from component is very low. The variation of input at point 27 and output at point 28 environmental impact at collector field is very low. The environmental impact rates are rejected at points 10 and 30 and its values are 43.37 and 177.2 mPts/s, respectively. The environmental impact per exergy unit at turbine exhaust gases at points 3 until 10 is 4412 mPts/GJ. The environmental impact per exergy unit of electricity produced at gas turbine and steam turbine are calculated to be 4626 mPts/GJ and 6209 mPts/GJ, respectively. Its average cost rate per exergy unit is 5312 mPts/GJ. The environmental impact per exergy unit of electricity produced at gas turbine is lower than steam turbine due to lower ratio component environmental impact rate per power at gas turbine ($624.7/(2 \times 274) = 1.14$ mPts/(h. MW)) than steam turbine ($727.9/173.5 = 4.20$ mPts/(h. MW)).

The environmental impact rate of electricity is composed by environmental impact rate of gas turbine more steam turbine minus consumed pumps evaluated at point 39. Its value as found to be 2246 mPts/s. Its environmental impact per exergy unit is 5312 mPts/GJ (22 mPts/kW h). Similar results have been reported in electricity environmental impact in Europe for high, medium and low voltage according Ref. [8]. The values of environmental impact per exergy unit of electricity produced in mix of country change from 6340 to 7500 mPts/GJ (23–27 mPts/kW h). These values are higher due to electricity production source at Europe are mainly by Natural Gas, Coal and Nuclear. According [10], the energy mix of a country influences in the electricity environmental impact and source as coal increases the environmental impact of electricity for this country.

The total environmental impact rate at point 40 is composed by the environmental impact rate of net electricity more rejected environmental impact at exhausted gases at point 10 and rejected environmental impact at hot water in condenser at point 30. The environmental impact rate is 2510 mPts/s. Its specific environmental impact per exergy unit is the rate between environmental impact cost rate and net exergy of electricity. Its value is 5936 mPts/GJ which is higher due to rejected environmental impact rate.

The combined cycle without solar field was evaluated. The data of mass flow rate, temperature, pressure, exergy, cost rate, cost rate per exergy unit, cost rate and cost rate per exergy unit, environmental impact rate and environmental impact per exergy unit at each stream are given in Table 6.

Table 7
Exergoeconomic data of power plants.

Feature	$\dot{C}_{\text{electr}} \text{ GT/ST } [\$/\text{GJ}]$	$\dot{W}_{\text{GT,net/ST}} = \text{overall} \text{ [MW]}$	$\dot{Z}_{\text{GT,net/ST}}^{Cl} [\$/\text{h}]$	$\dot{C}_{\text{NG}} [\$/\text{kg}]$	Hour per year [hr]	$\dot{W}_{\text{solar field}} \text{ [MW]}$	Ref.
Actual research ISCCS	53.27/ 84.62=65.89	$2 \times 126.3/173.5=422.8$	969.5/464.3	1.61	7500	51.9	–
Actual research CCPP with GT/ST	53.27/ 82.29=64.23	$2 \times 126.3/155.7=405.8$	969.5/430.4	1.61	7500	–	–
Turkey CCPP with GT/ST	13.96/37.69=18.89	23.7/6.29	238/66	0.311	8200	–	[2]
Iran ISCCS	60.89/76.75=66.83	$2 \times 125/150=400$	976.2/9.03	1.61	7500	51.9	[3]
Brazil ISCCS	10.40– 54.87/-	-/0.057	0.7123/-	1.61	3285	0.0524 – 0.0008	[1]

The value of net produced electricity is 405.8 MW. Its value is lower than ISCCS due to lack of solar field energy. The exergetic efficiency is lower 47.20%, it happens because the net produced electricity is lower. The cost rate of net electricity is reduced to 93,833 \$/h due to there is no collector field. The cost rate per exergy unit of electricity produced at gas turbine and steam turbine are calculated to be 53.27 \$/GJ and 82.29\$/GJ, respectively. Its average cost rate per exergy unit is 64.23 \$/GJ. The cost rate per exergy unit of electricity produced at steam turbine was reduced due to lower produced electricity and lower purchase cost of steam turbine and lack of collector purchase cost. The collector field increases the cost rate per exergy unit of electricity in 2.6%. The total cost rate at point 40 is 105,023 \$/h. Its cost rate per exergy unit is 71.89 \$/GJ.

