Exergoenvironmental and Exergoeconomic Modelling and Assessment in the Complex Energy Systems

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ABSTRACT: *Traditionally energy systems were analyzed technically, but current environmental issues and considerations have put new constraints on the planning and managing of energy systems. Such an exergoeconomic and exergoenvironmental analysis were born. This analysis is aimed to describe the necessity and application of a new concept in environmental liability accounting based on physical quantities to overcome the weaknesses of the developed allocation methods and the internalization of external environmental damages. The proposed method is modified in environmental analysis to consider the effect of non-energy flows on a macro-surface energy system. As a case study, this method is tuned for a complex energy system. It has been shown that environmental responsibilities, calculated based on exergy destruction in order, represent the role of the units in the overall emission and contribution to integrated environmental management. The comparison shows that responsibilities are higher than emission reductions for service units, and the difference between duties and permits may not reflect the costs of internal damage. The exergoeconomic and exergoenvironmental analysis is used to model the concept of the system's economic-environmental footprint in a quantitative process, which is the most crucial advantage of this method. This paper implements this method on a solar thermal power plant combined with the steam cycle system as a case study.*

KEYWORDS: *Exergoeconomics; Exergy analysis; Thermodynamical analysis; Entropy optimization; Exergoenvironmental analysis.*

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1021-9986/2022/3/989-1002 14/$/6.04

INTRODUCTION

Environmental pollution is recognized as an obstacle to sustainable development for the past four decades. Since human activities and their effects on air quality have led to adverse economic and social conditions, environmental considerations have put new constraints on the planning and management of energy systems. Many environmental management studies have been developed to assess actual environmental damages (and related costs), determine a standard emission level, and allocate emission permits between units of a system [1, 2]. The need for a large-scale emission-reduction process implemented on a system makes this method a valuable and scarce method to be considered. Numerous studies have examined the conventional ways of regulating environmental pollution (or resource scarcity) in cap and trade market designs and their applications on local, national, regional, and international scales—moreover, global environmental management systems, reviewing their feasibility and effectiveness. In a cap and trade market, authorities set the maximum release rate in a region and distribute initial permits between companies or departments based on two "grandfather" and "auction" (or a mixture of them) methods [1]. The mentioned quota transfer market is a topic of active debate for environmental policy researchers. Some of the new approaches are in the development phase, use an output-based allocation and optimization to overcome the shortcomings of conventional allocation methods [2]. Output-based allocation recommends splitting the permissions between the active units in a segment based on their outputs rather than their past releases. However, this method cannot be applied to complex energy systems because it produces a range of different end products, and there are many intermediate streams from medium or service providers whose share in each one of the end products is unclear. Besides, when using market values for each unit's products, prices may be misleading (especially in the case presented here) because they represent market inefficiencies and competitive products' competitive value from familiar contexts [3].

In their studies of environmental cost accounting, Muller and Mendelssohn provided a significant graph illustrating the impact of the distance between environmental damage and costs [4]. Their study has shown that the company goes beyond its optimum value, covering only a portion of its gross external losses. The analysis of the gap between permissions and responsibilities is the subject of this study. Although companies are allowed to issue their licenses, they must be held responsible for damages to the system[4]. In other words, unlike licenses, responsibilities are not assigned based on historical activities (such as grandparents) or the market strength of the company (such as auctions); still, they must be allocated based on actual assistance—moreover, secondary pollution caused by their performance within the system should also be considered. Current research work addresses the issue of allocation and many practical issues such as measuring responsibilities indexes and involving individual units to participate equitably in a supply chain responsibility in the presence of inter-organizational environmental management [5]. In particular, *Kong et al.* have analyzed inter-enterprise management systems' role in firms' interaction in the supply chain's environmental management when the choice is not readily available to the purchasing companies [6]. It has also been shown that in the case of an integrated management organization, service providers may require additional taxes from consumer units by raising prices in contracts. The allocation of responsibility is that all system members participate in problem-solving actions wherever environmental performance in the system is identified based on the entire production chain [7]. This approach may be applied to integrated environmental management systems by collecting responsibilities through environmental taxes and managing all units' emissions. The application of environmental liability accounting in real markets is discussed in various other references [8].

One of the most significant challenges of the 21st century for reliable energy supply is addressing climate change-related issues related to greenhouse gas emissions and considering the economic aspects essential to sustainable development. Therefore, future requirements for energy conversion systems are to reduce environmental impacts with limited cost reductions. In this context, the integration of solar energy into existing or anticipated combined-cycle power plants is one of the solutions that will increase interest in using solar thermal technology (currently an expensive alternative only when integrated into a proven and developed energy conversion system can be made a solution for the energy market) [9]. This integration is particularly attractive to Iran that uses natural gas as its primary energy source and can improve fossil fuels' environmental performance. This form of hybridization takes advantage of the infrastructure available in a conventional thermal power plant, including connecting to the grid and space available around the plant [10]. However, in addition to the extra cost to build and operate them, integrated solar power plants present some environmental challenges in land occupancy, the use of metal-based materials, and complex manufacturing process management problems. To identify the technical performance, costs, and environmental benefits, a comparison was made between a conventional Combined Cycle Gas Turbine (CCGT) and a solar-integrated hybrid gas turbine (ISCCGT), both concerning a power plant in northern Iran [9]. A plant model was developed that includes a one-year operation period and consists of climate variables (complete simulation of solar resource specifications and off-design effects for gas turbine operation). The model can predict the power plant's performance and calculate the complete equilibrium of exergy, including all the complex plant components in either mode (CCGT or ISCCGT). It then performs an extroversion analysis reconstructs the two power plants (CCGT and ISCGGT) and performs a detailed life cycle assessment [10]. These results are reviewed and validated by demonstrating the benefits of solar integration and suggesting possible improvements in design configuration.

