Exergy, Exergoeconomic, and Exergoenvironmental Analysis in Natural Gas Liquid Recovery Process

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ABSTRACT: *In this work, the real case study of the energy quality of the natural gas liquid recovery plant 800 is evaluated via exergy, exergy economy, and exergy environmental methods. The corresponding simulation is carried out using Aspen HYSYS V10 software and MATLAB. Sensitivity analysis will evaluate energy consumption, environmental impact, and the economics of inefficient equipment. The exergy analysis results show that the compressor (K103) and the heat exchanger (E101) with the highest exergy destruction are 510 and 629 kw, respectively. Improving the performance of these equipment can reduce exergy destruction and increase exergy efficiency. Furthermore, the results indicate that the main improvement priority belongs to the compressor (K103). According to the results of the exergoeconomic evaluation, the maximum value of the exergoeconomic factors belongs to the heat exchanger (E103). It should be replaced by a cheaper one. Furthermore, E100 and K102 have the potential for economic improvement in terms of their high exergy destruction and the relative cost difference. Furthermore, their low values of exergoeconomic factors show dominance in the exergy-related cost part. Improving the performance of these devices will significantly reduce the overall cost rate by up to 40%. The results show that the main improvement priority based on the exergoeconomic concept belongs to the compressor (K102). The highest value of the exergoenvironmental factor belongs to the heat exchanger (E-103) by 99%. This shows its high LCA environmental impact. The total impact rate may be reduced by up to 97 percent by optimizing the equipment's operating and maintenance parameters. Environmental results show that E101 and P100 have the potential for improvement. Improving the performance of these devices will significantly reduce the overall environmental impact by up to 40%. Furthermore, the main priority for improvements based on the exergoenvironmental concept belongs to the heat exchanger (E101).*

KEYWORDS: *NGL plant; Exergy analysis; Environmental analysis; Exergoeconomic analysis; Improvement criteria.*

INTRODUCTION

The increasing trend of energy consumption in the world has faced humans with a major environmental pollution crisis. One of the most important effects of increased carbon dioxide is global warming [1]. In recent years, fossil fuels have caused many environmental problems such as urban pollution and acid rain [2].

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Research shows that 47% of greenhouse emissions of carbon dioxide are emitted by various industries [3]. Environmental controls are pressuring the oil and gas industries to reduce the impacts of fossil fuel CO_2 emissions due to their high greenhouse gas emissions. [4]. And have put new environmental constraints on the entand planning of industrial plants [5].

Many countries have committed sufficient effort to control global temperature rise and prevent climate change to solve this problem. Therefore, conducting studies to improve the energy consumption pattern in Iranian industries is a big step towards a cleaner use of energy.

However, according to Climate Watch Institute historical studies, greenhouse gas emissions in Iran have been increasing, which raised Iran's World ranking from 10th in 1990 to 8th in 2017[6]. Global statistics show that Iran is ranked as the third country to burn industrial fluoride gases [7].

Furthermore, because of these constraints imposed by the environmental effect of CO2 emissions, natural gas is considered as the cleanest fossil fuel, and its usage is quickly increasing [8]. By 2030, natural gas is predicted to provide 30% of the world's fossil fuel supply [9]. Furthermore, according to the reports of this magazine, Iran with 16.2% of the proven natural gas reserves is ranked, as the world's second nation with the highest natural gas reserves [10]. This shows a promising future for its natural gas and NGL recovery industries.

The exergy analysis method is a key issue for a better understanding of inefficiency locations, causes, and process magnitudes. This analysis can determine the optimal state of energy consumption in relation to the environmental and operating conditions of the plant [11]. Many scientists and engineers suggest this thermodynamic evaluation in place of the conventional energy analysis to best evaluate the thermodynamic performance of a process [12]. Researchers have performed the exergy analysis method on NGL plants in the last decades to evaluate improvement priorities [13]. In this regard, *Mehrpooya et al.* [14] considered the exergy analysis method in NGL1300, one of the biggest NGL recovery units in southern Iran. *Jiang et al.* [15] performed the exergy analysis method on China’s ethane recovery processes based on rich gas. *Hu et al.* [16] studied NGL plant equipment and found that air coolers contributed to the highest exergy destruction.

Moreover, research were done for other chemical processes. *Noorpoor et al.* [17] assessed the Tehran Oil Refinery Company. Conventional exergy analysis showed that the highest exergy destruction belongs to the fired heater (57.24%). Furthermore, advanced exergy analysis reveals that avoidable- endogenous- and unavoidable-endogenous portions account for the bulk of exergy degradation in the fired heater.

On the other hand, considering the system's inefficiency impact on economic aspects, exergoeconomic analysis allows identifying the location and magnitude of system inefficiency costs. This method analyzes the system from economic and thermodynamic perspectives by considering comprehensive economic aspects such as investment costs and maintenance costs [18]. Economic investigation of equipment inefficiency in NGL and chemical processes was performed.

In this regard, *Khajehpour et al.* [19] studied the exergoeconomic aspect of the LNG and NGL recovery case studies. Their considerations show that the second heat exchanger has an exergy destruction cost (768.93 $/GJ). Moreover, the first air cooler in the liquefaction cycle has the lowest exergy destruction cost (19.38 $/GJ).
Mousavi et al. [20] studied the cascade absorption compression refrigeration system and found that the highest, and the lowest highest and lowest exergoeconomic factorsbelong to the gas heat exchanger and the evaporator, respectively, 79.95% and 9.17%. *Ghorbani et al.* [21] studied the behavior of integrated low-temperature natural gas processes. The heat exchanger (HX2) and the air cooler (AC2) have the largest and lowest investment costs for avoidable endogenous exergy degradation, respectively. *Hassanet al.* [22] considered exergoeconomic parameters in a new proposed scheme of a hybrid solar distiller comprising solar still. Their proposed scheme showed promising results of exergoeconomic parameters. *Wu et al.* [23] evaluated the refrigeration cycle of an air separation process integrated with LNG regasification. Results showed that the sub-coolers' outlet temperature reached optimum equipment investment cost as -21.00 C and -20.50 C, respectively. *Ansarinasab et al.* [24] considered the exergy concepts in a hydrogen liquefaction plant. The results show that the highest exergoeconomic factor values belong to the pump and the compressors. Thus, the high exergy destruction rate in heat exchangers has caused the lowest value of the exergoeconomic factor.

The environmental analyses are expected to expand over the coming decades in terms of their potential to address energy quality and their environmental impacts [25]. Exergy analysis is a powerful and accurate tool to evaluate the quality of energy. LCA method is used to evaluate the environmental impact of component's lifecycle on pollutant formation [26]. Exergoenvironmental analysis is a proper combination of these two analyses [27]. which can define the highest environmental impact caused by component inefficiencies and lifetime pollutants. It assesses the possible improvements of process's environmental impacts.

Some research has also analyzed the impacts of chemical process equipment on the environment. *Ansarinasab et al.* [28] performed exergy-base analysis for a biorefinery plant. Their study shows that reactors' inefficiency has the highest environmental impact. Cavalcanti [29], considered a dual-fuel marine driver of a trigeneration system. His assessment showed that the pollution of this driver could be controlled by improving the exergoenvironmental performance without great modification into the engine. *Rocha et al.* [26] evaluated an ultra-supercritical coal-fired power plant. *Norouzi et al.* [30] evaluated a Natural Gas Direct Chemical Looping Carbon capture and Formic acid Hydrogen storage system in a combined cycle power plant. Their modification decreased the plant's carbon emissions by more than 93%.

Their exergoenvironmental analysis results showed that the system has a low level of LCA environmental impact rate. The inefficiency of equipment has the main part of the environmental impact of the system. *Boyaghchiet al.* [31] considered the environmental impacts of a micro solar-geothermal CCHP system with water/CuO nanofluid. Multi-objective optimization results show that R1234ze is the best fluid with an overall environmental impact rate of (36.82 Pts/h). *Atilgan et al.* [32]., presented the environmental impacts of an aircraft engine. Results show that 83% of environmental impacts are caused by exergetic inefficiency. The remaining part is the result of LCA environmental impacts. *Morosuk et al.* [33] evaluated a mixed-refrigerant process used for small-scale LNG plants. They discovered that the heat exchanger in this system has the greatest environmental effect, which is due to the high rate of exergy destruction. By boosting the heat exchanger's performance, this metric may be lowered.

As a real case study, NGL plant No. 800 from National Iranian South Oil Company (NISOC) with a production capacity of 120,000 NGL barrels per day located in Ahvaz, Koreit Industrial Zone was chosen. As an innovation exergy, exergoeconomic, exergoenvironmental analyzes of NGL plant were assessed.

This study aims to identify inefficient equipment and its effects on economic and environmental impacts. After identifying this equipment, their modification methods are assessed. These changes are divided into two categories: performance enhancement and modifying operation and maintenance settings. Finally, the best outcomes are compared to the existing situation. This table can be used for accessing the concepts of the exergy in the equipment.

THEORETICAL SECTION

Process description

Fig. 1 shows PFD for the current operating condition of the NGL plant. According to the process flow diagram, NGL plant 800 has one input feed and two output productions, including NGL and sales gas. The feed stream enters the demethanizer column after cooling down to -23.3 ˚C by a triple heat exchanger (E101, E102 in the cryogenic cycle and E100 refluxed feed stream). After extraction in the demethanizer column, the sale gas and exchanged gas in the heat exchanger (E-100) will be sent to pressure-boosting units. NGL from the bottom of the demethanizer column will be sent to petrochemical companies at 48 ˚C and 63 psi for other uses. In this plant, the propane cryogenic cycle is completely separated from the production process for the procession and cooling of NGL product. Its streams can be seen in Fig. 1 marked with the letter "P". This cycle is pressurized up to 23.84 bars by the low-pressure compressor (K-101), medium- pressure compressor (K-102), and high-pressure compressor (K-103). Economizer towers (V-102, V-103, and V-104) separate propane gas (to return to compression system) from liquid propane which continues heat exchanging in the cryogenic cycle. Inlet feed streams and outlet product streams will exchange heat with liquid propane by heat exchangers (E-101, E-102, and E-103). Processing is completed by the condenser (E-105) and cooler (E-104). Cooler provides the required heat for the reboiler of the demethanizer columnand condenser cool down the pressurized propane to 65.55 ˚C.

The data were collected by the Iranian Petroleum Standards (IPS-E- PR-170) [36]. Peng-Robinson

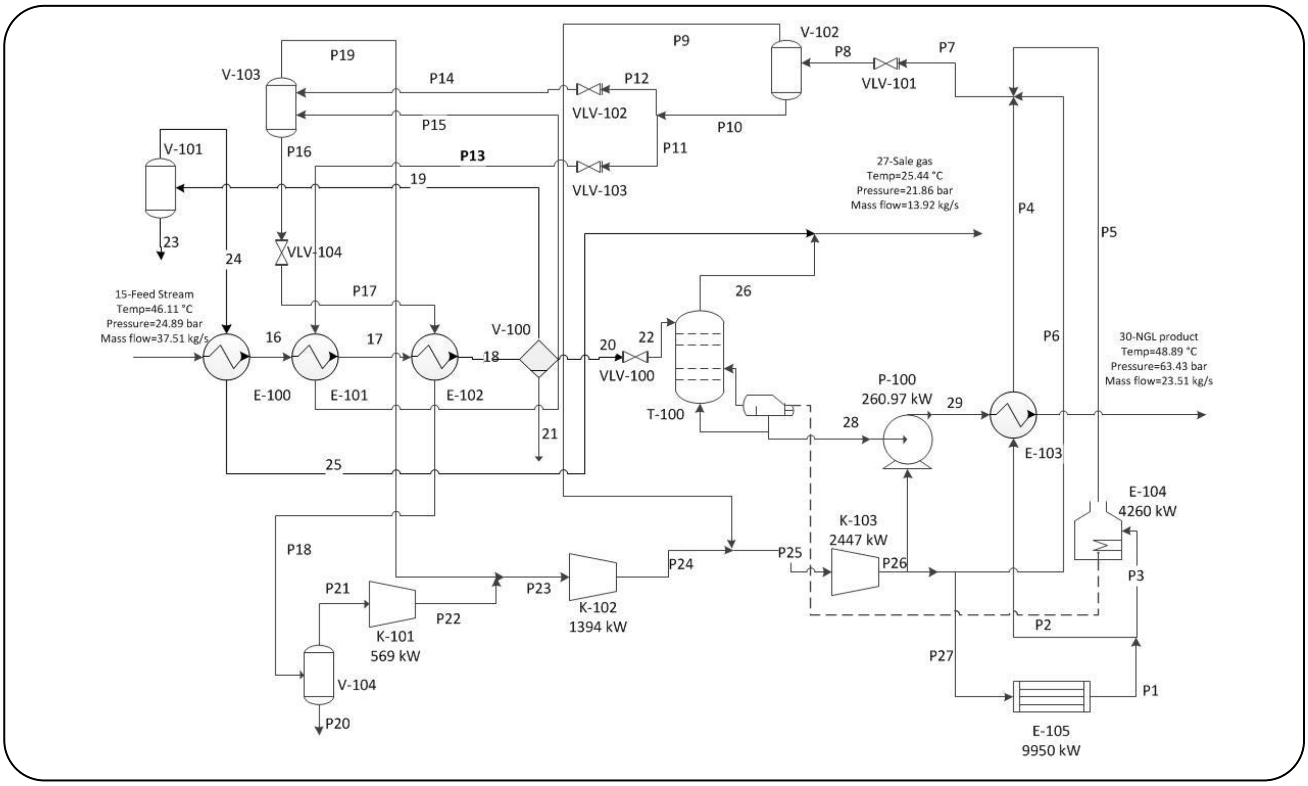

Fig. 1: PFD of NGL plant.

