

Assessing Exergy-Based Economic and Sustainability Analyses of a Military Gas Turbine Engine Fueled with Various Fuels

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Abstract: This research put forth exergy-based economic and sustainability analyses of a (J85-GE-5H) military turbojet engine (TJE). Firstly, sustainability, conventional exergoeconomic and advanced exergoeconomic cost analyses were executed utilizing kerosene fuel according to real engine working circumstances. The engine was likewise investigated parametrically, considering H₂ fuel utilization. The sustainable economic analysis assessment of the TJE was finally actualized by comparing the acquired outcomes for both fuels. The entire engine's unit exergy cost of product (c_{pr}) with kerosene was determined 76.45 \$/GJ for the military (MIL) process mode (PM), whereas it was computed 94.97 \$/GJ for the afterburner (AB) PM. Given the use of H₂, the c_{pr} increased to 179 and 288 \$/GJ for the aforementioned two modes, seriatim. While the sustainability cost index (SCI) values were obtained 52.86 and 78.84 \$/GJ for the MIL and AB PM, seriatim, they became 128 and 244 \$/GJ when considering H₂. Consequently, the higher exergy demolitions occurring in the afterburner exhaust duct (ABED) and combustion chamber (CC) sections led to higher exergy destruction costs in the TJE. However, the engine worked less cost efficient with H₂ fuel rather than JP-8 fuel because of the higher cost value of fuel.

Keywords: turbojet engine; sustainability analysis; performance assessment; advanced exergoeconomic analysis; H₂ fuel; cost effectiveness

1. Introduction

Energy is an underlying phenomenon in thermodynamics and the production phase of energy is based on the notable applications of engineering examination. The systems which generate power are designed simple in order to convert energy into another. Regardless of energy, type and mode of production, it takes place in every aspect of life as a parameter that constitutes the most important agenda of our near future. The increase in energy demand is directly proportional to technological development, population and economic growth. In this context, the increase in global warming and air pollution has become the focus of energy analysis because of post-combustion products released into the atmosphere [1–4]. Aviation, standing out as the sector that creates the most energy consumption and the most pollution, is the main field of international research [5–11]. In order to provide the basis for sustainable environment-friendly policies, the road map provided in the 2018 report predicts that fossil energy resources will provide a significant share in energy production by the 2040s [12]. Energy engineers must deal with the reduction of oil reserves in the world by taking into account the increase in oil prices and environmental concerns by that time. This then draws the

attention of researchers as an important issue, waiting to be resolved. Therefore, the importance of using alternative energy sources after exhaustion of fossil fuels stands out at this point. In this regard, hydrogen fuel, as a least-contaminant and eco-friendly resource, has been considered in research to alter these challenges. Fuel cell systems have become prominent in these studies with feasible results [13–24]. However, as time goes by, it has been determined that hydrogen has its disadvantages as well as its advantages [25–30]. The difficulties in obtaining and storing the hydrogen have become the serious challenges to be solved in aviation sector [31–33].

As is well-known, thermodynamic principles, on which the aircraft propulsion systems are based, are regarded as potent methods to assess systems in terms of efficiency and sustainability aspects. However, the performance analysis is the simultaneous evaluation of the energy efficiency obtained from energy sources and the cost effectiveness. Therefore, researchers aim to minimize the cost formation and environmental effects of aircraft engines in order to get maximum efficiency from the system by implementing design improvements and configuration changes [34–40]. This sustainable target can be achieved by using the highest quality fuel with the lowest fuel rate, reducing the exergy consumptions and minimizing the cost of investment regardless of the type of fuel utilized. Therefore, from an integrated viewpoint, aircraft engines have been considered and evaluated in scientific research not only with thermodynamic analysis but also with economic analysis. In accordance with the thermodynamic rules, exergy analysis is carried out to put forth the irreversible processes leading to exergy destructions in the system [41–47]. However, the interpretation of the irreversible processes will be completed by the implementation of the economic analysis. Economic analysis ensures cost values for investment, operating and maintenance and exergy flows. Exergoeconomic analysis, which integrates exergy and economic analyses, has been carried out in the gas turbine system to highlight the significant sections to be improved [37,48–53]. Researchers can perform a more comprehensive analysis by examining the interactions of sections with each other in terms of the value of exergy destructions as well as the value of investment costs in a gas turbine engine. Although the cost value of inefficiencies as a result of thermodynamic irreversible processes can be examined by conventional exergoeconomic analysis, further evaluation can only be attained via advanced exergoeconomic analysis by examining the provenance of the irreversible processes and recovery capacity in terms of cost to get accurate results [54–62].