This study aims to model a domestic combined Rankine-Bryton cycle integrated with the solar thermal power plant and exergoeconomic and exergoenvironmentally analyze the system as a case study for complex energy systems. This paper addresses the lack of enough Iranian domestic exergoenvironmental research and studies a large-scale complex energy system using the exergoenvironmental analysis.

EXPERIMENTAL SECTION

Exergoenvironmental analysis

The conventional environmental method developed by Tsatsaronis forms the proposed method's basic structure to consider a system's complexity [10]. Similarly, in the exergy cost theory to evaluate the exergy cost of flows, the extrinsic method presents the environmental charge per unit of exergy destruction or rate of streamflow used in solving a system of equations consisting of the principal environmental diffusion (or effects) equilibrium for each unit within the system and some auxiliary equations for allocating loads to more than one output per unit [11]. The solution of these equations may provide a waste-to-cost ratio. This method's specific appropriateness for accounting for environmental responsibility is the transfer of fertile contamination burden between service providers (or feeders) and consumers [12].

As presented in Norouzi and Talebi (2020), the main equations reflecting the equilibrium environmental charge (B($kton/yr$)) in k th unit with Y($kton/yr$) emission rate are as follows [13]:

$$B_{k,out} = B_{k,in} + Y_k \tag{1}$$

In equation 1, each of the total environmental load that enters and/or exits the unit is the summation of input (and/or output) streams loads. Also, each stream's environmental load is the product of exergy ($E(kW)$) in environmental load per unit of exergy ($b_i(kton/yr.kW)$) of the streams[14].

$$B_{k,in(out)} = \sum_{i=1,j=1}^{I(n)} b_{(i),k,in(out)} E_{i(j),k,in(out)} \tag{2}$$

The term Y_k represents the life cycle environmental impacts depending on the analysis [15].

In the advanced environmental approach, the effects/emissions of avoidable and unavoidable greenhouse gases have been identified, and the above equations have been written for avoidable parts[16]. However, as discussed in the literature, thanks to well-developed control techniques, it is almost impossible to prevent the release of PM10 footprints, and therefore the differentiation made in the advanced method is not necessary. The auxiliary equations of the ambient environment are required to solve equations 1 and 2, F-type equations are the specific environmental charge for the inlet, and outflows are unchanged from a fixed unit [17]. Also, P-type equations are for a flow coming out of a component and the exterior environmental charge has a significant value in this type of equation. Alongside these two rules, the per-unit loads of inlet currents through the system boundaries are assumed to be zero before experiencing any conversion. This assumption is due to the study's aim in which the emission of gases within the system contributing to local pollution is essential and is to be managed because the emission of greenhouse gases outside the boundaries before the delivery the delivery of feeds is of importance in the integrated environmental definition systems, which are not taken into account for integrated management [18].

Exergoeconomic analysis

The method for exergoeconomic analysis is similar to an exergoenvironmental analysis [19]. It combines an exergy analysis of the energy conversion system with an economic analysis based on the Total Revenue Requirements (TRR) method, covering the energy conversion system's entire life cycle. Initially, the total capital investment is calculated [20]. The total annual revenue needed is calculated based on the assumptions of economic, financial, operational, and market input parameters [21]. This TRR represents the cost of producing system products and offsets all costs incurred each year of the project's economic life to guarantee an industrial plant. After that, the product's annual variable costs related to investment, operation, maintenance, fueling, and other costs (cost categories) are leveled [22]. This equipment is converted into a series of fixed payments equivalent to an annuity[23]. Next, by calculating each material and energy flow's specific cost rate, the costs are assigned to the respective exergy flows [24]. Since the exergoeconomic analysis is well established, only the analogy formulas with those used for environmental analysis are presented in Table 2.

Reforms Required

The thermodynamic method for distributing the load across the outputs is useful for formulating complex energy systems with several desired energy products [25]. These approaches may make it possible to identify problems associated with the transfer of load at the micro-level, where conventional economic theories are difficult to apply [26]. However, due to the lack of process details and each subsystem's total process integration, it is less accurate in the macro-level analysis [27]. This combination creates a different allocation of shares among the stocks. Table 1 summarizes the mentioned rules.

It may be possible to calculate each unit's contribution to environmental gas emissions using the specific environmental charge calculated per the stream's exergy unit (b) [32]. Some of the other methods, such as the quasi-linearization method, can solve the governing equations of the concerned problem in complex energy systems [33].