Other results have been reported in power plants with and without solar energy. The data of gas turbine and steam turbine, as soon as, the cost rate per exergy unit, its power, the cost rate of capital investment, the natural gas cost, hour per years of operations, capacity of solar field are shown at Table 7.

In actual research, the presence of solar field increases the cost rate per exergy unit of electricity from 64.23 \$/GJ to 65.89 \$/GJ (2.6%). Other observation is that the solar field increases the steam flow rate and the power steam turbine. The cost rate per exergy unit of steam turbine is higher of gas turbine, and thus, the average cost rate increased.

In Turkey, at combined cycle with cost rate per exergy unit of gas turbine and steam turbine are 13.96 \$/GJ and 37.69 \$/GJ respectively and its average cost rate is 18.89 \$/GJ at Ref. [2]. The capacity and fuel price are lower, due to that the comparison is not coherent. The power of gas turbine and steam turbine are 23.7 MW and 6.29 MW and gas cost is 0.311 \$/kg. A important steam turbine data is the ratio between the cost rate of capital

investment (66 \$/h) per power (6.29 MW) of 10.5 \$/(h MW). This value for the present research changes from 2.67 to 2.76, which the power changes from 405 to 422 MW. In Iran, the most of data is equal as the power, the natural gas cost, hour per years of operations and capacity of solar field. However, the ratio between the cost rate of capital investment (9.03 \$/h) per power (150 MW) is different 0.06 \$/(h. MW). This value of cost rate of capital investment 9.03 \$/h for power of 150 MW is smaller than the value of Turkey of 66 \$/h for lower power of 6.29 MW. The capital investment cost value of steam turbine seems to be inconsistent. In Brazil, a Rankine cycle assisted for solar field uses steam turbine with power of 0.0567 MW. Its values of cost rate per exergy unit change 10.40 – 54.87 \$/GJ due to solar irradiation at solar field. Power system with lower capacity seems to have lower cost rate per exergy unit. The ratio between the cost rate of capital investment (0.7123 \$/h) per power (0.057 MW) of 12.5 \$/(h MW).

The environmental impact analysis reveals that environmental impact rates are similar with low difference. When the temperature or mass flow rate at steam is higher, the exergy rate is higher and the environmental impact rate is higher. The environmental impact rates are rejected at points 10 and 30 and its values are 43.37 and 178.6 mPts/s, respectively. The environmental impact per exergy unit at exhausted gases of turbine and electricity produced at gas turbine are equal. The environmental impact per exergy unit of electricity produced at steam turbine is higher of 6885 mPts/GJ due to the exergy which is lower 155.7 MW. The lower mass flow rate of steam reduces the exergy at point [38]. Therefore, the average environmental impact per exergy unit of electricity produced is higher of 5521 mPts/GJ (20 mPts/kWh). It means that the effect of collector field decreases the environmental impact per exergy unit of electricity in –3.9%. Similar result has been reported in electricity environmental impact in

Table 8
The thermoeconomic variables of the ISCCS.

Component	$E_D \text{ [kW]}$	$\varepsilon \text{ [%]}$	$c_F \text{ [$/GJ]}$	$c_P \text{ [$/GJ]}$	$\dot{C}_D \text{ [$/h]}$	$Z_T \text{ [$/h]}$	$r_k \text{ [%]}$	$f \text{ [%]}$
Air comp	12,530	91.52	53.27	59.68	2402	1428.0	12.0	37.29
Combustor	128,300	70.15	32.37	46.17	14,950	51.8	42.6	0.35
Gas turb	13,230	95.39	50.35	53.27	2398	969.5	5.8	28.79
Super heater HP	7710	77.23	50.35	67.06	1398	351.4	33.2	20.09
Evaporator HP	14,950	77.24	50.35	66.28	2710	409.9	31.6	13.14
Economizer	5736	64.03	50.35	83.94	1040	348.3	66.7	25.09
Super heater LP	938	41.37	50.35	163.5	170	199.3	224.8	53.97
Evaporator LP	3066	78.23	50.35	67.88	556	278.8	34.8	33.41
Steam Turb	26,370	86.81	72.81	84.62	6912	464.3	16.2	6.29
Condensate extr.P.	101	81.78	84.62	103.6	31	0.1	22.4	0.49
Condenser	16,400	50.13	72.81	145.5	4298	13.8	99.8	0.32
Deaerator	4455	48.35	50.35	117.3	808	396.1	133.0	32.91
Boiler feed P.	170	84.92	84.62	99.71	104	0.4	17.8	0.37
Oil P.	277	46.07	84.62	184.3	84	0.6	117.8	0.65
Collector	65,490	28.09	0.0	79.68	0	7339	–	100.0
Solar HE	517	98.00	80.64	82.57	150	25.5	2.4	14.54

Table 9

The thermoeconomic variables of the combined cycle without solar field.