Equation of State (PR-EOS) was selected to determine the thermodynamic properties of the NGL plant. This state equation was used in the previous simulations of NGL plants [37-41]. For simulating in Aspen HYSYS software, the operating conditions of the NGL plant are listed in Table 1. Furthermore, Table 2 shows the energy consumption of equipment**.** The following assumptions were used to simulate the NGL plant:

1- Peng Robinson's equation of state is applied to predict governing equations and calculate the balances in the simulation are considered.

2- NGL simulation is performed in a steady state.

3- Pipelines are assumed to be insulated in HEN and do not have heat loss.

Product specifications and simulation deviations from operating conditions are also shown in Table 3. The error rate in this simulation indicates that the simulation is in compliance with operating conditions.

Exergy evaluation

Exergy is a thermodynamical measure of the energy quality and determines the equipment's deviation from the environmental reference state [34]. In real processes, exergy is consumed or destroyed by irreversibility. This method can detect energy quality and prevent opportunities to use wasting energy. This analysis determines the most inefficient equipment and shows where the energy is wasted in operating conditions [35, 36]. Therefore, it is important to determine the ambient conditions to conduct the exergy analysis.

Ahvaz city average ambient conditions were assumed as T_0 = 25 °C and P_0 = 101.325 kPa [37]. According to Eq. (1), the total exergy of the system for the material stream is split into four parts, namely kinetic ($\dot{E}x_{ke}$), potential ($\dot{E}x_{po}$), physical ($\dot{E}x_{ph}$), and chemical ($\dot{E}x_{ch}$) exergies [38]. The potential and kinetic exergies are neglected [39].

$$\dot{E}x = \dot{E}x_{po} + \dot{E}x_{ke} + \dot{E}x_{ph} + \dot{E}x_{ch} \tag{1}$$

So, the material stream of exergy analysis is defined as the sum of chemical and physical parts [40, 41].

$$\dot{E}x = \dot{E}x_{ph} + \dot{E}x_{ch} \tag{2}$$

The physical and chemical exergy are defined as Eqs (3) and (4) [39, 42]:

Table 1: The operating conditions and specifications of the NGL plant components.

Rotary machines						
	Operating type	Isentropic efficiency. (%)	Power (kW)	ΔP (kPa)	P ratio (-)	Head [m]
K-101	Centrifugal	75	568.92	237.15	2.48	4273
K-102	Centrifugal	75	1393.59	384.85	1.97	3330
K-103	Centrifugal	75	2447.37	1601.13	3.046	5719
P-100	Centrifugal	75	260.97	4136.85	2.88	849

Heat Exchangers						
	Type	Minimum approach (ºC)	LMTD (ºC)	Duty (kW)	Cold Pinch Temp. (ºK)	Heat exchanging area(m^2)
E-100	Shell and tube Horizontal-AEL	10.645	28.80	1550.55	308.62	66.1
E-101	Shell and tube Horizontal-AEL	5.556	18.26	6548.00	267.57	61.9
E-102	Shell and tube Horizontal-AEL	7.791	16.84	3663.56	242.04	61.6
E-103	Shell and tube Horizontal-AEL	5.555	10.11	411.62	315.67	71.6

Cooler					
	Type	ΔT(ºC)	ΔP (kPa)	Duty (kW)	Heat exchanging area(m^2)
E-104	Cooler	-50.44	0	4259.92	532
E-105	Cooler	-22.76	0	9949.96	2761

Column						
T-100	Type	Number of stages	Feed stage	Tray/Packed Space (m)	Tray/Packed Volume (m^3)	Tower diameter (m)
	demethanizer	10	1	0.5	0.883	1.5
	Type	Orientation	ΔT(ºC)	ΔP (kPa)	Duty(kW)	Heat exchanging area(m^2)
	Kettle Reboiler	Horizontal	29.26	0	4259.92	532.7

Column						
	Type	Orientation	ΔP (kPa)	Volume (m^3)	Diameter (m)	phases
V-100	Separator	Horizontal	13.79	2.86	1.066	3
V-101	Separator	Vertical	0	12.95	1.67	2
V-102	Separator	Vertical	0	26.42	1.82	2
V-103	Separator	Vertical	0	47.80	2.59	2

Table 2: The operation conditions of the NGL plant.

Stream No.	Temperature [ºC]	Pressure [bar]	Molar Flow [kmol/s]
15(Feed stream)	46.1	24.9	0.15
16	37.2	24.5	0.61
17	0	24.2	0
18	-23.3	23.9	0.76
19	-23.4	23.7	0.76
20	-23.5	23.7	0.03
21	-23.4	23.7	0.74
22	-24.5	22.1	0.46
23	-23.6	23.6	0.28
24	-23.6	23.6	0.46
25	35.5	22.5	0.28
26	-24.6	21.9	0.46
27(Sale gas)	25.4	21.9	0.24
28	37.9	22.1	0.24
29	42.5	63.4	0.24
30(NGL product)	48.9	63.4	0.5
P1	65.6	23.8	0
P2	65.6	23.8	0.24
P3	65.6	23.8	0.24
P4	48.1	23.8	0.74
P5	15.1	23.8	0.74
P6	88.3	23.8	0.76
P7	22.1	23.8	0.76
P8	17.5	7.8	0.76
P9	17.5	7.8	0.15
P10	17.5	7.8	0.61
P11	17.5	7.8	0
P12	17.5	7.8	0.76
P13	-5.6	4	0.76
P14	-5.6	4	0.03
P15	-5.6	4	0.74
P16	-5.6	4	0.46
P17	-31.1	1.6	0.28
P18	-31.1	1.6	0.46
P19	-5.6	4	0.28
P20	-31.1	1.6	0.46
P21	-31.1	1.6	0.24
P22	8.4	4	0.24
P23	-1.1	4	0.24
P24	30.4	7.8	0.5
P25	30	7.8	0
P26	88.3	23.8	0.24
P27	88.3	23.8	0.24

Table 3: Specifications of the plant's production streams, operational conditions data and error analysis of simulator output.

Stream number	Sale gas (27)			NGL Product (30)		
	Simulation	Real	Error (%)	Simulation	Real	Error (%)
Temperature (°C)	25.44	25.49	0.19	48.89	49.01	0.24
Pressure (bar)	21.86	21.81	0.22	63.43	63.49	0.09
Mass flow (kg/s)	13.92	13.91	0.07	23.51	23.53	0.08
Composition (mole fraction)						
H2O	0	0	0	0	0	0
H2S	0	0	0	0	0	0
CO_2	0.006	0.006	0.2	0.003	0.003	0.846
Methane	0.774	0.774	0.013	0.025	0.026	0.407
Ethane	0.17	0.169	0.177	0.278	0.273	1.756
Propane	0.042	0.043	1.408	0.334	0.333	0.24
i-Butane	0.003	0.003	0.793	0.064	0.065	0.619
n-Butane	0.005	0.005	0	0	0	0
i-Pentane	0.001	0.001	0	0.18	0.18	0
n-Pentane	0	0	0	0.044	0.044	0
n-Hexane	0	0	0	0.031	0.032	0.317
n-Heptane	0	0	0	0.024	0.024	0.043

$$\dot{E}x_{ph} = \dot{m}.\left[\left(h-h_0\right)-T_0.\left(s-s_0\right)\right] \tag{3}$$

$$\dot{E}x_{ch} = \sum_{i=1}^{N} y_i e_i^0 + G - \sum_{i=1}^{N} y_i G_i \tag{4}$$

The "0" subscription refers to the ambient condition in the above equations. And T_0, h_0, and s_0 are ambient reference temperature, specific enthalpy, and specific entropy, respectively, in equation (3).[39]

Exergy destruction and exergy efficiency are two major parameters of the process that must be determined in exergy analysis [43]. These essential parameters are investigated and discussed for the *k*th component of the process components by Eq. (5) and (6).

$$\dot{E}x_D = \dot{E}x_F - \dot{E}x_P \tag{5}$$

$$\varepsilon = \frac{\dot{E}x_P}{\dot{E}x_F} = 1 - \frac{\dot{E}x_D}{\dot{E}x_F} \tag{6}$$

Where *P*, *D*, and *F* represent the product, destruction, and fuel in these equations, respectively. According to the fuel-product methodology, Table 4 presents exergy calculation formulas in the main component of the NGL plant.

Exergoeconomic analysis

Exergoeconomic analysis is a more comprehensive analysis which combines the exergy and economic fundamentals analyses to provide essential information to evaluate the cost of systems inefficiencies [49]. This analysis includes depreciation, operation, maintenance, and fuel costs, defined as thermodynamic variable functions [50]. Designing engineers can use this analysis to make a good estimate of the economic performance of the system.

In this regard, by conducting a comprehensive analysis, balance equations of equipment costs are obtained. Moreover, thermoeconomic indicators are evaluated. Finally, the equipment whose inefficiency has high economic costs is identified.

Exergy cost related to input and output streams, work, and heat transfer is in the form of Eqs (7) to (10) [51].

Table 4: Exergy calculation formulas in the main component of the NGL plant.

Compressor [44, 45]	Exergy destruction	$\dot{E}x_D = \sum(\dot{m}.e)_{in} + W - \sum(\dot{m}.e)_{out}$
	Exergy efficiency	$\varepsilon = \frac{\sum(\dot{m}.e)_{in} - \sum(\dot{m}.e)_{out}}{W}$
Heat exchanger [8]	Exergy destruction	$\dot{E}x_D = \left[\sum(\dot{m}.e)\right]_{in,(Hot)} + \left[\sum(\dot{m}.e)\right]_{1,(cold)} - \left[\sum(\dot{m}.e)\right]_{out,(Hot)} - \left[\sum(\dot{m}.e)\right]_{2,(cold)}$
	Exergy efficiency	$\varepsilon = \frac{\left[\sum(\dot{m}.e)\right]_{in,(Hot)} - \left[\sum(\dot{m}.e)\right]_{out,(Hot)}}{\left[\sum(\dot{m}.e)\right]_{2,(cold)} - \left[\sum(\dot{m}.e)\right]_{1,(cold)}}$
Column/Tee/ Mixer [46, 47]	Exergy destruction	$\dot{E}x_D = \sum(\dot{m}.e)_{in} - \sum(\dot{m}.e)_{out}$
	Exergy efficiency	$\varepsilon = \frac{\sum(\dot{m}.e)_{out}}{\sum(\dot{m}.e)_{in}}$
Cooler [43, 48]	Exergy destruction	$\dot{E}x_D = \sum(\dot{m}.e)_{in} + Q\left(1 - \frac{T}{T_0}\right) - \sum(\dot{m}.e)_{out}$
	Exergy efficiency	$\varepsilon = \frac{Q\left(1 - \frac{T}{T_0}\right)}{\sum(\dot{m}.e)_{in} - \sum(\dot{m}.e)_{out}}$
Pumps [45, 47]	Exergy destruction	$\dot{E}x_D = \sum(\dot{m}.e)_{in} + W - \sum(\dot{m}.e)_{out}$
	Exergy efficiency	$\varepsilon = \frac{\sum(\dot{m}.e)_{in} - \sum(\dot{m}.e)_{out}}{W}$
Expansion valves [45, 47]	Exergy destruction	$\dot{E}x_D = \sum(\dot{m}.e)_{in} - \sum(\dot{m}.e)_{out}$
	Exergy efficiency	$\varepsilon = \frac{e_{out}^{\Delta T} - e_{in}^{\Delta T}}{e_{in}^{\Delta P} - e_{out}^{\Delta P}}$

$$\dot{C}_{in} = c_{in}\dot{E}_{in} = c_{in}\left(\dot{m}_i e_i\right) \tag{7}$$

$$\dot{C}_{out} = c_{out}\dot{E}_{out} = c_{out}\left(\dot{m}_{out} e_{out}\right) \tag{8}$$

$$\dot{C}_w = c_w\dot{E}_W = c_w W \tag{9}$$

$$\dot{C}_q = c_q\dot{E}_q \tag{10}$$

Where c is the average costper unit of exergy. Based on these equations, the cost balance equation for *kth* component is presented according to Equation (11) [52].

$$\dot{C}_{q,k} + \sum_i \dot{C}_{i,k} + \dot{Z}_k = \dot{C}_{w,k} + \sum_e \dot{C}_{e,k} \tag{11}$$

Eq. (12) is used to convert equipment investment cost to cost per time unit. In this equation, $\dot{Z}_k$ represents the investment cost rate for *kth* equipment [53]. Furthermore, it is calculated as Eq. (12).

$$\dot{Z}_k = \frac{Z_k^0 \times CRF \times \phi}{3600 \times \tau} \tag{12}$$

Where, Z_k^0 is the initial capital cost of equipment in USD. Moreover, the capital recovery factor is obtained according to the below equation [54]. According to studies by the Economic Trading Institute shown in Fig. 2, the interest rate in Iran, is 18%. The coefficients used in Eqs (12) and (13) are as shown in Table 5. ϕ and τ are maintenance factor, and equipment's total annual operating hours, respectively.

$$CRF = \frac{i \times (1+i)^N}{(1+i)^N - 1} \tag{13}$$

Table 5: Coefficients and economic constants of the NGL plant.