In contrast to prior research, the J85-GE-5H turbojet engine's (TJE) comparative cost analyses, taking into account advanced exergoeconomic analyses by using hydrogen fuel, have not been perceived in the course of the literature review. The main significance and the individuality of this research can be summarized by numerically analyzing the mentioned analyses as follows:

- Reckon the exergy destruction costs of the entire engine and sections;
- Investigate the exergy, exergoeconomic and sustainability performance parameters for the military (MIL) and afterburner (AB) process modes (PM) for both kerosene and hydrogen fuel utilizations;
- Assign advanced exergoeconomic cost rates of the entire engine and sections by breaking them down to unavoidable/avoidable and exogenous/endogenous portions;
- Check the advanced exergoeconomic cost rates for both kerosene and hydrogen fuel utilizations;
- Reveal the sections that can be ameliorated by calculating economic benefit of amelioration potential (EBAP) for JP-8 and H₂ fuels.

2. Methodology

2.1. Specification of TJE

(J85-GE-5H) TJE has high impulse and lightness characteristics provided by the integrated eight-level axial compressor and two-level axial turbine. The compressor (AC) and gas turbine (GT) consist of rotor (moving) and stator (fixed) blades. Rows of rotor and stator fins form a stage. There are six cellular-circular combustion chambers (CC) between the AC and the GT. The second part, where post-combustion occurs, is called the afterburner exhaust duct (ABED). The burning process takes

place in the orbicular CC and ABED sections. The basic configuration sections that form the TJE are as listed below:

- Compressor (AC)
- Combustion chamber (CC)
- Gas turbine mechanical shaft (GTMS)
- Gas turbine (GT)
- Forward exhaust duct (FED)
- Afterburner exhaust duct (ABED)

The technical parameters are demonstrated as follows:

The power output was reckoned with the values of 5106 and 8575 kW for the MIL and AB PM, seriatim [63]. The take-off thrust is 25.80 kN, the outside diameter of the TJE is 0.52 m, the engine length is 2.75 m, the engine weight is 265 kg, the flight speed range is 301–1004 m/s, the maximum operating altitude is 45,000 ft and the starting altitude range is 0–25,000 ft [64].

In this study, a cost analysis of J85-GE-5H TJE, used in T-38 training aircraft, was assessed with regards to its thermodynamic and thermoeconomic aspects. In this context, exergy-based sustainability, exergoeconomic and advanced exergoeconomic analyses of the engine were executed by considering the calculated costs in line with the data obtained from the engine test unit. The experimental throughput has been displayed in the control unit in order to trace values such as pressure (P), mass rates ($\dot{m}$) and temperature (T), which have been obtained by indicators attached on the TJE. As the engine worked in the engine test cell, the inlet duct was not taken into account in the analysis [63]. The physicochemical properties of JP-8 and H₂ are indicated as follows:

The kerosene fuel consists of approximately 9% C₈–C₉ aliphatic hydrocarbons, 65% C₁₀–C₁₄ aliphatic hydrocarbons, 7% C₁₅–C₁₇ aliphatic hydrocarbons and 18% aromatics with molecular weight: ≈ 180 , synonyms: JP-8, freezing point maximum: -47 °C, boiling point: 175 – 300 °C, vapor pressure: 0.52 mm Hg (10 °C), 1.8 mm Hg (28 °C), specific gravity: minimum: 0.775 kg/L (15 °C), maximum: 0.840 kg/L (15 °C), the lower heating value (LHV) $119,450$ kJ/kg and viscosity: 8×10^{-6} kg/(m·s) (-20 °C) [65]. The liquefied hydrogen consists of two hydrogen atoms with molecular weight: 2.0159 , synonyms: H₂, melting point: -259.35 °C, boiling point: -252.88 °C, the LHV $43,124$ kJ/kg, density (gas): 0.08988 g/L (0 °C, 1 atm) and density (liquid): 70.8 g/L (at -253 °C) [66]. The air entering the engine is pressurized in the compressor section and passes to the combustion chamber section. Here, the mixture formed with pulverized sprayed JP-8 jet fuel is burned with spark plugs. The burnt gases expand in the GT and create mechanical work. While some of the mechanical work provides the movement of the AC and other engine accessories by rotating the mechanical shaft, the remaining part provides the necessary thrust for the flight. An extra impulse that may be needed depending on the flight characteristic is achieved by burning the sprayed AB fuel with the combustion gases in the ABED section. A basic cross section of TJE and the flow directions of air and gases are shown in Figure 1.