Component	E_D [kW]	ε [%]	c_F [\$/GJ]	c_P [\$/GJ]	\dot{C}_D [\$/h]	Z_T [\$/h]	r_k [%]	f [%]
Air comp	12,530	91.52	53.27	59.68	2402	1428.0	12.0	37.29
Combustor	128,300	70.15	32.37	46.17	14,950	51.8	42.6	0.35
Gas turb	13,230	95.39	50.35	53.27	2398	969.5	5.8	28.79
Super heater HP	6921	76.81	50.35	67.53	1255	327.3	34.1	20.69
Evaporator HP	16,320	77.72	50.35	66.19	2958	401.6	31.5	11.95
Economizer	4945	63.64	50.35	83.80	1040	327.3	66.4	26.75
Super heater LP	955	42.66	50.35	157.5	173	202.0	212.8	53.85
Evaporator LP	3172	78.85	50.35	67.26	575	290.5	33.6	33.56
Steam Turb	23,400	86.93	70.87	82.29	5971	430.4	16.1	6.72
Condensate extr.P.	91	81.78	82.29	100.70	27	0.1	22.4	0.53
Condenser	14,885	50.13	70.87	141.6	3798	12.5	99.8	0.33
Deaerator	3969	48.85	50.35	116.9	719	378.3	132.2	34.46
Boiler feed P.	150	84.92	82.29	96.97	89	0.4	17.8	0.41

Austria according Ref. [8]. Its value of environmental impact per exergy unit of electricity produced is 5000 mPts/GJ (18 mPts/kW h). These values are slightly lower due to electricity production source at Austria are mainly by mix of Hydroelectric 60% and Natural Gas. Renewable sources as solar, wind or hydroelectric source reduce the environmental impact of electricity. The total environmental impact rate at point 40 is 6175 mPts/GJ.

Thermoeconomic variables of cogenerative system, exergy destruction, exergy efficiency, average unit cost of fuel and product, the cost rate of exergy destruction rate, total cost rate, relative cost difference and exergoeconomic factor for each component are given in Table 8.

The combustor is the most exergy destructive component of cycle due to its inherent nature. The collector exergetic efficiency is 28.09%. This is the lowest value among the cycle components which is due to low exergy at collector product compared with collector fuel.

The higher average unit cost of fuel is 84.62 \$/GJ at three pumps which is the electricity cost per exergy unit. The higher average unit cost of product is 184.3 \$/GJ at oil pump due to low increase of exergy using the highest unit cost of fuel. The combustor has the higher cost rate for exergy destruction rate due to higher exergy destruction. The higher cost rates are at collector and air compressor. The higher relative cost difference is at super heater LP where the pinch point happens. The lower value of exergoeconomic factor is at condenser.

The same thermoeconomic variables of cogenerative system without solar field for each component are given in Table 9.

The data are very similar. Some values are slightly high or low for two reasons. The first is the mass flow rate of water and steam

were reduced due to lack of solar collector. The second is the exhausted gases after the gas turbine has changed its temperature for reaches the output temperature of 113 °C. This changes slightly the temperature difference between the hot and cool fluids and changes slightly the destruction exergy by temperature difference effect. The lowest exergetic efficiency is at deaerator of 48.85% because there is no collector. The higher average unit cost of fuel is again at pumps and it value is 82.29 \$/GJ corresponding to the electricity cost per exergy unit. The higher average unit cost of product is 157.5 \$/GJ at super heater low pressure. The combustor has the higher cost rate for exergy destruction rate. The higher cost rates are at air compressor and gas turbine. The higher relative cost difference is at super heater LP. The lower value of exergoeconomic factor is at condenser. Therefore, the exergoeconomic analysis, in combined cycle systems with and without solar collector, reveals that the condenser needs to increase investment costs to increase the total thermodynamic efficiency.

The exergoenvironmental analysis of ISCCS was performed. The values of average environmental impacts per exergy unit for product and fuel, environmental impact rate associated with the exergy destruction within the component, component-related environmental impact and exergoenvironmental factor are shown at Table 10.