CASE STUDY

In this study, this method is implemented on a solar thermal power plant combined with the steam cycle system as a case study to investigate the proposed method's results in complex systems. The case study is a power plant in Tehran, Iran, the reference point and starting point for studying solar energy integration. The Combined Cycle Gas Turbine (CCGT) system investigated is a three-pressure heat recovery steam generator (HRSG) [33]. A model of the basic CCGT was developed using the Matlab software version 2015a, and a simulation tool was developed to simulate complex power plants—V94 power it(I)-50Hz gas turbine powered by siemens. The gas turbine is designed with a capacity of 148 MW[34]. The gas turbine is displayed artificially with temperature, mass flow rate, and flue gas composition. The mathematical model of the HRSG triaxial and steam cycle follows this scheme, as shown in Fig. 1. A cycle is a laying machine that features dual-stage turbines with HP-IP hybrid segments and double flow at the low-pressure stage, including steam heating at medium pressure level[35].

The modeling approach requires defining specific temperature differences between the flue gases and the water within the HRSG. The design point analysis shows that two gas turbines and 143 MW can produce 286 MW of power by steam turbines with an overall electrical efficiency of 43.9%. After measuring the heat exchangers, it was also possible to perform an annual design analysis, where environmental conditions affect the gas turbine's performance. A detailed description of the assumed reference design data and energy and exergy results can be found in the system [36].

Solar thermal hybridization is mostly a useful development, which involves adding a solar thermal field to an existing fossil fuel power plant. In practice, an integrated solar thermal power plant may operate in a fuel-saving or flexible-energy state. One of the popular hybrid installations is the PTC50 Alvarado (Acciona Energy Corporation), a 50 MW solar power plant that integrates a central receiver solar system with biomass and natural gas fire cycle[37]. The second system is a hybrid solar biomass power plant using parabolic solar-powered thermosolar plants; an example of Spain. This study's idea of integration is to reduce the evaporation process bottlenecks by adding solar heat in parallel couplings. Three sets of solar collectors mounted on solar farms

Table 1: The method in different cases.

Case	Specification	Allocation Rule	Formulation
Feed 1, Feed 2 → Energy conversion unit → Product 1, Product 2, Product 3	Energy carriers e.g., Cogeneration unit	P-type/F-type [28]	$b_1 = b_2 = b_3$
Feed 1, Feed 2 → Non-Energy unit → Product 1, Product 2, Product 3	Non-energy carriers e.g. Ammoniac and Ammonia plants	P-type/F-type replacing exergetic costs instead of exergies [29]	$\frac{b_1 E_1}{CEXC_1} = \frac{b_2 E_2}{CEXC_2} = \frac{b_3 E_3}{CEXC_3}$
Feed 1, Feed 2 → Energy/Non-Energy unit → Product 1, Product 2, Product 3	P1 and P2: Energy carriers P3: Non-energy carrier e.g., crude oil distillation column	5th principle suggested by Finnveden subtracting P3 and Conventional exergoenvironmental P-type/ F-type [30]	$b_1 = b_2$ $\frac{b_3 E_3}{CEXC_3} = cte$
Feed 1, Feed 2 → Energy/Non-Energy unit → Product 1, Product 2, Product 3	P1, P2: NonEnergy carriers P3: Energy carrier e.g., Cement production with waste heat recovery power plant	5th principle suggested by Finnveden subtracting P3 And Conventional exergoenvironmental P-type/ F-type replacing exergetic costs instead of exergies [31]	$b_3 = cte$ $\frac{b_1 E_1}{CEXC_1} = \frac{b_2 E_2}{CEXC_2}$