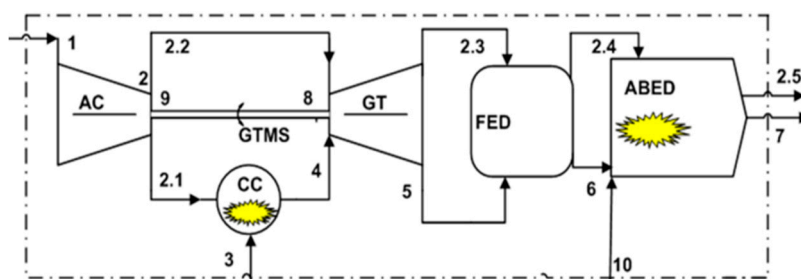


Figure 1. A simply view and flow diagram of the turbojet engine (TJE) [63].

2.2. The Flow Process of the Analyses

The main flow process of the analyses is charted as shown in Figure 2.

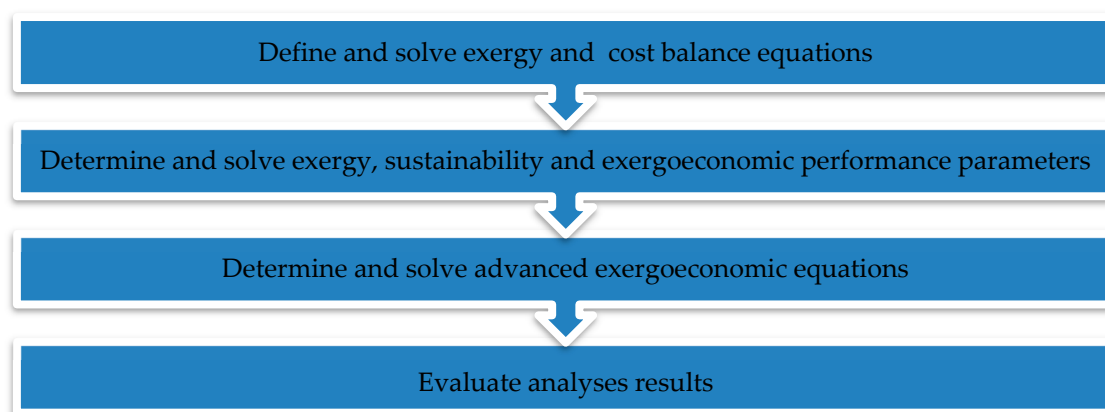


Figure 2. A flow process of the analyses.

The process starts with the definition of the process and ends up with the analyses of the outcomes of the study.

2.3. Assumptions Made

The listed assumptions are given as follows:

- Calculations for air and burnout gases were considered with the ideal gas assumption.
- The TJE operated under constant conditions.
- The fully burned gases were gained upon the completion of the operation.
- Not only in kinetic exergy but also in potential exergy, no changes occur.
- The inlet velocity (V_{in}) was considered zero because of the constant test conditions.
- The heat transfer ratios in AC and GT sections were regarded adiabatic [6,15].
- Kerosene and hydrogen are taken into account as fuels in this research.

2.4. Exergy Analysis

Exergy, an effective appliance, uses not only the second law of thermodynamics, but also the principles of mass and energy conservation. Exergy makes it possible to use the energy resources more efficiently by considering the best performance of the gas turbine systems because it can state the site and amount of wastes. In other words, the consumption of exergy leads to an entropy production as an output of the irreversible processes in a system. The general balance equation regarding the exergy is expressed as follows:

$$\sum_n \left(1 - \frac{T_o}{T_n} \right) \dot{Q}_n - \dot{W} + \sum_{in} \dot{Ex}_{in} - \sum_{out} \dot{Ex}_{out} - \dot{Ex}_D = 0 \quad (1)$$

The $\dot{Q}_n$, $\dot{W}$, $\dot{Ex}$ and $\dot{Ex}_D$ represent the ratio of heat transfer at T_n temperature, the ratio of work, the flow ratio of exergy and the ratio of exergy destruction, seriatim.