The higher average environmental impact per exergy unit of fuel is 6209 mPts/GJ at three pumps which is the electricity environmental impact per exergy unit. The average environmental impact per exergy unit of exhausted gases is 4412 mPts/GJ. The higher average environmental impact per exergy unit of product is 13478 mPts/GJ at oil pump due to same reason of exergoeconomic

Table 10

The exergoenvironmental variables of the ISCCS.

Component	E_D [kW]	ε [%]	b_F [mPts/GJ]	b_P [mPts/GJ]	\dot{B}_D [mPts/h]	\dot{Y} [mPts/h]	f_b [%]
Air comp	12,530	91.52	4626	5054	208,600	65.1	0.0312
Combustor	128,300	70.15	2893	4125	133,6000	337.6	0.0253
Gas turb	13,230	95.39	4412	4626	210,124	624.7	0.2964
Super heater HP	7710	77.23	4412	5722	122,474	1672.0	1.3470
Evaporator HP	14,950	77.24	4412	5711	237,497	98.6	0.0415
Economizer	5736	64.03	4412	6934	91,111	24.3	0.0266
Super heater LP	938	41.37	4412	10,686	14,897	96.1	0.6407
Evaporator LP	3066	78.23	4412	5641	48,702	43.8	0.0899
Steam Turb	26,370	86.81	5389	6209	511,598	727.9	0.1421
Condensate extr.P.	101	81.78	6209	7593	2248	0.6	0.0235
Condenser	16,400	50.13	5389	10,751	318,087	3.7	0.0012
Deaerator	4455	48.35	4412	9125	70,762	12.1	0.0171
Boiler feed P.	170	84.92	6209	7312	7615	0.2	0.0031
Oil P.	277	46.07	6209	13,478	6195	0.5	0.0083
Collector	65,490	28.09	0	7	0	636.3	100.000
Solar HE	517	98.00	130	133	242	23.5	8.8300

Table 11

The exergoenvironmental variables of the combined cycle without solar field.

Component	E_D [kW]	ε [%]	b_F [mPts/GJ]	b_P [mPts/GJ]	\dot{B}_D [mPts/h]	\dot{Y} [mPts/h]	f_b [%]
Air comp	12,530	91.52	4626	5054	208,600	65.1	0.0312
Combustor	128,300	70.15	2893	4125	133,6000	337.6	0.0253
Gas turb	13,230	95.39	4412	4626	210,124	624.7	0.2964
Super heater HP	7710	77.23	4412	5753	109,945	1491.0	1.3380
Evaporator HP	14,950	77.24	4412	5713	259,229	104.5	0.0403
Economizer	5736	64.03	4412	6892	78,543	21.4	0.0272
Super heater LP	938	41.37	4412	10,364	15,173	102.1	0.6681
Evaporator LP	3066	78.23	4412	5596	50,386	46.0	0.0912
Steam Turb	26,370	86.81	5985	6885	504,241	672.6	0.1332
Condensate extr.P.	101	81.78	6885	8420	2265	0.5	0.0227
Condenser	16,400	50.13	5985	11,939	320,690	3.4	0.0011
Deaerator	4455	48.35	4412	9033	63,042	13.6	0.0215
Boiler feed P.	170	84.92	6885	8108	7425	0.2	0.0028

analysis. The combustor has the higher environmental impact rate associated with the exergy destruction of 1336 Pts/h due to higher exergy destruction, according [7]. The higher component-related environmental impact is at super heat high pressure. All exergoenvironmental factors, except for collector, are very low. The collector has no environmental impact rate associated with the exergy destruction. The low value of exergoenvironmental factor indicates that the component-related environmental impact is neglected compared with the high value of environmental impact rate associated with the exergy destruction. The lower value of exergoeconomic factor is at condenser.

The same exergoenvironmental variables of cogenerative system without solar field for each component are given in Table 11.

The higher average environmental impact per exergy unit of fuel is 5719 mPts/GJ at pumps which is the electricity environmental impact per exergy unit. Its value increased due to decreasing of produced electricity. The average environmental impact per exergy unit of exhausted gases is the same of 3664 mPts/GJ. The higher average environmental impact per exergy unit of product is 9916 mPts/GJ at condenser due to low exergy of hot water which leaves this component. Again, the combustor has the higher environmental impact rate associated with the exergy destruction due to higher exergy destruction, [7]. The higher component-related environmental impact is at super heat high pressure, however its value is lower due to lower size of component. When the power is lower, less materials is used and lower is the environmental impact related to materials production. The lower value of exergoeconomic factor is at condenser. Therefore, the exergoenvironmental analysis reveals that the condenser needs to increase its exergetic efficiency to reduce the total environmental impact.