Coefficient	unit	value
Plant life time	Year	25
Total annual operating hours of the system including overhaul time	Hour	7300
Interest rate[55]	%	18
Maintenance factor [20]	-	1.06

Fig. 2: Interest rate in Iran during 1996 to 2020, according to studies of the Economic Trading Institute [55].

The initial capital costs are thermodynamic functions of various equipment design characteristics, both direct and indirect. Eqs (17), (18), and (19) are used to compute the equipment's initial cost. According to these equations, the basic cost is corrected by the pressure rating and construction material [56]. This assessment is called Bare Module Cost Factor classified by *Turton* [57].

$$\mathrm{CEPCI} \times C_P^0 F_{BM} = \mathrm{CEPCI} \times \left[C_P^0 \left(B_1 + B_2 F_M F_P \right) \right] \tag{14}$$

$$\log C_P^0 = \left[K_1 + K_2 \left(\log A \right) + K_3 \left(\log A \right)^2 \right] \tag{15}$$

$$\mathrm{og}\, F_P^0 = \left[C_1 + C_2 \left(\log P_{max} \right) + C_3 \left(\log P_{max} \right)^2 \right] \tag{16}$$

Where, F_P, and F_M are correction factors for operating pressure and material, respectively. B_1, B_2, K_1, K_2, K_3, C_1, C_2, and C_3 in Equations (14) - (16) are cost evaluation coefficients. These coefficients were previously determined in the study by Turton [58]. Moreover, according to Equation (20), CEPCI (Chemical Engineering Plant Cost Index) values are equal to 668 and 397 for 2020 and 2009, respectively [57, 59, 60]. Table 6 lists all of the parameters that were used in the basic costs.

$$\mathrm{CEPCI} = \frac{\mathrm{CEPCI}_{2020}}{\mathrm{CEPCI}_{2009}} \tag{17}$$

Also, the pressure correction factor for the vessels is calculated according to Eq. (18).

$$F_{P,vessels} = \frac{\dfrac{(P+1)D}{2\left(850 - 0.6(P+1)\right)} + 0.0315}{0.0063} \tag{18}$$

Where P is the vessel's maximum pressure and D is the vessel's diameter [62, 63].

In the following, the cost balance equation based on fuel and product definitions is rewritten as follows [64]:

$$\dot{C}_{P,k} = \dot{C}_{F,k} + \dot{Z}_k \tag{19}$$

Hence, the average cost per unit of fuel and product is obtained according to Eqs (20) and (21) [65].

$$c_{F,k} = \frac{\dot{C}_{F,k}}{\dot{E}_{F,k}} \tag{20}$$

$$c_{P,k} = \frac{\dot{C}_{P,k}}{\dot{E}_{P,k}} \tag{21}$$

After determining the exergy loss, the cost of this inefficiency is determined according to Eq. (22) [64].

$$\dot{C}_{D,k} = c_{F,k} \dot{E}_{D,k} \tag{22}$$

Where $\dot{C}_{D,k}$ he is the cost rate of the exergy destruction rate.

A linear matrix in the form of an equation is created by combining the cost balance equations of the equipment with their auxiliary Eq. (23).

$$\left[\dot{E}_k\right] \times \left[c_k\right] = \left[\dot{Z}_k\right] \tag{23}$$

Where $\left[\dot{E}_k\right]$, $\left[c_k\right]$ and $\left[\dot{Z}_k\right]$ are the exergy rate matrices, costs per exergy unit vector, and investment cost rate vector of the *kth* component, respectively.

Regarding the greater number of unknowns in these equations, auxiliary equations are used based on the fuel and product subset equations. To complete the additional auxiliary equations are presented in Table 7.

Table 6: Cost evaluation coefficients for bare module cost of NGL plant equipment [58, 61].

Component	Compressors	Heat exchanger	Pump	Kettle reboiler	Process vessel
K_1	2.2897	4.3247	3.3892	4.4646	3.4974
K_2	1.3604	-0.303	0.0536	-5277	0.4485
K_3	-0.1027	0.1634	0.1538	0.3955	0.1074
C_1	-	0.03881	-0.03935	0.03881	Pressure factor is according to equation (18).
C_2	-	-0.11272	0.3957	-0.1127	
C_3	-	0.08183	-0.00226	0.08183	
B_1	-	1.36	1.89	1.36	2.25
B_2	-	1.66	1.35	1.66	1.82
F_M	-	1.35	1	1.75	3.1
F_{BM}	2.8	-	-	-	
Capacity, A unit	power, kW	Area, m^2	power, kW	Area, m^2	Area, m^2

Table 7: Auxiliary equation Constants for economic analysis.

Parameter	Unit	Value
Cost per exergy unit of electricity [64]	($/GJ)	25
Cost per exergy unit of heat load [66]	($/GJ)	2.056

Exergoeconomic evaluation

Based on the matrix outputs in Eq. (23), two economic evaluation parameters can be calculated. The relative increases in average fuel and product costs can be presented by relative cost differences. This parameter is important for evaluating and optimizing equipment costs [20].

$$r_{k,c} = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} \tag{24}$$

Exergoeconomic factor expresses the ratio among non-exergy costs (including maintenance costs and investment costs) to the total cost of equipment (which includes exergy destruction costs) [20].

$$f_{k,c} = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}} \tag{25}$$

High values of this parameter indicate that the cost of maintenance and equipment purchase is higher than the cost of inefficiency. To reduce process costs, the cost of investment should be reduced. The low values of this index indicate the impact of inefficiency costs of this equipment, and the performance of this equipment should be reviewed.

Exergoenvironmental analysis

The environmental impacts of process equipment are obtained by adapting thermodynamic definitions with two perspectives of Life Cycle Assessment (LCA) and equipment inefficiencies. This combination can express the environmental impacts of equipment's operation and maintenance along with its inefficient effects on the environment from a thermodynamical point of view.

Life Cycle Assessment (LCA)

This life cycle assessment is a method of evaluating industrial processes [67]. This method can consider the impact of NGL plant equipment on the environment during its service life (destruction, operation and maintenance, and disposal). Eco-indicator 99 is a popular method for assessing the life cycle of equipment and identifying its inefficient impact on the environment [18, 24].

The environmental impacts of kth equipment can be calculated as Eq. (26) which w_k and y_k are the equipment weight and environmental impact per mass of equipment [68].

$$Y_k = w_k \times y_k \tag{26}$$

Eco-indicator method categorizes environmental impact into construction Y_k^{Co}, operation and maintenance Y_k^{OM}, and final disposal parts Y_k^{Di} [69].

$$Y_k^{TOT} = Y_k^{Co} + Y_k^{OM} + Y_k^{Di} \tag{27}$$

Table 8: Eco-indicator for NGL plant equipment.

Component	Material (mPts/kg)			Process (mPts/kg)	Disposal (mPts/kg)	Total (mPts/kg)
	Material composition	Eco indicator [70]	points			
Heat exchanger [71]	Steel 67% Copper 33%	86 1400	519	12.1	−70	461.1
Condenser[71]	Steel 100%	86	86	12.1	−70	28.1
Pump [71]	Steel 35% Cast iron 65%	86 240	186	16.9	−70	132.9
compressor[72]	steel 33.3% Steel low alloy 44.5% Cast iron 22.2%	86 110 240	130	11.7	-70	71.7
demethanizer [69]	Steel 100%	86	86	12.1	-70	28.1

Table 9: The weight equations of NGL plant's equipment.

Component	Weight function
Pump[72]	$w_{pump} = 0.125.\ln(\dot{W}) - 0.041 \quad \text{ton, kW}$
Heat exchanger[69]	$w_{HE} = 2.14.Q^{0.7} \quad \text{ton, kW}$
Cooler[71]	$w_{HE} = 0.073.Q^{0.99} \quad \text{ton, MW}$
Compressor	Calculated by HYSYS software
Column	Calculated by HYSYS software

Considering the estimated equipment lifetime as 25 years, in which the operational period is 7300 h per year (considering overhaul hours); the environmental impact of a kth component will be changed into the environmental impact rate by Eq. (28) [70].

$$\dot{Y}_k = \frac{Y_k^{TOT}}{N \times \tau} \tag{28}$$

The related LCA environmental impacts damage categories are weighted and expressed as Eco-indicator points (mPts or Pts) in Tables 8 and 9.

Environmental impact balance equation is expressed in Eq. (29). This equation is reformed as Eq. (30) in according to fuel and product parameters.

$$\dot{B}_{q,k} + \sum_i \dot{B}_{i,k} + \dot{Y}_k = \dot{B}_{w,k} + \sum_e \dot{B}_{e,k} \tag{29}$$

$$\dot{B}_{k,P} = \dot{B}_{k,F} + \dot{Y}_k \tag{30}$$

Where $\dot{B}_{k,P}$, $\dot{B}_{k,F}$ are the product and fuel environmental impacts rate. Easily, the unit fuel environmental impact ($b_{k,F}$) and unit product environmental impact ($b_{k,P}$) can be calculated as follows:

$$b_{k,F} = \frac{\dot{B}_{k,F}}{\dot{E}_{k,F}} \tag{31}$$

$$b_{k,P} == \frac{\dot{B}_{k,P}}{\dot{E}_{k,P}} \tag{32}$$

After extracting all main and auxiliary equations, they can be converted into the form of a linear matrix of Eq. (33).

$$\left[\dot{E}_k\right] \times \left[b_k\right] = \left[\dot{Y}_k\right] \tag{33}$$

Where, $\left[\dot{Y}_k\right]$ and $\left[b_k\right]$ are the vectors of environmental impact and unit environmental impact of *kth* component, respectively.

Exergoenvironmental evaluation

Based on r_k, f_b, $\dot{B}_D$, $\dot{B}_{TOT}$ parameters, exergoenvironmental analysis assesses the environmental impact of the process. According to equation (34), $\dot{B}_{k,D}$ considers the inefficiency of *kth* component in terms of the environmental impact rate $\dot{B}_{k,TOT}$, depicts each component's overall environmental impacts and calculates as equation (35). This parameter indicates the potential for improvement of environmental impacts of *kth* component [20].

$$\dot{B}_{k,D} = b_{k,F} \dot{E}_{k,D} \tag{34}$$

$$\dot{B}_{k,TOT} = \dot{B}_{k,D} + \dot{Y}_k^{TOT} \tag{35}$$

The relative difference is the environmental effect, which may be used to determine the equipment's ability to reduce environmental impact. It depicts the relative differences between fuel and product in terms of environmental impact. The higher rate of this parameter shows the equipment environmental operational problems [73].

$$r_{k,b} = \frac{b_{k,P} - b_{k,F}}{b_{k,F}} \quad (36)$$

According to Eq. (37) exergoenvironmental factor indicates the ratio of non-exergy-related environmental impacts ($\dot{Y}_k$) to total impacts ($\dot{Y}_k + \dot{B}_{k,D}$). And shows which aspect of the environment is dominant [20].

$$f_{k,b} = \frac{\dot{Y}_k^{TOT}}{\dot{Y}_k^{TOT} + \dot{B}_{k,D}} \quad (36)$$

RESULTS AND DISCUSSION

Exergy evaluation

In this study, exergy rates of the streams were computed and carried out in ASPEN HYSYS, Microsoft Excel, and MATLAB software. The results are shown in Table 10. The highest and lowest exergy rates belong to stream 18(1,843,867 kW) and stream 20 (0 kW), respectively. The reason for the low-level exergy rate in stream 20 is its low flow rate.

Product, fuel, and exergy destruction equations based on the NGL plant equipment are presented in Table 11. Using these equations will investigate two main parameters of exergy efficiency and exergy destruction.