The equation regarding the exergy can be expressed as follows [15,41,42]:

$$\dot{Ex}_F = \dot{Ex}_{Pr} + \dot{Ex}_D \quad (2)$$

where $\dot{Ex}_F$ and $\dot{Ex}_{Pr}$ represent the ratio of fuel exergy and the ratio of product exergy, seriatim.

The $\dot{Ex}_L$ and $\dot{Ex}_C$ represent the exergy losses and exergy consumption, seriatim. The sum of $\dot{Ex}_L$ and $\dot{Ex}_D$ is $\dot{Ex}_C$ [6,63]:

$$\dot{Ex}_C = \dot{Ex}_D + \dot{Ex}_L \quad (3)$$

2.5. Conventional Exergoeconomic Analysis

The method of exergy analysis is utilized to assess thermodynamically the inefficiencies arising from irreversible processes. The assessment of the inefficiencies in the system by assigning cost values expresses the economic dimension of engineering analysis. The analysis method, which deals with the engineering analysis of the system integrated with exergy-based thermodynamic and economic analysis, is called exergoeconomic analysis. Exergoeconomic analysis takes into account all the expenditures made during the life cycle starting from the design phase of the system. It provides an extensive assessment opportunity. The types of costs can be determined by the exergoeconomic analysis method with (i) investment costs, (ii) maintenance and operating costs, (iii) exergy destruction costs and (iv) exergy loss costs [4,48,50]. There is more than one method in the literature related to the exergoeconomic analysis. The Specific Exergy Cost (SPECOC) method was applied in this research. This method involves determining the exergy flows inserting and outgoing the process and solving equilibrium equations and related auxiliary equations created for unit exergy cost value analysis [35]. With this scope, the hourly leveled cost methodology has been chosen and the regarding equations have been demonstrated in Table 1 [48,49,51,52].

Table 1. The hourly leveled cost parameters of the TJE.

Description	Unit	Equation	Equation No
The cost rate of exergy flow, $\dot{C}_n$	(\$/h)	$c_n \dot{E}x_n$	(4)
The hourly rate of total investment cost, $\dot{Z}_n^{TIC}$	(\$/h)	$\dot{Z}_n^{IC} + \dot{Z}_n^{OM}$	(5)
The hourly rate of the TJE's maintenance cost, $\dot{Z}_{TJE}^{OM}$	(\$/h)	$\frac{OM \dot{C}_{TJE}}{\tau}$	(6)
The hourly rate of maintenance cost, $\dot{Z}_n^{OM}$	(\$/h)	$\dot{Z}_{TJE}^{OM} \frac{TIC_n}{TIC_{TJE}}$	(7)
The hourly rate of the TJE's investment cost, $\dot{Z}_{TJE}^{IC}$	(\$/h)	$\frac{A \dot{C} C_{TJE}}{\tau}$	(8)
The hourly rate of investment cost, $\dot{Z}_n^{IC}$	(\$/h)	$\dot{Z}_{TJE}^{IC} \frac{TIC_n}{TIC_{TJE}}$	(9)
The total hourly rate of the TJE's investment cost, $\dot{Z}_{TJE}^{TIC}$	(\$/h)	$\dot{Z}_{TJE}^{IC} + \dot{Z}_{TJE}^{OM}$	(10)

The equations regarding the TJE and its sections' hourly cost rate method algorithms are given in Table 2.

Table 2. The cost methodology algorithms of the TJE.

Description	Unit	Equation	Equation No
The TJE's present worth, PW_{TJE}	(\$)	$TIC_{TJE} - SV_{TJE} PVF(i, n)$	(11)
The TJE's salvage value, SV_{TJE}	(\$)	$TIC_{TJE} SVR$	(12)
The TJE's present value factor, PVF	(-)	$\frac{1}{(1+i)^n}$	(13)
The TJE's yearly capital cost rate, $A \dot{C} C_{TJE}$	(\$/yr)	$PW_{TJE} CRF(i, n)$	(14)
Capital recovery factor, CRF	(-)	$\frac{i(i+1)^n}{(i+1)^n - 1}$	(15)
The cost rate of yearly fuel, $F \dot{C}$	(\$/yr)	$FP \dot{m}_F \tau 3600$	(16)

$$\text{The TJE's hourly fuel cost rate, } \dot{C}_F \quad (\$/h) \quad \frac{F\dot{C}}{\tau} \quad (17)$$