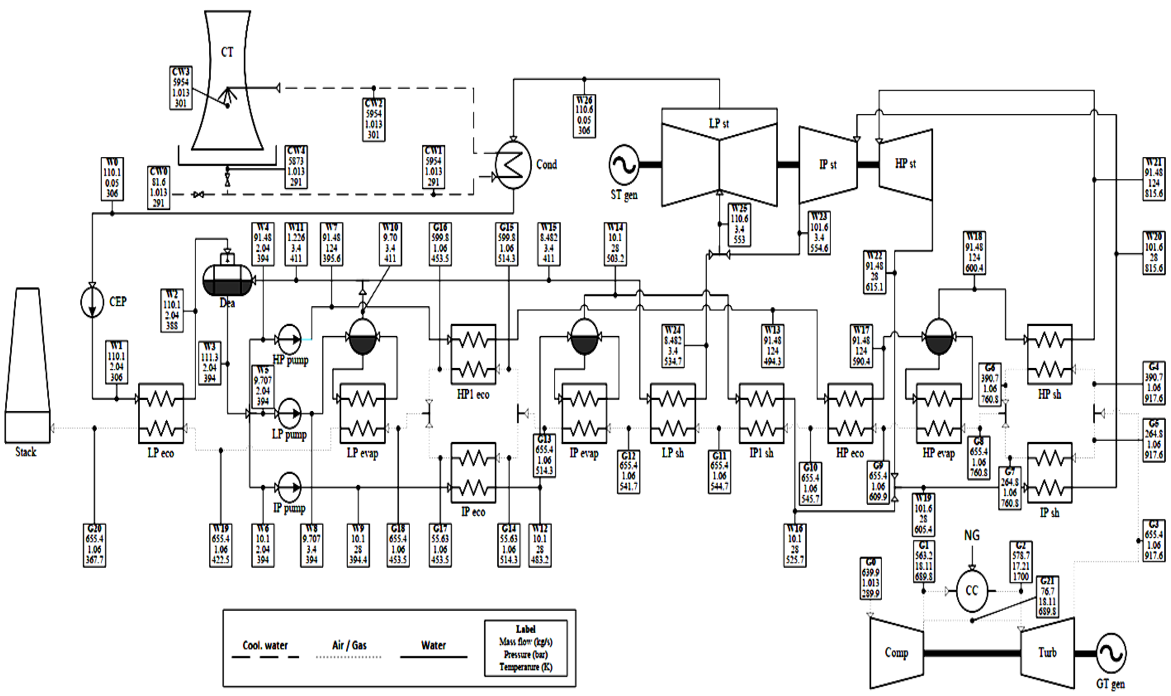

Fig. 1: Combined Cycle of Rankine-Bryton layout.

Table 2: Equations for exergoeconomic and exergoenvironmental assessments.

Exergoeconomics		Exergoenvironmental	
Exergy stream cost rate	$\dot{C}_j = c_j * \dot{E}_j$	Exergoenvironmental stream impact rate:	$\dot{B}_j = b_j \cdot \dot{E}_j$
Component cost balance	$\sum \dot{C}_{j,k,in} + \dot{Z}_k = \sum \dot{C}_{j,k,out}$	Component environmental impact balance	$\sum \dot{B}_{j,k,in} + \dot{Y}_k = \sum \dot{B}_{j,k,out}$
Component-related cost rate	$\dot{Z}_k = \dot{Z}_k^{CL} + Z_k^{OM}$	Component-related environmental impact rate	$Y_k = Y_K^{CO} + \dot{Y}_K^{OM} + Y_K^{DI}$
The component relative cost difference	$r_k = \frac{C_{P,k} + C_{F,k}}{C_{F,k}}$	Component relative environmental impact difference	$r_{b,k} = \frac{b_{P,k} - b_{F,k}}{b_{F,k}}$
Component exergoeconomic factor	$f_k = \frac{Z_k}{Z_k + C_{D,k}}$	Component exergoenvironmental factor	$f_{b,k} = \frac{Y_k}{Y_k + B_{D,k}}$

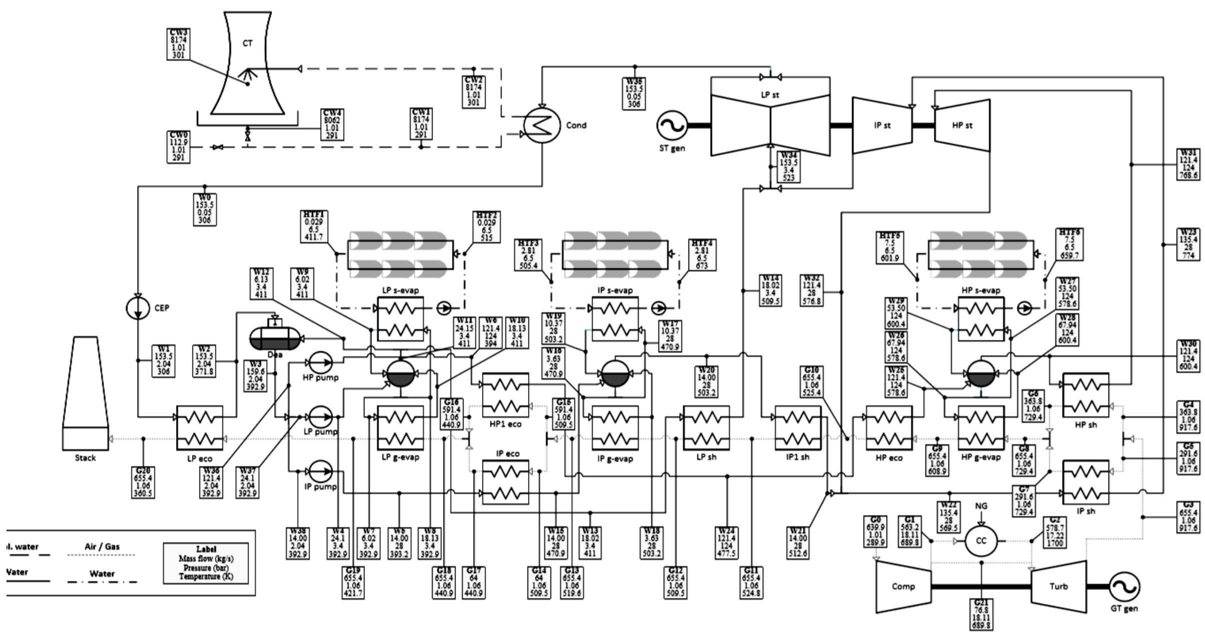

Fig. 2: Combined Cycle of Rankine-Bryton integrated with the Solar thermal unit's layout.

support active evaporators inside the HRSG (see Fig. 2). Solar integration is designed to add additional heat to the evaporators from a parallel solar heat exchanger to reduce the local temperature difference between the water and steam/gas flow in the HRSG. This system increases the power plant's energy efficiency by increasing the steam cycle power due to the prolonged heat generated in the HRSG [38].