The results of the main equipment, analysis are presented in Table 12. The exergy destruction percentage of other equipment is the least to consider for improvement. According to this table results, the highest exergy destruction rates are in compressors K103 and heat exchanger E-101 with 510 and 629 kW, respectively. The highest and lowest Exergy efficiency belongs to E104 and E101 heat exchangers, respectively.

Furthermore, the Grassmann diagram is a graphical illustration of the exergy flows of a system. In this diagram, the quantitative and qualitative evaluation of the exergy loss of equipment is made according to the first and second laws of thermodynamics [74]. Hence, it helps the reader to easily identify where the system's highest exergy destruction is located [75]. The width of flow arrows

Table 10: Summarized exergy analysis of process and cryogenic cycle streams.

Stream No.	Physical exergy(kW)	Chemical exergy(kW)	Total exergy(kW)
15(Feed stream)	8672.3	1834696	1843368
16	8559.3	1834696	1843255
17	8678.5	1834696	1843375
18	9170.4	1834696	1843867
19	4536.2	589253	593789.2
20	3863.6	1246656	1250520
21	1.8	34.1	35.9
22	3854	1246656	1250510
23	0.1	20.4	20.4
24	4529	589232.6	593761.6
25	4358.7	589232.6	593591.3
26	855.6	114293.6	115149.2
27(Sale gas)	5145.2	703526.2	708671.4
28	2334.7	1132771	1135105
29	2526.5	1132771	1135297
30(NGL product)	2553.2	1132771	1135324
P1	4338.2	1650154	1654493
P2	853.2	324531.5	325384.7
P3	3485	1325623	1329108
P4	813.2	324531.5	325344.7
P5	3264	1325623	1328887
P6	0	0	0
P7	4049.3	1650154	1654204
P8	3942.2	1650154	1654096
P9	125.6	56791.3	56916.9
P10	3816.6	1593363	1597180
P11	2371.3	989974.3	992345.6
P12	1445.3	603388.7	604834
P13	2300.2	989974.3	992274.5
P14	1402	603388.7	604790.6
P15	1551.9	989974.3	991526.2
P16	1254.2	509105.2	510359.4
P17	1210.6	509105.2	510315.8
P18	361.3	509105.2	509466.5
P19	1699.7	1084258	1085958
P20	0	0	0
P21	361.3	509105.2	509466.5
P22	777.3	509105.2	509882.5
P23	2472.5	1593363	1595835
P24	3520.6	1593363	1596884
P25	3645.6	1650154	1653800
P26	5583	1650154	1655737
P27	5583	1650154	1655737

Table 11: Fuel, product and exergy destruction equations of NGL plant equipments.

Component	$\dot{E}_F$	$\dot{E}_p$	$\dot{E}_D$
E-100	$\dot{E}_{15} - \dot{E}_{16}$	$\dot{E}_{25} - \dot{E}_{24}$	$\dot{E}_{15} + \dot{E}_{24} - \dot{E}_{25} - \dot{E}_{16}$
E-101	$\dot{E}_{16} - \dot{E}_{17}$	$\dot{E}_{P15} - \dot{E}_{P13}$	$\dot{E}_{16} + \dot{E}_{P13} - \dot{E}_{17} - \dot{E}_{P15}$
E-102	$\dot{E}_{17} - \dot{E}_{18}$	$\dot{E}_{P18} - \dot{E}_{P17}$	$\dot{E}_{17} + \dot{E}_{P17} - \dot{E}_{18} - \dot{E}_{P18}$
E-103	$\dot{E}_{P2} - \dot{E}_{P4}$	$\dot{E}_{30} - \dot{E}_{29}$	$\dot{E}_{P2} + \dot{E}_{29} - \dot{E}_{30} - \dot{E}_{P14}$
VLV-100	$\dot{E}_{15}$	$\dot{E}_{22}$	$\dot{E}_{20} - \dot{E}_{22}$
VLV-101	$\dot{E}_{P7}$	$\dot{E}_{P8}$	$\dot{E}_{P7} - \dot{E}_{P8}$
VLV-102	$\dot{E}_{P12}$	$\dot{E}_{P14}$	$\dot{E}_{P12} - \dot{E}_{P14}$
VLV-103	$\dot{E}_{P11}$	$\dot{E}_{P13}$	$\dot{E}_{P11} - \dot{E}_{P13}$
VLV-104	$\dot{E}_{P16}$	$\dot{E}_{P17}$	$\dot{E}_{P16} - \dot{E}_{P17}$
MIX-100	$\dot{E}_{P4} + \dot{E}_{P5} + \dot{E}_{P6}$	$\dot{E}_{P7}$	$\dot{E}_{P4} + \dot{E}_{P5} + \dot{E}_{P6} - \dot{E}_{P7}$
MIX-100	$\dot{E}_{P19} + \dot{E}_{P22}$	$\dot{E}_{P23}$	$\dot{E}_{P19} + \dot{E}_{P22} - \dot{E}_{23}$
MIX-101	$\dot{E}_{25} + \dot{E}_{26}$	$\dot{E}_{27}$	$\dot{E}_{25} + \dot{E}_{26} - \dot{E}_{27}$
MIX-102	$\dot{E}_{P19} + \dot{E}_{P22}$	$\dot{E}_{P23}$	$\dot{E}_{P19} + \dot{E}_{P22} - \dot{E}_{P23}$
MIX-103	$\dot{E}_{P9} + \dot{E}_{P24}$	$\dot{E}_{P25}$	$\dot{E}_{P9} + \dot{E}_{P24} - \dot{E}_{P25}$
TEE-100	$\dot{E}_{P1}$	$\dot{E}_{P2} + \dot{E}_{P3}$	$\dot{E}_{P1} - \dot{E}_{P2} - \dot{E}_{P3}$
TEE-101	$\dot{E}_{P10}$	$\dot{E}_{P11} + \dot{E}_{P12}$	$\dot{E}_{P10} - \dot{E}_{P11} - \dot{E}_{P12}$
TEE-102	$\dot{E}_{P25}$	$\dot{E}_{P6} + \dot{E}_{P27}$	$\dot{E}_{P26} - \dot{E}_{P6} - \dot{E}_{P27}$
K-101	$\dot{W}_{K101}$	$\dot{E}_{P22} - \dot{E}_{P21}$	$\dot{W}_{K101} - \dot{E}_{P22} + \dot{E}_{P21}$
K-102	$\dot{W}_{K102}$	$\dot{E}_{P24} - \dot{E}_{P23}$	$\dot{W}_{K102} - \dot{E}_{P22} + \dot{E}_{P23}$
K-103	$\dot{W}_{K103}$	$\dot{E}_{P26} - \dot{E}_{P25}$	$\dot{W}_{K103} - \dot{E}_{P26} + \dot{E}_{P25}$
P-100	$\dot{W}_{P100}$	$\dot{E}_{29} - \dot{E}_{28}$	$\dot{W}_{P100} - \dot{E}_{29} + \dot{E}_{28}$
E-104	$\dot{E}_{Q-E104}$	$\dot{E}_{P5} - \dot{E}_{P3}$	$\dot{E}_{P3} + \dot{E}_{Q-E104} - \dot{E}_{P5}$
E-105	$\dot{E}_{Q-E105}$	$\dot{E}_{P1} - \dot{E}_{P27}$	$\dot{E}_{Q-E105} + \dot{E}_{P27} - \dot{E}_{P1}$
V-100	$\dot{E}_{18}$	$\dot{E}_{19} + \dot{E}_{20} + \dot{E}_{21}$	$\dot{E}_{18} - \dot{E}_{19} - \dot{E}_{20} - \dot{E}_{21}$
V-101	$\dot{E}_{19}$	$\dot{E}_{23} + \dot{E}_{24}$	$\dot{E}_{19} - \dot{E}_{23} - \dot{E}_{24}$
V-102	$\dot{E}_{P8}$	$\dot{E}_{P9} + \dot{E}_{P10}$	$\dot{E}_{P8} - \dot{E}_{P9} - \dot{E}_{P10}$
V-103	$\dot{E}_{P14} + \dot{E}_{P15}$	$\dot{E}_{P19} + \dot{E}_{P16}$	$\dot{E}_{P14} + \dot{E}_{P15} - \dot{E}_{P19} - \dot{E}_{P16}$
V-104	$\dot{E}_{P18}$	$\dot{E}_{P20} + \dot{E}_{P21}$	$\dot{E}_{P18} - \dot{E}_{P20} - \dot{E}_{P21}$
T-100	$\dot{E}_{Q-T-100} + \dot{E}_{22}$	$\dot{E}_{26} + \dot{E}_{28}$	$\dot{E}_{22} + \dot{E}_{Q-T-100} - \dot{E}_{26} - \dot{E}_{28}$

Table 12: The exergetic results of NGL plant main equipment.

Component	Exergy destruction (kW)	Exergy efficiency (%)
Rotary machines		
P100	69.19	73.49
K101	152.85	73.13
K102	345.48	75.21
K103	509.99	79.16
Heat exchangers		
E100	283.25	66.31
E101	629.04	15.93
E102	357.46	57.91
E103	13.24	66.88
E104	420.65	90.33
E105	228.39	84.5
Columns		
T100	455.39	80.01

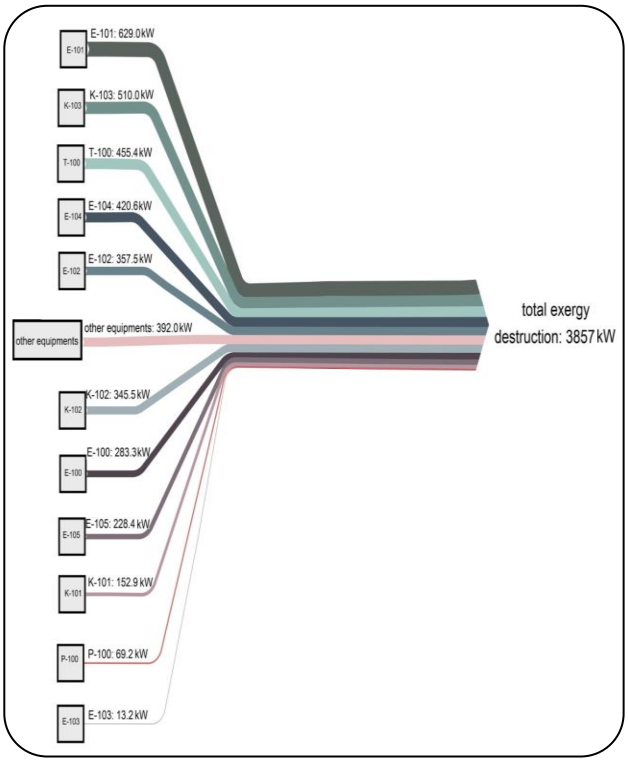

Fig. 3: Grassmann diagram of the main component exergy destruction.

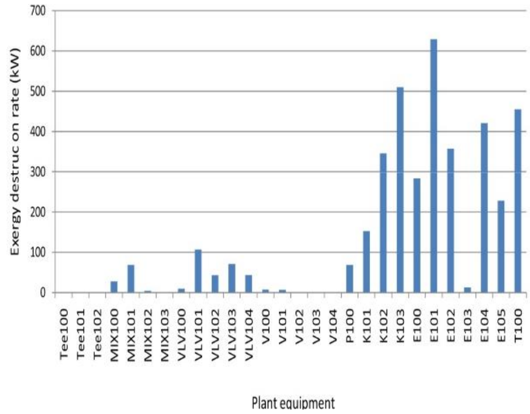

Fig. 4: The exergy destruction rate of NGL plant's equipment.

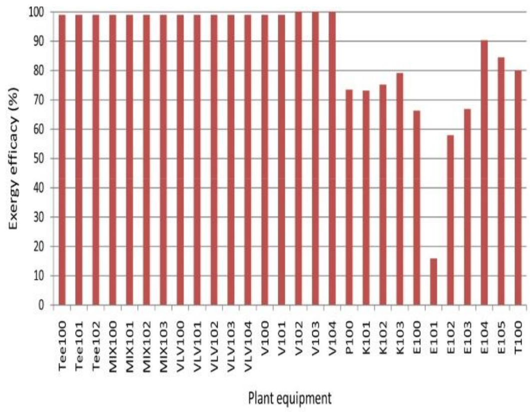

Fig. 5: The exergy efficiency of NGL plant's equipment.

represented the amount of the stream's exergy. According to Fig. 3, NGL plant main equipment's exergy destruction is modeled in e! Sankey Pro.

The detailed exergy destruction and exergy efficiency values of the NGL plant's types of equipment are presented in Figs. 4 and 5. As can be seen in the figures, the lowest exergy efficiency belongs to heat exchanger E101 which has caused its high exergy destruction.

The performance assumptions for rotary and heat-exchanging equipment are shown in Table 13. This table can be used for accessing the concepts of exergy in the equpments.