4. Conclusions

An integrated solar combined cycle systems was evaluated from exergoeconomic and exergoenvironmental point of view. The analysis presented in this study demonstrates the effect of collector field. The Exergoeconomic and exergoenvironmental data at each stream of the ISCCS and combined cycle without solar field are shown at Tables 5 and 6, respectively.

The effects of solar field at exergoeconomic analysis are: Increase of the net produced electricity in 4.2%; average cost rate per exergy unit of electricity is increased in 2.6%; cost rate per exergy unit of electricity produced at gas turbine is the same, but the cost rate per exergy unit of electricity produced at steam turbine increased in 2.8%; the total cost rate per exergy unit of electricity is increased in 2.8% in point [40].

The environmental impact analysis of solar field reveals that average specific environmental impact per exergy unit of

electricity is reduced in -3.8% ; specific environmental impact per exergy unit of electricity produced at gas turbine is the same, but specific environmental impact per exergy unit of electricity produced at steam turbine is reduced in -9.8% ; the total environmental impact per exergy unit of electricity is reduced in -3.9% in point [40].

The exergoeconomic variables at each component of the ISCCS and the cogenerative system without solar field are shown at Tables 8 and 9. Data of exergy destruction, exergy efficiency, average unit cost of fuel and product, the cost rate of exergy destruction rate, total cost rate, relative cost difference and exergoeconomic factor for each component are discussed.

The exergoenvironmental variables at each component of the ISCCS and the cogenerative system without solar field are shown at Tables 10 and 11. Data of average environmental impacts per exergy unit for product and fuel, environmental impact rate associated with the exergy destruction within the component, component-related environmental impact and exergoenvironmental factor for each component are discussed. In analysis, the condenser needs to increase its exergetic efficiency for improving the overall performance and to reduce the total environmental impact.

An integrated solar combined cycle system is used as an example to demonstrate the application of exergoeconomic and exergoenvironmental. As result, the effect of collect fields is evaluated and the component with the highest potential for improvement is identified. The LCA of components have limitations, however they are not meaningful when there is burned fuel due to the environmental impact of fuel is the most source of the overall environmental impact.

Exergoenvironmental analysis is a promising approach for the analysis of energy conversion system. Its interesting aspect is likely to be its application to green energy conversion system to improve the environmental performance. A further exergoeconomic analysis with different costs as higher fuel cost and lower solar collector purchase cost and a further exergoenvironmental analysis with uses of others environmental impacts of natural gas from different countries are disable.

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Appendix A

See Tables A1 and A2.

Table A1

Data of component-related environmental impact in LCA.

Equipment	Materials composition Eco'99 mPts/kg	Weight ton.	Material mPts/kg	Process mPts/kg	Disposal mPts/kg	Total mPts/kg	Total Pts
Compressor	steel 33,33% 86 Steel low allow 44,5% 110 Cast iron 22,22% 240	170.0	130	11.7	−70.0	71.7	12,200
Combustion Chamber	Steel 33,34% 86 Steel high alloy 66,66% 910	108.2	635	20.0	−70.0	585.0	63,300
Gas turbine expander	Steel 25% 86 Steel high alloy 75% 910	181.4	704	11.7	−70.0	645.7	117,000
SH_HP	Steel 26% 86 Steel high alloy 74% 910	491.3	696	12.1	−70.0	638.0	313,000
EVA_HP	Steel 100% 86	658.8	86	12.1	−70.0	28.0	18,500
ECO_HP	Steel 100% 86	162.2	86	12.1	−70.0	28.0	4550
SH_LP	Steel 26% 86 Steel high alloy 74% 910	28.2	696	12.1	−70.0	638.0	18,000
EVA_LP	Steel 100% 86	292.9	86	12.1	−70.0	28.0	8220
DEA	Steel 100% 86	80.8	86	12.1	−70.0	28.0	2270
ST	Steel 25% 86 Steel high alloy 75% 910	211.3	704	12.1	−70.0	646.0	136,000
cond	Steel 100% 86	25.0	86	12.1	−70.0	28.0	702
CEP	Cast iron 65% 240 Steel 35% 86	0.75	186	16.9	−70.0	132.8	99
BFP x2	Cast iron 65% 240 Steel 35% 86	0.34	186	16.9	−70.0	132.8	45
OILP	Cast iron 65% 240 Steel 35% 86	0.19	186	16.9	−70.0	132.8	26
SHE	Steel 100% 86	41.9	86	12.1	−70.0	28.0	1180
COLL	Steel 98% 86 glass 2% 58	1390	85	7.3	−69.0	23.2	32,300

Table A2

Correlation of cost and weight function for components.