Integrated Solar Cycle Gas Turbine (ISCCGT) plant model supports additional heat (Solar) for the evaporation surface. The increase in the heat from each solar collector cycle is calculated by multiplying the solar collector's efficiency through solar radiation reaching the collector surface. The solar collector model is based on the second-order equation 3[23, 38]:

$$\eta_{SC} = \eta_0 - a_1\left(\frac{\Delta T_m}{G}\right) - a_2\left(\frac{\Delta T_m^2}{G}\right) \quad (3)$$

Where

$$\Delta T_m = \Delta T_{HTF} - \Delta T_{amb} \quad (4)$$

The manufacturers present the performance parameters. The LP evaporator is supported by a solar field using PolyTrough 1800 with pressurized water as heat transfer fluid, produced by NEP SOLAR AG. For high and medium HRSG pressures, the EuroTough ET-150 collectors with SYLTHERM 800 as the heat transfer fluid are considered. Simulation of total solar collectors for the year showed that the June 17 morning design clock provided one of the highest heat gain yields from collectors with ambient temperatures close to ISO standards (16.7 ° C) [25, 26]. Evaporator support scale and solar field size are defined for these design conditions. A satisfactory level of design heat objective of the evaporator's solar backup was found to perform a sensitivity analysis. The system should reach a significant reduction of stack temperature of more than 4.1 k. As a result, 32, 15.6, and 61.9 MW of thermal energy must be supplied by solar fields at low, medium, and high-pressure evaporators, respectively. A creative idea used for this solar integration case was to arrange the collector rings for the high and medium pressure evaporators as a flexible solar field. In the first step, after a proper study of solar thermal energy conversion systems, the solar coefficient SF = 1.5 was used [27]. The configuration and amount of loops assigned to intermediate or high-pressure evaporators can be adapted to meteorological conditions using a simple collector switching setting, with lower solar IP priority and higher efficiency (due to the absorption bottom temperature). Besides, with the use of control routines, the correct increase in HTF temperature, and the solar collector control mode is enhanced. Instead of setting ΔT_{HTF} as a constant, it is dynamically consistent with radiation and environmental conditions. This control law's basic idea is to maximize the collectors' exergy efficiency [38, 39].

RESULTS AND DISCUSSION

For the Integrated Solar Combined Cycle Gas Turbine (ISCCGT), the design clock simulation showed that steam generation capacity could be increased to 152 MW, and the electrical efficiency of the Combined fossil power plant could reach 45.52%. The energy efficiency of the ISCCGT is calculated by a marginal approach, assuming that only natural gas contributes to the energy input. Hence, marginal electrical efficiency increased by more than 7%. The CO_2 emission factor is reduced from 346 gCO_2/kWh to 315 gCO_2/kWh. The exhaust gas temperature on the stack decreases from 367.7 K to 360.5 K, proving that the hybridization process effectively achieves its design goals. Under design conditions, the external efficiency increased by 4.42% to 46.12% concerning CCGT's 41.7%. This increase is because solar radiation is considered a source of high-pressure heat flow. If solar radiation is considered a free exergy source, the marginal output efficiency (for fuel only) reaches 51.22%.

Exergoeconomic analysis

Economic analysis is performed for design operating conditions. The results show that the combustion chamber's exergy destruction cost is dominant due to the high reversibility of the combustion process for both power plant adjustments [40]. The reduction term depends on the cooling materials and techniques used and the ratio of gas turbine pressure. This type of progress goes beyond the scope of the present analysis. The impact of hybridization on power plant capital costs is significant, as shown in Table 3 [41]. The cost breakdown is shown in Table 4 concerning the main components. Exposure to substantially higher capital costs can be well-motivated (return on investment is more than five years). According to the ISCCGT plant, a significant component cost (actually the second-highest overall cost) is associated with solar collectors. The capital cost + O&M cost for the three solar fields represent more than 40% of the plant's total investment cost [42]. The parabolic solar system is the most proven solar thermal energy technology. The capital cost in solar collector fields represents a primary additive due to the current hybrid cycle, and this is a critical threshold for the large-scale development of CSP technology commercialization. However, ISCCGT plants exhibit a bridge technology concerning solar plants of the same size, as solar energy generally shows marginal support for HRSG; It replaces natural gas excess fuel (additional duct burners) for the excessive heat recovery process. Since solar energy is assumed to be zero in fuel cost, the cost of exergy destruction for collectors is considered 0 $ per hour. Other essential components in cost, construction includes the condenser, HP evaporator, HP superheater, and steam turbine for CCGT and ISCCGT. Low associated FC values indicate that a reduction in these components' exergy destruction cost is possible with a higher investment cost, and this solution improves system performance [43-46].