Fig. 6 shows the heat exchangers' exergy destruction and exergy efficiency variation with ΔTmin. It could be seen that decreasing the ΔTmin will increase the efficiency, and decreases the exergy destruction part. It shows that more attention shall be concentrated on improving heat exchangers' performance due to the exergy concepts.

Table 13: Assumptions for calculating endogenous and unavoidable exergy destruction the actual, theoretical and unavoidable conditions [76].

Components, *k*	Actual conditions	Ideal conditions
Pump	η_{is}= 75%	η_{is}= 100%
Compressor	η_{is}= 75%	η_{is}= 100%
Heat exchanger	ΔT_{min}=real	ΔT_{min}=0 K
	ΔP=real	ΔP=0 kPa

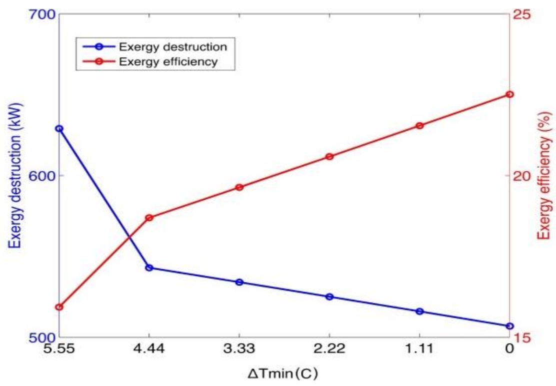

Fig. 6: Effect of ΔTmin on the exergy parameters of the heat exchanger (E-102).

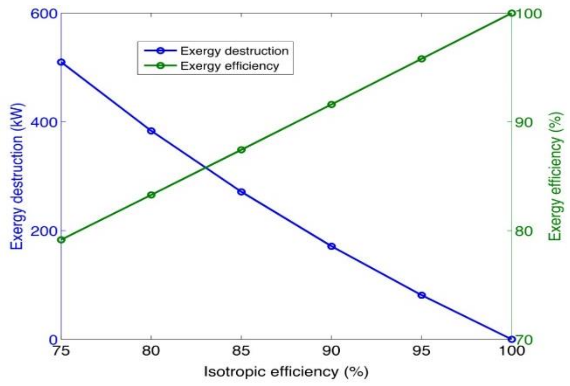

Fig. 7: Effect of isotropic efficiency on the exergy parameters of the compressor (K103).

Also, Fig. 7 displays a change in the compressor's isentropic efficiency with exergy destruction and exergy efficiency. Increasing compressors̉ efficiency will increase exergy efficiency and decrease exergy destruction. This shows that more attention shall be focused on the performance of these equipment in terms of the exergy concepts.

On the other hand, improving compressor performance will dramatically reduce exergy destruction.This shows that this equipment has the main priority, for having qualified energy consumption.

Exergoeconomic analysis results

The main equations and auxiliary equations used forcost balance of each device are shown in Table 14.

Moreover, Table 15 represents the value of the exergy rate, the unit exergy cost, and the exergy cost rate of the streams of the NGL equipment. The highest cost rate belongs to flow 18 (533049.9&/h). It is because of its high exergy rate.

Table 16 represents the exergoeconomic variables of the equipment. According to this table, E103 has the highest exergoeconomic factor value. It shows that the non-exergy costs of this equipment are higher than other equipment. In this sense, this equipment should be replaced by cheaper equipment. Or the related cost indicators of the equipment should be reviewed, (including the capital, operating, and maintenance costs). In addition, for equipment with the smallest coefficient of exergoeconomic factor, the performance improvement of these types of equipment should be evaluated.

In this regard, E100 and K102 were reviewed. These equipment have a high rate of exergy destruction and a high rate of relative cost difference. It indicates the potential for optimizing the associated costs. And their exergoeconomic factor values dominatet the exergy-related cost part.

Figs. 8. (a-e) show the E100 heat exchangers' exergoeconomic parameters variation with ΔTmin. Fig. 8 a shows the potential of this equipment to improve exergy concepts by modifying the performance. According to this figure, by decreasing ΔTmin, exergy destruction decreases, and exergy efficiency increases. Normally, reducing exergy destruction directly affects the exergy

Table 14: Exergoeconomic cost balance main and auxiliary equation of the NGL plant equipment.

Device	Main equation	Auxiliary equation
E-100	$\dot{C}_{15}+\dot{C}_{24}+\dot{Z}_{E100}=\dot{C}_{16}+\dot{C}_{25}$	$c_{15}=c_{16}$
E-101	$\dot{C}_{16}+\dot{C}_{P13}+\dot{Z}_{E101}=\dot{C}_{17}+\dot{C}_{P15}$	$c_{16}=c_{17}$
E-102	$\dot{C}_{17}+\dot{C}_{P17}+\dot{Z}_{E102}=\dot{C}_{18}+\dot{C}_{P18}$	$c_{17}=c_{18}$
E-103	$\dot{C}_{29}+\dot{C}_{P2}+\dot{Z}_{E103}=\dot{C}_{30}+\dot{C}_{P4}$	$c_{P2}=c_{P4}$
E-104	$\dot{C}_{P3}+\dot{C}_{Q-E104}+\dot{Z}_{E104}=\dot{C}_{P5}$	c_{Q-E104} = 2.056 ($/GJ)
E-105	$\dot{C}_{P27}+\dot{C}_{Q-E105}+\dot{Z}_{E105}=\dot{C}_{P28}$	c_{Q-E105} = 2.056 ($/GJ)
VLV-100	$\dot{C}_{20}=\dot{C}_{22}$	none
VLV-101	$\dot{C}_{P7}=\dot{C}_{P8}$	none
VLV-102	$\dot{C}_{P12}=\dot{C}_{P14}$	none
VLV-103	$\dot{C}_{P11}=\dot{C}_{P13}$	none
VLV-104	$\dot{C}_{P16}=\dot{C}_{P17}$	none
K-101	$\dot{C}_{W-K101}+\dot{C}_{P21}+\dot{Z}_{K101}=\dot{C}_{P22}$	c_{W-K101} = 25 ($/GJ)
K-102	$\dot{C}_{W-K102}+\dot{C}_{P23}+\dot{Z}_{K102}=\dot{C}_{P24}$	c_{W-K102} = 25 ($/GJ)
K-103	$\dot{C}_{W\_K103}+\dot{C}_{P25}+\dot{Z}_{K103}=\dot{C}_{P26}$	c_{W-K103} = 25 ($/GJ)
MIX-100	$\dot{C}_{P4}+\dot{C}_{P5}+\dot{C}_{P6}=\dot{C}_{P7}$	none
MIX-101	$\dot{C}_{25}+\dot{C}_{26}=\dot{C}_{27}$	none
MIX-102	$\dot{C}_{P19}+\dot{C}_{P22}=\dot{C}_{P23}$	none
MIX-103	$\dot{C}_{P9}+\dot{C}_{P24}=\dot{C}_{P25}$	none
P-100	$\dot{C}_{W-P100}+\dot{C}_{28}+\dot{Z}_{P100}=\dot{C}_{29}$	c_{W-P100} = 25 ($/GJ)
TEE-100	$\dot{C}_{P1}=\dot{C}_{P2}+\dot{C}_{P3}$	$c_{P2}=c_{P3}$
TEE-101	$\dot{C}_{P10}=\dot{C}_{P11}+\dot{C}_{P12}$	$c_{P11}=c_{P12}$
TEE-102	$\dot{C}_{P26}=\dot{C}_{P6}+\dot{C}_{P27}$	$c_{P6}=c_{P27}$

Table 15: Values of exergy rate, unit exergy cost andexergy cost rate of the for the NGL plant's streams.

Stream number	Total exergy(kW)	c ($/GJ)	C($/h)
15	1843368.369	80.304	532905.903
16	1843255.428	80.304	532873.253
17	1843374.625	80.304	532907.712
18	1843866.475	80.304	533049.903
19	593789.202	80.284	171619.441
20	1250519.777	80.284	361430.462
21	35.867	0	0
22	1250510.154	80.285	361430.462
23	20.435	2332841.893	171619.441
24	593761.598	0.015	33.046
25	593591.283	0.097	207.881
26	115149.175	80.302	33288.097
27	708671.353	13.061	33320.75
28	1131805.225	83.302	339413.355
29	1135297.002	80.207	327811.56
30	1136923.731	80.092	327811.233
P1	1654492.477	0.007	40.693
P2	325384.658	0.004	4.489
P3	1329107.82	0.004	18.336
P4	325344.693	2.918	3418.056
P5	1328886.812	0.004	20.823
P6	0	0.004	0
P7	1654203.584	0.037	220.282
P8	1654096.434	0.037	220.282
P9	56916.866	1.075	220.282
P10	1597179.569	0.09	520.091
P11	992345.584	0.09	320.281
P12	604833.985	0.09	195.211
P13	992274.461	0.091	323.83
P14	604790.636	0.091	197.374
P15	991526.225	0.01	34.457
P16	510359.374	0.006	11.016
P17	509466.474	0.005	9.182
P18	510911.474	0.255	469.028
P19	1085957.487	0.006	23.44
P20	0	0	0
P21	509466.474	0.024	43.16
P22	509882.544	0.056	101.995
P23	1595835.446	0.022	125.436
P24	1596883.565	0.125	718.733
P25	1653799.861	0.037	220.282
P26	1655737.245	0.09	536.613
P27	1655737.245	0.004	21.055

Table 16: The results of exergoeconomic evaluation of the NGL plant main equipments.

Equipment ID	$\dot{Z}(\$/h)$	$\dot{C}_d$ $(\$/h)$	$\dot{C}^{TOT}$ $(\$/h)$	c_F ($/GJ)	c_P ($/GJ)	r_c (%)	f_c (%)
P100	0.002	6.227	6.229	25	922.946	3591.782	0.033
K101	0.006	13.757	13.763	25	39.28	57.119	0.046
K102	0.012	31.093	31.105	25	246.113	884.45	0.04
K103	0.018	45.899	45.917	25	45.355	81.419	0.04
E100	0.002	81.887	81.89	80.304	285.15	255.089	0.003
E101	0.006	181.851	181.857	80.304	107.428	33.777	0.003
E102	0.004	103.34	103.344	80.304	88.398	10.08	0.004
E103	0.004	0	0.004	0.004	0.056	1356.986	95.752
E104	0.144	3.113	3.257	2.056	3.126	52.033	4.422
E105	0.021	1.69	1.711	2.056	4.382	113.151	1.22
T100	0.003	86.244	86.247	52.607	83.025	0.578	0.003