Component	Cost function: \$	Weight function:
Air compressor	$PEC_c = 71.1 \cdot \dot{m}_{air} \cdot \left[\frac{1}{0.92 - \eta_c} \right] \cdot \frac{P_c}{P_i} \cdot \ln \left(\frac{P_c}{P_i} \right)$	ton Eqs.(2) and (3), FS=2.0, vel _{axial} =15 m/s
Combustion chamber	$PEC_{cc} = 46.08 \cdot \dot{m}_{ar} \cdot \left[\frac{1}{0.995 - \frac{P_c}{P_i}} \right] \cdot (1 + e^{(0.018 \cdot T - 26.4)})$	ton Eqs. (2) and (3), FS=1.6, vel _{axial} cc=6.2 m/s FS=2.0, vel _{axial can} =13 m/s
Gas turbine	$PEC_t = 479.34 \cdot \left[\frac{\dot{m}_g}{0.93 - \eta_t} \right] \cdot \ln \left(\frac{P_i}{P_c} \right) \cdot (1 + e^{(0.036 \cdot T - 54.4)})$	ton Eqs. (2) and (3), FS=4.3, vel _{axial} =50 m/s
HRSG	$PEC_{HRSG} = 6570 \cdot \left[\left(\frac{Q_{ec}}{\Delta T_{ec}} \right)^{0.8} + \left(\frac{Q_{ev}}{\Delta T_{ev}} \right)^{0.8} + \left(\frac{Q_{sh}}{\Delta T_{sh}} \right)^{0.8} \right] + 21276 \cdot \dot{m}_w + 1184.4 \cdot \dot{m}_g^{1.2}$	ton, MW $w_{SH} = 8.424 \cdot \dot{Q}^{0.87}$ $w_{Eva} = 13.91 \cdot \dot{Q}^{0.68}$ $w_{ECO} = 2.340 \cdot \dot{Q}^{1.15}$ P > 25 bar $w_{ECO} = 2.989 \cdot \dot{Q}^{0.97}$ P < 25 bar
Solar Field	$PEC_{coll} = 355 \text{ $/m}^2$	ton, m, curve length=6.20 m $W_{coll} = 0.0626 \cdot L(\text{length})$
Condensate Pump	$PEC_{pump} = 2100 \cdot \left(\frac{\dot{W}}{10} \right)^{0.26} \cdot \left(\frac{1 - \eta_p}{\eta_p} \right)^{0.5}$ $PEC_{Gen} = 500 \cdot \left(\frac{\dot{W}}{10} \right)^{0.87} \cdot \left(\frac{1 - \eta_p}{\eta_p} \right)$	ton, kW $w = 0.0061 \cdot W^{0.95}$, P=3.5 bar
Steam Turbine	$PEC_{ST} = 2210 \cdot \dot{W}^{0.7}$	ton, MW, $w_{ST} = 4.90 \cdot \dot{W}^{0.73}$
Pump and motor	$PEC_{pump} = 2100 \cdot \left(\frac{\dot{W}}{10} \right)^{0.26} \cdot \left(\frac{1 - \eta_p}{\eta_p} \right)^{0.5}$ $PEC_{Gen} = 500 \cdot \left(\frac{\dot{W}}{10} \right)^{0.87} \cdot \left(\frac{1 - \eta_p}{\eta_p} \right)$	ton, kW $w = 0.175 \cdot \ln(W) - 1.06$, P=135 bar $w = 0.0631 \cdot \ln(W) - 0.197$, P=25 bar $w = 0.125 \cdot \ln(W) - 0.0415$, P=4.3 bar
Heat Exchanger	$PEC_{HE} = 12000 \cdot \left(\frac{A}{100} \right)^{0.6}$	ton, kW, $w_{HE} = 2.14 \cdot \dot{Q}^{0.7}$
Condenser	$PEC_{conl} = 1773 \cdot \dot{m}$	ton, MW, $w_{cond} = 0.073 \cdot \dot{Q}^{0.99}$
Deaerator	$PEC_{HRSG} = 6570 \cdot \left[\left(\frac{Q_{ec}}{\Delta T_{ec}} \right)^{0.8} \right] + 1184.4 \cdot \dot{m}_g^{1.2}$	ton, kg/s, $w_{Dea} = 2.49 \cdot \dot{m}_w^{0.7}$

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