In the exergoeconomic analysis (see Table 5), considering the exergoeconomic factor's value, all the components can be classified into three categories. In the first category, the exergy factor is of high importance. It is understood that the capital cost for these components is very high for this category, and the exergy destruction rate and exergy destruction costs should be reduced. In this study, ISCCGT is most valuable because of the high cost of purchased equipment and short service life [47].

Table 3: Thermodynamic results of the plant simulation.

Point	Press.	Temp.	Enthalpy	Entropy	Mass flow	State
1	101.33	285.4	298.5	5.65	149.64	air
2	2938.43	862.32	1004.99	5.97	149.64	Com. air
3	2938.43	1275.84	1484.29	6.63	155.64	HP. exhaust
4	101.33	742.18	995.02	7.06	155.64	LP. exhaust
5	101.33	285.4	298.5	5.65	149.64	air
6	2938.43	864.06	1007.66	5.97	149.64	Com. air
7	2938.43	1277.87	1486.66	6.63	155.64	HP. exhaust
8	101.33	743.45	997.14	7.06	155.64	LP. exhaust
9	5035	695.24	3249.67	6.72	14.19	steam
10	530	547.65	3010.93	7.34	5.13	steam
11	5035	695.24	3249.67	6.72	14.19	steam
12	530	547.65	3010.93	7.34	5.13	steam
13	10	319.01	2344.68	7.4	38.64	water
14	10	319.01	263.57	0.87	38.64	water
15-15'	10	319.01	275.54	0.91	19.32	water
16	5035	354.69	364.25	1.14	14.19	water
17	530	307.12	166.32	0.57	5.13	water
18	5035	354.69	364.25	1.14	14.19	water
19	530	307.12	166.32	0.57	5.13	water
20	101.33	410	426.1	7.49	155.64	flare flue
21	101.33	410	426.1	7.49	155.64	flare flue
22	101.3	285.4	44000	0	6	Natural gas
23	101.3	285.4	44000	0	6	Natural gas
24	530	341.21	285.11	0.93	19.32	water
24'	530	341.21	285.11	0.93	19.32	water

Table 4: Results of the exergoeconomic analysis.

Component	ISCCGT	CCGT
HRSG	142	121
Gas Turbine	347	392
Steam Turbine	207	190
Condensing system	155	138
Solar collectors	432	0
Other	81	89
Total	1364	930
Fixed O&M ($/kW-y) or [$/kWh]	24.2 [0.0029]	14.81 [0.0022]
Fuel-related running cost ($/kWh)	0.0639	0.0677

Table 5: Exergetic and exergoeconomic analysis stream data.

Comp.	ε (%)	c_f ($/h)	c_p ($/h)	C_D ($/h)	Z_T ($/h)	r_k (%)	f_k (%)
AC_2	90.2488	10.6991	12.0765	0.004074	0.00291	15.5491	40.643
CC	74.6512	5.9364	7.663	0.026772	0.000175	29.2067	0.6402
GT_2	86.6404	7.663	10.6991	0.009603	0.02134	37.248	66.8136
AC_1	83.8759	29.682	12.028	0.002522	0.00064	15.55395	2.3765
HX_1	74.3408	7.663	10.379	0.002716	6.11E-05	33.7075	2.1631
HX_2	65.3198	7.663	12.028	0.000279	4.46E-05	54.611	13.4636
SC	75.3496	8.4099	30.167	0.027451	0.139292	251.6859	80.995
GT_1	86.4561	7.563	10.8866	0.009523	0.03562	37.234	66.8853
HRSG	90.5377	4.384	8.971	0.008324	0.003164	33.7996	55.783

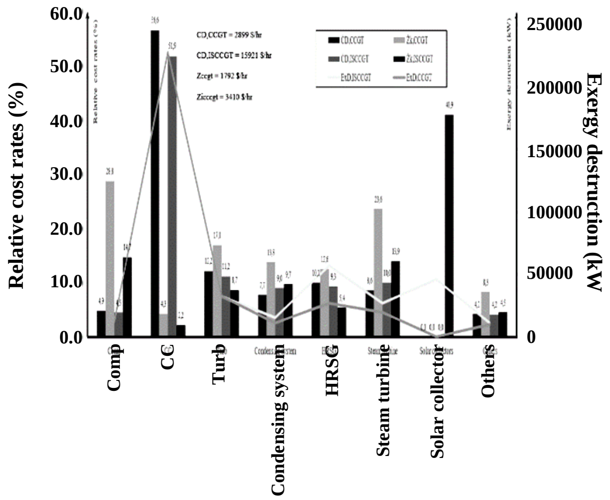

Fig. 3: The exergoeconomic analysis results.

In the second category, the exergy factor is of low value, and even if the component yield decline is accepted, the investment cost should be reduced. As shown in the results, the lowest value is for HX_1 and HX_2, as the capital cost of HX_1 equipment is low. In CC, due to chemical reactions, significant exergy destruction occurs. Given the low capital cost and the high exergy loss for CC, the cost factor, and the loss ratio should be increased by adding capital costs [41, 48].