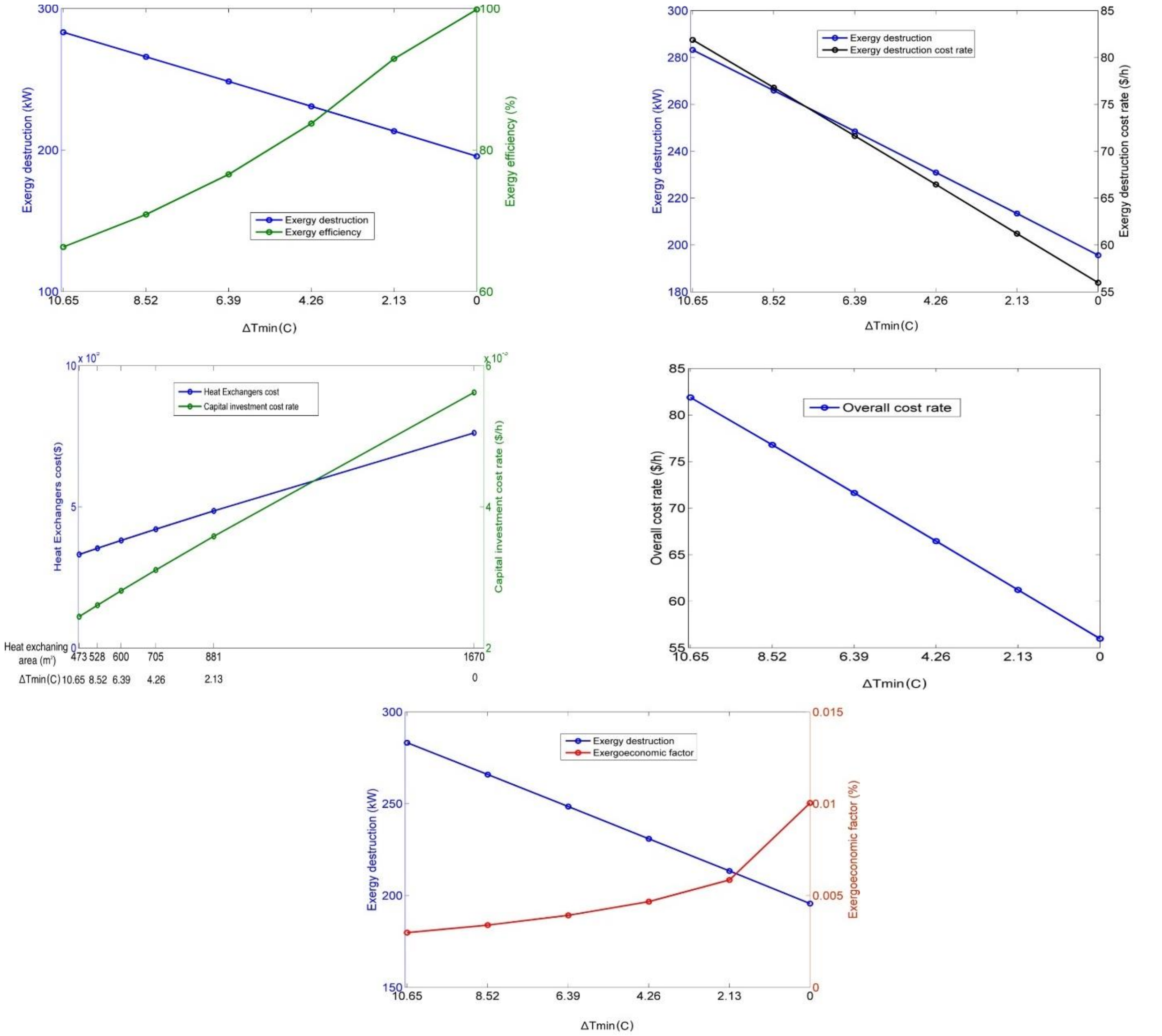

Fig. 8: a) Effect of ΔTmin variation on the exergy parameters of the heat exchanger (E-100). b) Effect of ΔTmin variation on the exergy destruction and exergy destruction cost rate of the heat exchanger (E-100). c) Effect of ΔTmin variation on the heat exchanging area, heat exchanger'scost and capital investment rate of the heat exchanger (E-100). d) Effect of ΔTmin variation on the overall cost rate of the heat exchanger (E-100). e) Effect of ΔTmin variation on the exergy destruction and exergoeconomic factor of the heat exchanger (E-100).

destruction cost rate decrement (Fig. 8.b). On the other hand, decreasing the ΔTmin is inversely increases the final capital investment cost and capital investment cost rate of the heat exchanger. This can be seen in Fig. 8.c. Finally, in according to Fig. 8.d, the overall cost rate of equipment will be significantly reduced by improving performance. The reduction in exergy destruction costs dominates over the capital investment cost rate. It results in increasing the exergoeconomic factor (Fig. 8.e).

Figs. 9. (a-e) shows the compressor K102 exergoeconomic parameters variation with isentropic efficiency. Improving compressor(K102) performance is the same as the heat exchanger(E100). Modifying the performance will decrease, the rate of exergy destruction, the rate of exergy destruction costs, and the overall cost rate. The difference is that according to Fig. 9.c, compressor costs and capital investment cost rates decrease with modifying the isentropic efficiency of the compressor.

On the other hand, the exergoeconomic factor slope in the compressor (K102) is much higher than the heat exchanger (E100). This indicates its main priority of improving based on exergoeconomic concepts belongs to the compressor(K102).

Sensitivity analysis was performed on operating and maintenance capital costs associated with equipment (lifetime, interest rate). According to the results of Figs. 10a, 10b, 11a, 11b, operating life changes do not significantly change the capital cost rate. Hence, the improvement focus should be on the interest rate.

Exergoenvironmental evaluation results

Similarly, for solving the exergoenvironmental analysis, the main and auxiliary equations must be extracted. Tables 17 and 18 show the environmental impact balance equations for the NGL plant equipment.

The values of the stream's exergy rate, unit environmental effect, and environmental impact rate linked with the stream's exergy rate are shown in Table 19. Stream 18 (145,060 Pts/h) has the greatest environmental impact rate, according to these data.

Table 20 shows the exergoenvironmental variable results. According to this table, E103 has the highest exergoenvironmental factor value. The non-exergy-related environmental impact of this equipment is greater than the other equipment. In this sense, the relevant environmental impact indicators of the equipment should be reviewed (including equipment materials, service life, and operation and maintenance time).

Besides, some of the sequipment ha the smallest exergoenvironmental factor. Performance improvement assessments should be made for these types of equipment.

Table 20 shows that E101 and P100 have the greatest environmental effect. This inefficiency stems from their high rate of exergy loss and environmental impact relative difference. This shows their potential for improvement. Furthermore, they have low values of exergoenvironmental factors, which indicate the predominance of their exergy-related part. In this regard, performance improvement sensitivity analysis was assessed for these equipments.

Fig. 12 shows the E101 heat exchangers' exergoenvironmental parameters variation with ΔTmin. Fig. 12.a shows E101 heat exchanger's potential to improve exergy concepts. According to this figure, by decreasing ΔTmin, exergy destruction decreases, and exergy efficiency increases.Normally, reducing exergy destruction causes the exergy destruction environmental impact decrement(Fig. 12.b). But, decreasing ΔTmin value, increases the heat exchanger's area and consequently increases its weight and environmental impact rate. This can be seen in Fig. 12.c.

The decrease in exergy destruction's environmental effect rate dominates the component's environmental impact rate, as seen in Fig. 12.d. As a result, by boosting performance, the equipment's total environmental impact rate will be greatly lowered. On the other hand, the results of Fig. 12.e show that reducing the exergy destruction increases the exergoenvironmental factor.

Finally, the results of Fig. 12 show that changing the performance of this equipment can affect the environmental impacts very sufficiently.

Fig. 13 shows P100 pump environmental parameters variation with isentropic efficiency. The environmental results of improving compressor(P100) performance are the same as the heat exchanger(E101). By modifying its performance, the exergy destruction, the rate of exergy environmental impact, and the overall environmental impact rate dramaticallydecrease. However, the difference is that the pump's weight and environmental impact rates decrease with modifying the isentropic efficiency of the pump. (Fig. 13.c) On the other hand, exergoeconomic factor slope in the heat-exchanger (E101) is much higher than the pump (P100). This indicates its main priority of improving based on environmental impact concepts.

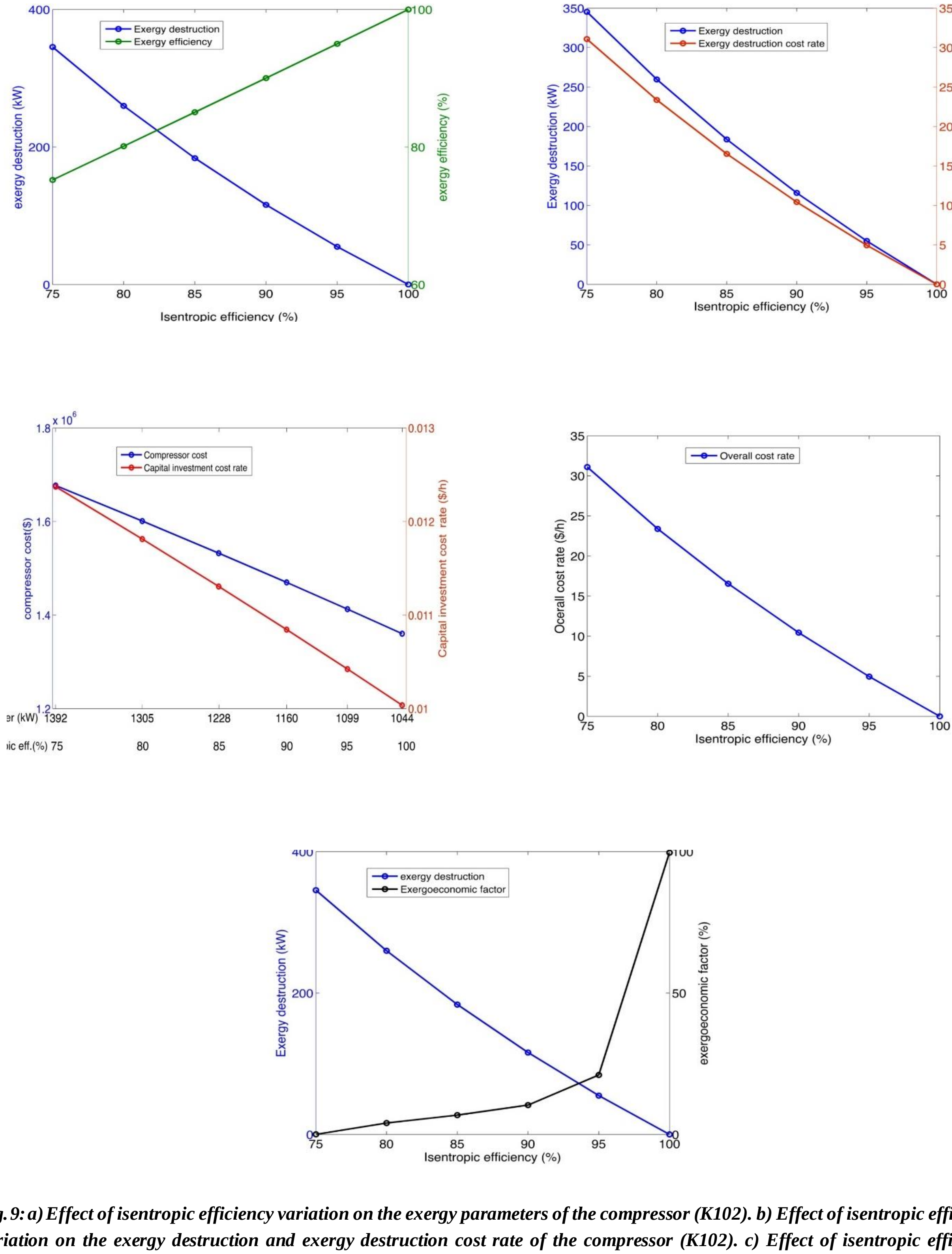

***Fig. 9:** a) Effect of isentropic efficiency variation on the exergy parameters of the compressor (K102). b) Effect of isentropic efficiency variation on the exergy destruction and exergy destruction cost rate of the compressor (K102). c) Effect of isentropic efficiency variation on the compressor's power, compressor's cost and capital investment rate of the compressor (K102). d) Effect of isentropic*

efficiency variation on the overall cost rate of the compressor (K102). e) Effect of isentropic efficiency variation on the exergoeconomic factor of the compressor (K102).

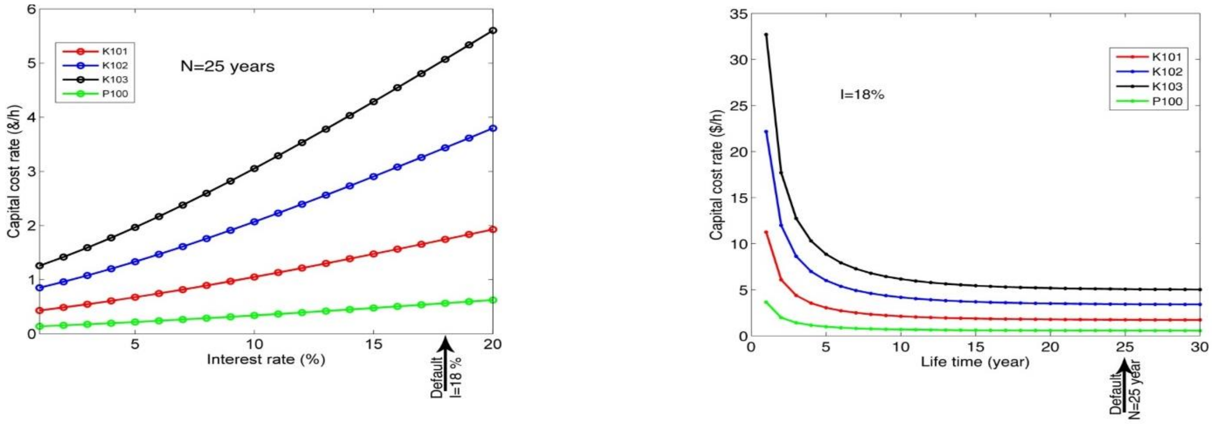

Fig. 10: a) Effect of interest rate variation on capital cost rate of rotational equipments.
b) Effect of life time variation on capital cost rate of rotational equipments.