All of the components with moderate values for socioeconomic factors are in the third category, and advanced exergy analysis is suggested to improve these components. Tables 6 to 8 and Figure 3 show the advanced analysis data of the ISCCGT system [44].

Exergoenvironmental analysis

Following the LCA inventory results, a significant contribution to the system's environmental impact from its manufacturing components is detected. This outcome is because of their need for substantial quantities of resources and minerals for construction, such as generators, HRSG, and steam turbines. When considering the ISCCGT configuration, solar farms' development is predominant in the system's environmental impact. However, this contribution is not comparable to the combustion chamber since the gas turbine emission's environmental burden is entirely attributable to this component.

Despite the increase in Y_{tot}, the specific environmental impacts per unit of energy generated by the integrated solar power plant (33.1 mPts/kW) are lower than the conventional combined cycle (38.1 mPts/kWh). With more insight, one can obtain the interpretation of impact through the traditional LCA method. Figures 4 and 5 show the significant reductions in specific environmental impacts classified and referred to by solar integration as the functional unit (1 kWh). Some of them have negative values , such as land use and mineral and resource depletion. In particular, the reduction in raw materials for the ISCCGT is due to the availability of materials needed to build solar fields compared to the CCGT. The most significant savings are related to climate change and fossil fuel reduction. This result is confirmed by the carbon footprint, which has been resumed for refund analysis, as shown in Figure 6, which is illustrated the emission rate per kWh of energy. This fact leads to a significant reduction in CO_{2-Eq} during the power plant (see Table 9).

Table 6: Splitting the exergy destruction within the kth component.

Component	(kW)	(kW)	(kW)	(kW)
AC_1	71.8479	15.14752	60.8287	22.2615
AC_2	340.2372	44.8334	262.3462	103.3438
FC	59.2379	32.1167	77.0956	32.0585
HX_1	23.7886	10.6181	26.5689	8.4554
HX_2	23.6486	10.4081	26.5489	8.5554
CC	3363.931	993.0957	3777.432	593.5818
SC	2459.484	430.2823	2544.339	621.8379
GT_2	1079.882	130.9306	1033.584	175.4245
GT_1	145.7037	15.0738	142.6579	20.8065

Table 7: Splitting the exergy destruction cost rate within the kth component.

Component	($/s)	($/s)	($/s)	($/s)
AC_1	0.002056	0.000466	0.001746	0.000747
AC_2	0.003531	0.000534	0.002813	0.001261
HX_1	0.000208	7.66E-05	0.000197	7.19E-05
HX_2	0.000204	7.61E-05	0.000194	7.16E-05
CC	0.016257	0.010476	0.022795	0.003919
SC	0.022048	0.005432	0.02134	0.005917
GT_2	0.007964	0.001649	0.007954	0.001649
GT_1	0.003715	0.000747	0.003783	0.000689

Table 8: Splitting the capital cost within the k-th component.

Component	($/s)	($/s)	($/s)	($/s)
AC_1	5.16E-05	1.24E-05	4.56E-05	1.84E-05
AC_2	2.52E-03	3.90E-04	2.16E-03	7.52E-04
HX_1	4.58E-05	1.55E-05	4.63E-05	1.49E-05
HX_2	3.19E-05	1.32E-05	3.68E-05	8.37E-06
CC	8.18E-05	9.67E-05	1.12E-04	6.70E-05
SC	1.12E-01	2.76E-02	1.12E-01	2.80E-02
GT_2	1.73E-02	4.08E-03	1.76E-02	3.76E-03
GT_1	1.01E-04	2.75E-05	1.09E-04	2.04E-05

Table 9: The exergoenvironmental analysis of the system.

Components	Z[$/h]	f[%]	r[%]	C_D[$/h]	Y_k[hpts/h]	f_b[%]	r_b[%]	B_D[hpts/h]	e[%]
AC	105.0336	31.6416	21.1008	213.6768	5.059584	0.54912	14.1504	88.3968	83.6736
CC	27.264	4.1376	20.832	604.5888	24.82176	0.94944	20.7552	250.7328	78.9504
Gas Turbine	56.064	30.7584	4.6752	118.8864	31.00512	6.00288	4.4928	49.2768	91.7376
Super heater	5.2896	24.6336	52.6368	15.3312	7.179552	10.7232	39.5712	6.3552	68.1984
Evaporator	18.9888	18.7968	28.32	77.952	1.943232	0.57696	22.7808	32.3136	77.5968
$Economizer_2$	15.0816	66.5472	31.872	6.6816	0.234048	0.8112	9.7824	2.7648	87.1296
$Economizer_1$	9.2832	35.952	55.7856	15.504	0.221184	0.33024	34.9056	6.4224	70.4064
Deaerator	2.832	94.5024	74.352	0.048	0.163968	18.1728	22.848	0.0192	54.864
Preheater	5.424	3.888	212.736	128.4768	0.05568	0.0096	117.408	53.2416	43.1904
Deaerator	0.1056	8.064	3.504	1.2096	0.016416	0.41856	3.2064	0.3744	92.8992
HRSG Pack	56.8992	17.9616	36.0192	247.2384	9.79776	0.9168	24.8256	102.4704	76.656
Pump	0.0768	4.8768	49.008	1.4976	0.047712	0.73728	46.5504	0.624	64.6656
HX	0.288	0.0864	734.592	320.7936	0.022752	0.00096	733.824	121.6704	11.1072
SC	680.42	100.00	-	0	0.07712	100.00	-	0.08532	98.7656