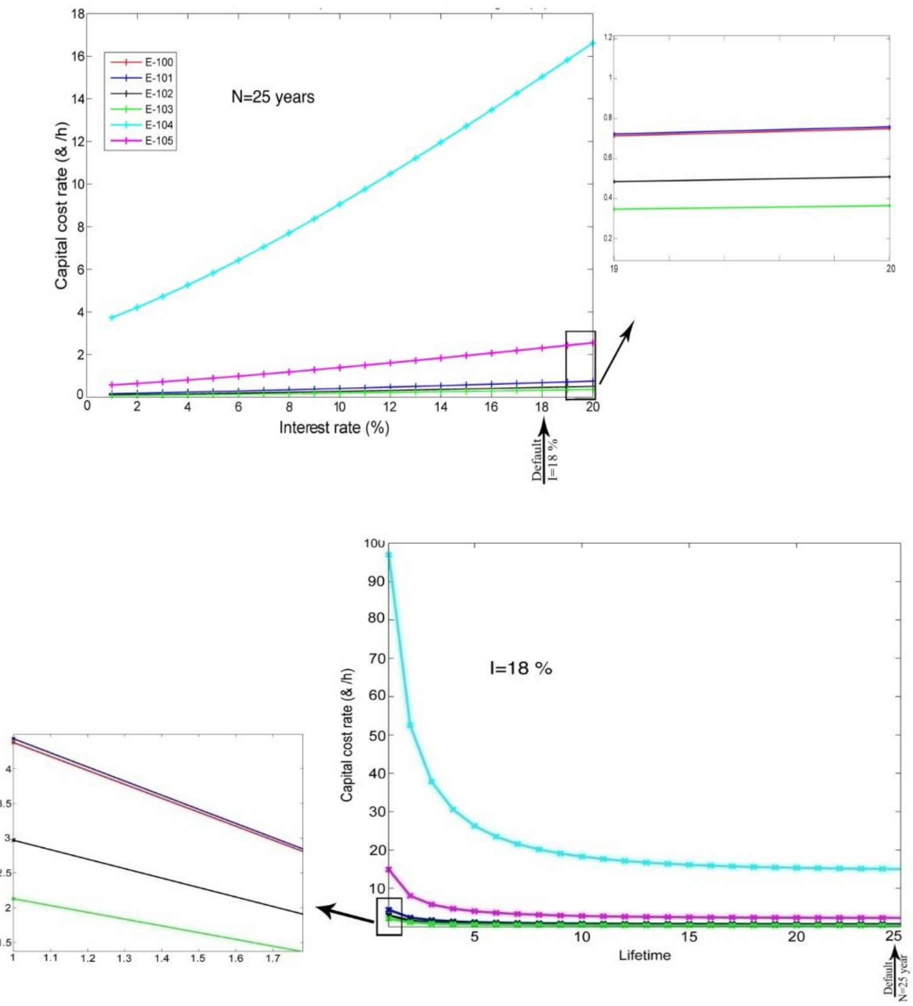

Fig. 11: a) Effect of interest rate variation on capital cost rate of heat exchanging equipments.
b) Effect of life time variation on capital cost rate of heat exchanging equipments.

Table 17: Environmental impact balance equations of the NGL plant equipment.

Equipment ID	Main equations	Auxiliary equations
E-100	$\dot{B}_{15}+\dot{B}_{24}+\dot{Y}_{E100}=\dot{B}_{16}+\dot{B}_{25}$	$b_{15}=b_{16}$
E-101	$\dot{B}_{16}+\dot{B}_{P13}+\dot{Y}_{E101}=\dot{B}_{17}+\dot{B}_{P15}$	$b_{16}=b_{17}$
E-102	$\dot{B}_{17}+\dot{B}_{P17}+\dot{Y}_{E102}=\dot{B}_{18}+\dot{B}_{P18}$	$b_{17}=b_{18}$
E-103	$\dot{B}_{29}+\dot{B}_{P2}+\dot{Y}_{E103}=\dot{B}_{30}+\dot{B}_{P4}$	$b_{P2}=b_{P4}$
P-100	$\dot{B}_{W\_P100}+\dot{B}_{28}+\dot{Y}_{P100}=\dot{B}_{29}$	$b_{W-P100}=$ 6206 (mPts/GJ)
K-101	$\dot{B}_{W-K101}+\dot{B}_{P21}+\dot{Y}_{K101}=\dot{B}_{P22}$	$b_{W-K101}=$ 6206 (mPts/GJ)
K-102	$\dot{B}_{W-K102}+\dot{B}_{P23}+\dot{Y}_{K102}=\dot{B}_{P24}$	$b_{W-K102}=$ 6206 (mPts/GJ)
K-103	$\dot{B}_{W-K103}+\dot{B}_{P25}+\dot{Y}_{K103}=\dot{B}_{P26}$	$b_{W-K103}=$ 6206 (mPts/GJ)
VLV-100	$\dot{B}_{20}=\dot{B}_{22}$	*none*
VLV-101	$\dot{B}_{P7}=\dot{B}_{P8}$	*none*
VLV-102	$\dot{B}_{P12}=\dot{B}_{P14}$	*none*
VLV-103	$\dot{B}_{P11}=\dot{B}_{P13}$	*none*
VLV-104	$\dot{B}_{P16}=\dot{B}_{P17}$	*none*
MIX-100	$\dot{B}_{P4}+\dot{B}_{P5}+\dot{B}_{P6}=\dot{B}_{P7}$	*none*
MIX-101	$\dot{B}_{25}+\dot{B}_{26}=\dot{B}_{27}$	*none*
MIX-102	$\dot{B}_{P19}+\dot{B}_{P22}=\dot{B}_{P23}$	*none*
MIX-103	$\dot{B}_{P9}+\dot{B}_{P24}=\dot{B}_{P25}$	*none*
TEE-100	$\dot{B}_{P1}=\dot{B}_{P2}+\dot{B}_{P3}$	$b_{P2}=b_{P3}$
TEE-101	$\dot{B}_{P10}=\dot{B}_{P11}+\dot{B}_{P12}$	$b_{P11}=b_{P12}$
TEE-102	$\dot{B}_{P26}=\dot{B}_{P6}+\dot{B}_{P27}$	$b_{P6}=b_{P27}$
E-104	$\dot{B}_{P3}+\dot{B}_{Q-E104}+\dot{Y}_{E104}=\dot{B}_{P5}$	$b_{Q-E104}=$ 5320(mPts/GJ)
E-105	$\dot{B}_{P27}+\dot{B}_{Q-E105}+\dot{Y}_{E105}=\dot{B}_{P28}$	$b_{Q-E105}=$ 5320(mPts/GJ)
V-100	$\dot{B}_{18}+\dot{Y}_{V100}=\dot{B}_{19}+\dot{B}_{20}+\dot{B}_{21}$	$b_{21}=0$
V-101	$\dot{B}_{19}+\dot{Y}_{V101}=\dot{B}_{23}+\dot{B}_{24}$	*none*
V-102	$\dot{B}_{P8}+\dot{Y}_{V102}=\dot{B}_{P9}+\dot{B}_{P10}$	$b_{P10}=0$
V-103	$\dot{B}_{P14}+\dot{B}_{P15}+\dot{Y}_{V103}=\dot{B}_{P19}+\dot{B}_{P16}$	$b_{P19}=b_{P16}$
V-104	$\dot{B}_{P18}+\dot{Y}_{V104}=\dot{B}_{P21}+\dot{B}_{P20}$	$b_{P20}=0$
T-100	$\dot{B}_{22}+\dot{B}_{Q\_E104}+\dot{Y}_{T100}=\dot{B}_{26}+\dot{B}_{28}$	$b_{Q-E104}=$ 5320(mPts/GJ)

Table 18: Auxiliary equation constants forEnvironmental analysis.

Parameter	Unit	Value

Environmental impact per exergy unit of electricity[20]	(mPts/GJ)	6206
Environmental impact per exergy unit of heat load[20]	(mPts/GJ)	5320

Table 19: Values of exergy rate, Unit environmental impact and Environmental impact rate associated with exergy of the NGL plant's streams.

Stream number	Total exergy(kW)	b (mPts/GJ)	B (Pts/h)
15	1843368.369	21853.318	145021.4
16	1843255.428	21853.318	145012.5
17	1843374.625	21853.318	145021.9
18	1843866.475	21853.318	145060.6
19	593789.202	21848.074	46703.34
20	1250519.777	21848.074	98357.22
21	35.867	0	0
22	1250510.154	21848.242	98357.22
23	20.435	634843653	46703.34
24	593761.598	6.591	14.088
25	593591.283	0	0
26	115149.175	81853.562	33931.33
27	708671.353	3554.743	9068.921
28	1131805.225	21853.562	89042.31
29	1135297.002	21851.297	89307.76
30	1136923.731	21850.872	89433.99
P1	1654492.477	4.737	28.214
P2	325384.658	4.737	5.549
P3	1329107.82	4.737	22.665
P4	325344.693	4.737	5.548
P5	1328886.812	1.537	7.353
P6	0	0	0
P7	1654203.584	9.182	54.679
P8	1654096.434	9.182	54.679
P9	56916.866	266.855	54.679
P10	1597179.569	0	0
P11	992345.584	0	0
P12	604833.985	0	0
P13	992274.461	0	0
P14	604790.636	0	0
P15	991526.225	23.917	85.37
P16	510359.374	1.19	2.187
P17	509466.474	7.191	13.225
P18	510911.474	71.369	130.897
P19	1085957.487	1.19	4.654
P20	0	0	0
P21	509466.474	31.369	57.534
P22	509882.544	14.427	26.482
P23	1595835.446	5.42	31.136
P24	1596883.565	0	0
P25	1653799.861	9.184	54.679

P26	1655737.245	0	0
P27	1655737.245	0	0

Table 20: The results of exergoenvironmental analysis ofNGL plant main equipments.

Component ID	$\dot{Y}\left(mPts/h\right)$	$\dot{B}_d\left(mPts/h\right)$	$\dot{B}^{TOT}\left(mPts/h\right)$	$b_F\left(mPts/GJ\right)$	$b_P\left(mPts/GJ\right)$	r_b (%)	f_b (%)
P-100	0.477	1545.855	1546.332	6206	21117.17	240.27	0.031
K-101	0.312	3414.988	3415.3	6206	56090.52	803.811	0.009
K-102	0.522	7718.465	7718.987	6206	8251.725	32.964	0.007
K-103	0.576	11393.98	11394.555	6206	7839.726	26.325	0.005
E-100	925.308	22284.198	23209.505	21853.318	22977.79	5.146	3.987
E-101	2536.413	49487.702	52024.115	21853.318	31693.05	45.026	4.875
E-102	1689.19	28122.317	29811.508	21853.318	24742.32	13.22	5.666
E-103	365.673	0.226	365.899	4.737	21554.4	454927.4	99.938
E-104	0.047	8056.222	8056.269	5320	19245.73	261.762	0.001
E-105	0.109	4374.161	4374.27	5320	6296.146	18.349	0.002
T-100	1.509	44539.963	44541.471	27168.242	27394.22	0.832	0.003

On the other hand, exergoeconomic factor slope in the heat-exchanger(E101) is much higher than the pump(P100). This indicates its main priority of improving based on environmental impact concepts.

According to Table 20, some of the equipment have high LCA environmental impacts. And, their high value of exergoenvironmental factor's shows the domination of non-exergy related parts. To decrease the environmental impact rate associated with equipment, either lighter equipment should be used or revise the operational and maintenance parameters.

Fig. 14 shows the heat exchanger (E103) overall environmental impact rate variation with LCA environmental impacts parameters. According to this figure, changing the heat exchanger material has the most influence on improving the overall environmental impact rate. Comparing the current operational condition with the final improved state in this equipment shows that the overall environmental impact rate will be reduced up to 97% by applying all related changes.

Compared to this study, a review of similar considerations shows the following result. *Mehrpooya et al.* [77] reached similar results in considering the effects of interest rate and lifetime variation on capital cost rate. Their findings revealed that extending the life of a plant lowers the capital cost rate. In addition, when the interest rate rises, so does the capital cost rate.

Hashemi et al. [64] considered the effect of acid gas preheater ΔTmin on exergoeconomic factor, and the cost rate of exergy destruction. Their study shows that modifying the performance can decrease the exergy destruction and increase the exergoeconomic factor. The consideration of this study shows similar results in Fig. 12. e.

Khajehpour et al. [78] comprised the environmental impact of various complex energy system units. Their considerations show that the lowest environmental emission belongs to the unit which has the highest exergy efficiency.

Hamut et al. [79] considered the thermal management of the hybrid electric vehicle. Minimum overall environmental impacts accrue on the highest exergy efficiency. The consideration of our study show similar results in Fig. 13.d

CONCLUSIONS

This paper evaluated the economic and environmental impact of the NGL plant's equipment by exergoeconomic and exergoenvironmental analyses. Furthermore, the equipment with high inefficiency is assessed by sensitivity analysis. Summary of these analyzes is resulted in the following.

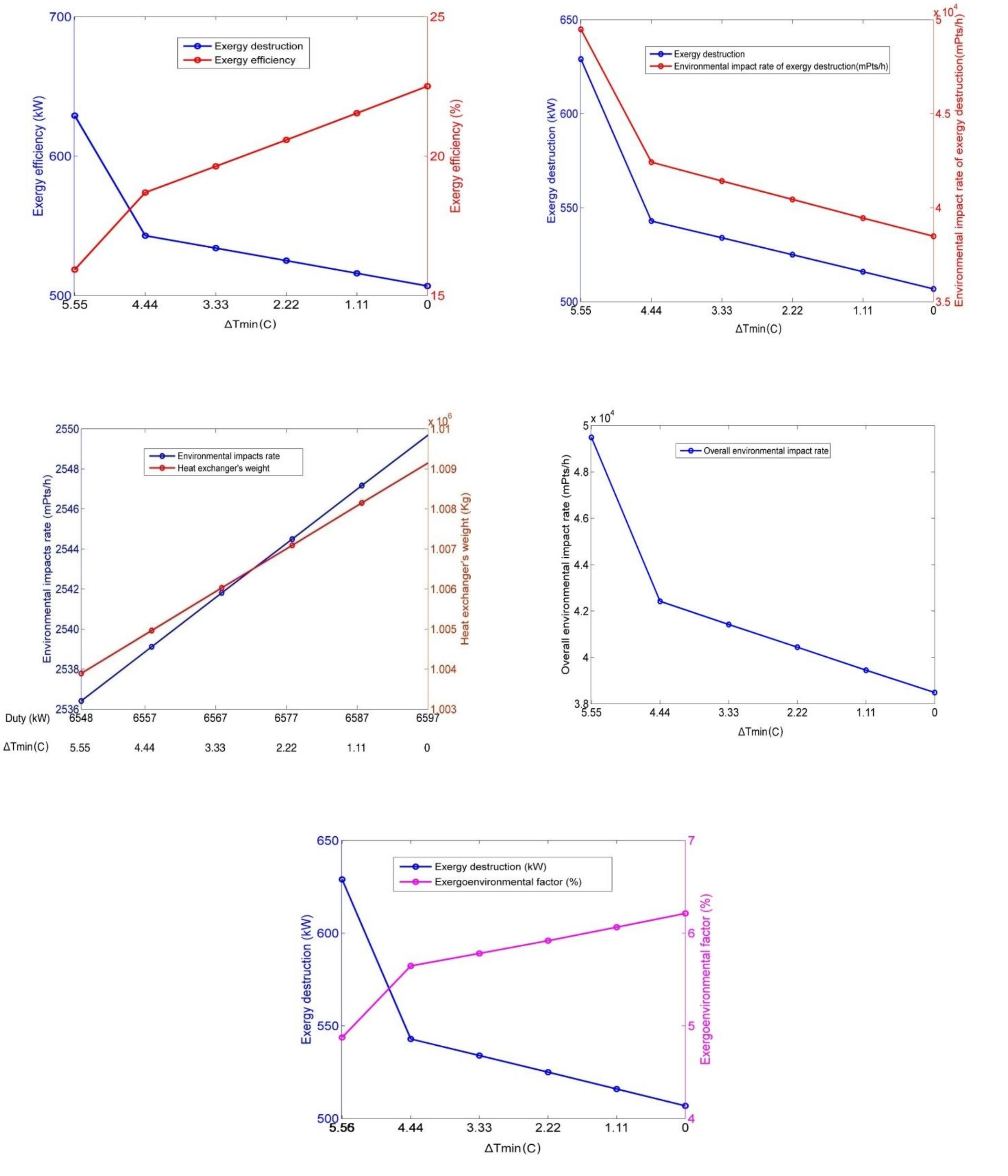

Fig. 12: a) Effect of ΔTmin variation on the exergy parameters of the heat exchanger (E-101). b) Effect of ΔTmin variation on the exergy destruction and environmental impact rate of exergy destruction of the heat exchanger (E-101). c) Effect of ΔTmin variation on the heat exchanging duty, heat exchanger's weight and environmental impact rate of the heat exchanger (E-101). d) Effect of ΔTmin variation on the overall environmental impact rate of the heat exchanger (E-101). e) Effect of ΔTmin variation on the exergy destruction and exergoenvironmental factor of the heat exchanger (E-101).

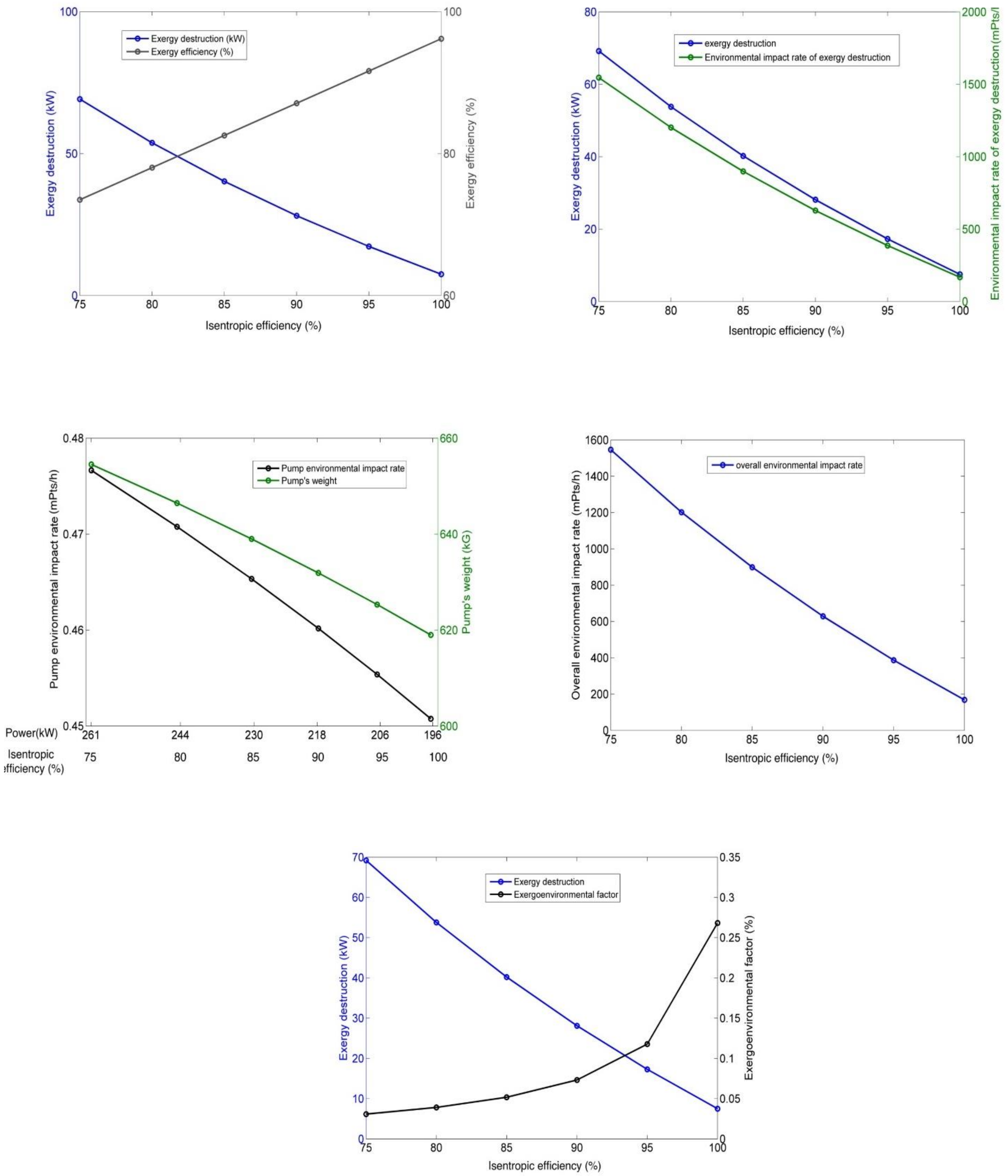

Fig. 13: a) Effect of isentropic efficiency variation on the exergy parameters of the pump (P-100). b) Effect of isentropic efficiency variation on the exergy destruction and environmental impact rate of exergy destruction of the pump (P-100). c) Effect of isentropic efficiency variation on the pump duty, pump's weight and environmental impact rate of the pump (P-100). d) Effect of isentropic efficiency variation on the overall environmental impact rate of the pump (P-100). e) Effect of isentropic efficiency variation on the exergy destruction and exergoenvironmental factorof the of the pump (P-100).

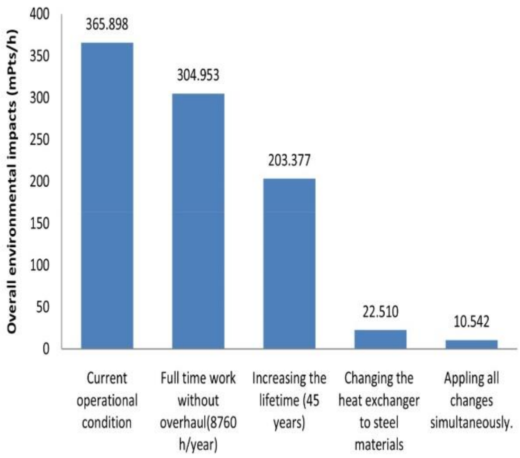

Fig. 14: Effect of LCA environmental impacts sensitivity analysis onheat exchanger (E-103).

1- Exergy analysis results show that the highest amount of exergy destruction belonged to compressors (K103) and heat exchangers (E-101) with 510 and 629 kW, respectively, Improving the performance of this equipment decreases the exergy destruction and increases the exergy efficiency.

2- According to the results of the exergoeconomic evaluation, the maximum value exergoeconomic factor (f) belongs to the heat exchanger (E103). It should be replaced by a cheaper one.Furthermore, E100, K102 have low values of exergoeconomic factor which dominant the exergy-related cost part. The sensitivity analyzes show that improving the performance of these equipment will dramatically decrease the overall cost rate.

3- The highest value of exergoenvironmental factor (F) belongs to the heat exchanger (E-103) by 99%. The sensitivity analyzes show that the overall environmental impact rate can be reduced up to 97% by optimizing related parameters. Moreover, inefficiencies of the E101 and P100 have great environmental impacts. The sensitivity analyses show that improving the performance of this equipment will decrease the overall environmental impact rate.

Nomenclature

°C	Temperature in Celsius
e_i^0	Standard chemical exergy, kJ/kg mol
Gi	Gibbs free energy, kJ/kg mol
h	Specific enthalpy, kJ/kg mol
HEN	Heat Exchanging Network
K	Temperature in Kelvin
kPa	Pressure in kilopascal
kW	Power in Kilowatt
$\dot{m}$	Molar Flow rate, kmol/s
MW	Power in Megawatt
NGL	Natural Gas Liquid
P	Propane
P	Pressure in Kilopascal
PFD	Process flow diagram
PR-EOS	Peng-Robinson equation of state
PSI	Pound per square inch
Q	Heat load, kW
s	Specific entropy, kJ/kmol.K
T	Temperature, K
Tcf	Trillion cubic feet
W	Work, kW
Yi	Mole fraction of component i

Greek symbols

ε	Exergy efficiency, %
η_{is}	Isotropic efficiency, %
ΔTmin	Minimum approach temperature, °C

Subscripts

0	Ambient condition
C	Cold
Ch	Chemical
D	Destruction
F	Fuel
H	Hot
i	Inlet
in	Inlet
Ke	Kinetic
L	Loss
o	Outlet
out	Outlet
P	Product
Ph	Physical
Po	Potential

Abbreviations used for process flow diagrams

E	Heat exchanger, Reboiler, and condenser
K	Compressor
MIX	Mixer
P	Pump
T	Demethanizer column
TEE	Tee

V	Separators and flash drum
VLV	Throttle valve

Abbreviation used for exergoenvironmental evaluations

b	Unit environmental impact, mPts/GJ
$\dot{B}$	Environmental impact rate associated with exergy, mPts/h
f_b	Exergoenvironmental factor, %
LCA	Life cycle assessment
N	Lifetime, year
Pts	Persistent toxic substances
r_b	Relative environmental impacts difference, %
y	Environmental impact per mass, mPts/kg
Y	Environmental impact, mPts
$\dot{Y}$	Environmental impact rate, mPts/h
w	Weight, kg

Greek symbols

τ	Annual operating hours, h

Subscripts

b	Environmental

Superscript

Co	Construction
Di	Disposal
OM	Operation and maintenance
Tot	Total

Abbreviation used for exergoeconomic evaluations

$\dot{C}$	Exergy cost rate, $/h
C	Unit exergy cost, $/GJ
CEPCI	Chemical engineering plant cost index
CRF	Capital recovery factor, -
D	Diameter, m
F_c	Exergoeconomic factor, %
F_{BM}	Bare modules factor
F_m	Correction factors for material
F_P	Correction factors for operating pressure
i	Interest rate, %
N	Lifetime, year
P	Operating pressure, Barg
PEC	Purchased equipment cost, $
rc	Relative cost difference, %
USD	U.S.A Dollar
Z	Purchased equipment cost, $
$\dot{Z}$	Capital investment cost flow rate, $/h

Greek symbols

φ	Maintenance factor, -

Subscripts

Cost	Cost

Superscript

$\dot{Z}_k^0$	Initial equipment cost, $
Tot	Total

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