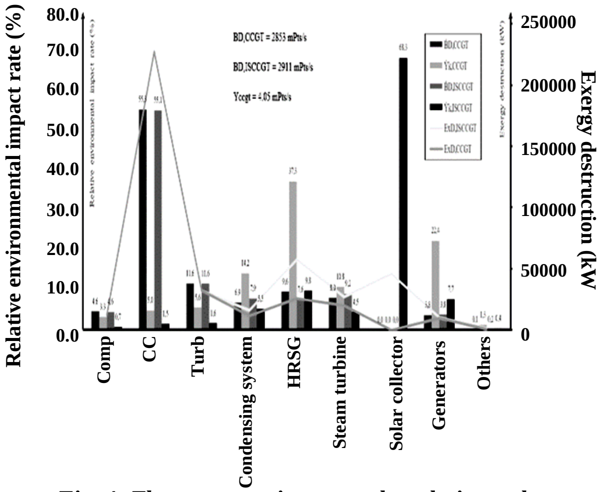

Fig. 4: The exergoenvironmental analysis results.

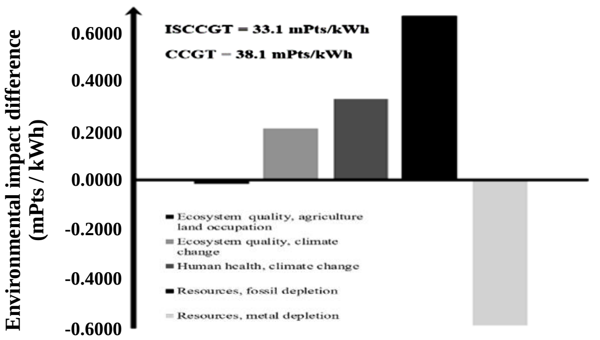

Fig. 5: Environmental impact reduction by the ReCiPe impact category.[17].

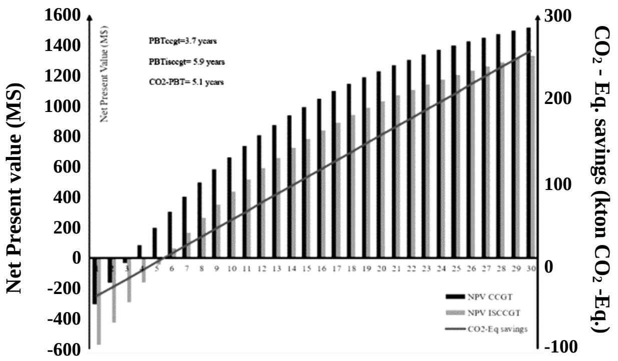

Fig. 6: The NPV analysis [14].

CONCLUSIONS

The present work examines the environmental and economic performance of an ISCCGT and compares it with the conventional CCGT system with a detailed exergoenvironmental analysis basis. In particular, the ISCCGT combination was designed to improve heat recovery in HRSG, reduce pinch problems, and achieve lower stack temperatures. Besides, the dynamic allocation of CSP solar fields supports medium- and high-pressure evaporators and flow rate control to minimize the exergy destruction of solar collectors in addition to the significant loss applied to the results for off-year performance. The capital cost increases by about 41% using solar hybridization, but the return on investment (5.9 years) is not significantly affected due to the combined effect of saving precious natural gas resources and increasing power. Besides, it should be considered that the plant is located in an area that does not provide the most optimal solar radiation in the country. The level of the solar field yield, and therefore the investment cost, is higher than what is needed in areas with better climates. The results confirm that, despite the higher capital cost and LCA cost coefficient, ISCCGT technology offers significant environmental benefits thanks to the lower consumption of fossil fuels per unit of energy produced, thus reducing greenhouse gas emissions during the operational lifespan.

Nomenclature

a_1 and a_2	Collector constant, W/(m.K)
E	Exergy rate, MJ/s
b_j	Specific environmental impact with the jth material flow per exergy unit of the same flow, ReCiPe mPts/GJ
B_j	Environmental impact rate of the jth material flow, ReCiPe mPts/s
C_j	Cost rate of the jth material flow, $/h cj specific costs with the production of the jth material stream per exergy unit of the same flow, $/GJ
CC	Combustion chamber
GT	Gas Turbine
G	Overall radiation, W/m^2
AC	Air compressor
Y	Component-related environmental impact rate associated with the life cycle of the component, ReCiPe pts/s
Z	Component-related cost rate associated with the life cycle of the component, $/h
HX	Heat Exchanger
SC	Solar collector
ST	Steam turbine

Acknowledgment

"The author(s) are extremely grateful to the learned reviewers for their comments to improve the quality of the manuscript and also all of the scientific support of the Amirkabir university of technology."

Received : Sep.. 20, 2020 ; Accepted : Dec. 7, 2020

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