2.6. Economic Data

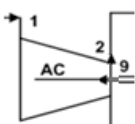
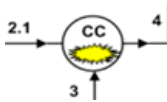
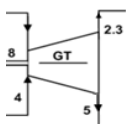
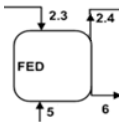
The TIC_{TJE} and $OM\dot{C}_{TJE}$ values of the TJE are 1,200,000 \$ and 72,000 \$/yr, seriatim [64]. The yearly working time of the system, the interest rate, the salvage value rate and the engine lifetime are assumed to be 300 h/yr, 10%, 15% and 15 years, seriatim. While the selling price of JP-8 is considered 0.572 \$/kg [64], it is considered to be 5.5 \$/kg for H₂ fuel [52]. The $\dot{C}_F$ of JP-8 are reckoned 10.26 and 10.10 \$/h for MIL and AB PM, seriatim, whereas they are calculated 10.16 and 16.54 \$/h. The cost of equipment and the hourly cost rates are shown in Table 3.

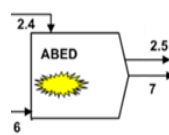
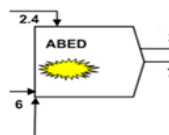
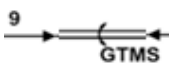
Tables A1 and A2 indicate the rates of energy, exergy, mass flow, pressure and specific heat capacity for the TJE sections, seriatim, in Appendix A [63]. The equations respecting exergy and cost balance are denoted in Table 4.

Table 3. The TJE and its sections' cost of equipment and the hourly cost rates.

SEC.	RC(%)	TIC(\$)	$\dot{Z}^{IC}(\$/h)$	$\dot{Z}^{OM}(\$/h)$	$\dot{Z}^{TIC}(\$/h)$
AC	31.67	380,000	133	76.00	209
CC	20.83	250,000	87.64	50.00	138
GT	29.17	350,000	123	70.00	193
FED	6.25	75,000	26.29	15.00	41.29
ABED	10.00	120,000	42.07	24.00	66.07
GTMS	2.08	25,000	8.76	5.00	13.76
TJE	100.00	1,200,000	421	240.00	661

Table 4. The equations respecting exergy and cost balance of the TJE.

Section	Unit	Equation	Equation No.
 (AC)	(kW)	$\dot{E}x_1 + \dot{E}x_9 - \dot{E}x_2 = \dot{E}x_{D,AC}$	(18)
	(\$/h)	$(\dot{C}_1 + \dot{C}_9) + \dot{Z}_{AC}^{TIC} = \dot{C}_2 = c_2 \dot{E}x_2$	(19)
	(\$/GJ)	$\frac{\dot{C}_2}{\dot{E}x_2} = \frac{\dot{C}_{2,1}}{\dot{E}x_{2,1}} = \frac{\dot{C}_{2,2}}{\dot{E}x_{2,5}} = c_{2,2,1,2,2}$	(20)
 (CC)	(kW)	$\dot{E}x_{2,1} + \dot{E}x_3 - \dot{E}x_4 = \dot{E}x_{D,CC}$	(21)
	(\$/h)	$(\dot{C}_{2,1} + \dot{C}_3) + \dot{Z}_{CC}^{TIC} = \dot{C}_4 = c_4 \dot{E}x_4$	(22)
 (GT)	(kW)	$(\dot{E}x_4 - \dot{E}x_5) + (\dot{E}x_{2,2} - \dot{E}x_{2,3}) - \dot{W}_8 = \dot{E}x_{D,GT}$	(23)
	(\$/h)	$(\dot{C}_4 - \dot{C}_5) + (\dot{C}_{2,2} - \dot{C}_{2,3}) + \dot{Z}_{GT}^{TIC} = \dot{C}_8 = c_8 \dot{W}_8$	(24)
 (FED)	(kW)	$(\dot{E}x_5 - \dot{E}x_6) + (\dot{E}x_{2,3} - \dot{E}x_{2,4}) = \dot{E}x_{D,FED}$	(25)
	(\$/h)	$(\dot{C}_5 + \dot{C}_{2,3}) + \dot{Z}_{DC}^{TIC} = (\dot{C}_6 + \dot{C}_{2,4})$	(26)

 (ABED-MIL)	(kW)	$(\dot{E}x_6 - \dot{E}x_7) + (\dot{E}x_{2.4} - \dot{E}x_{2.5}) + \dot{E}x_{10} = \dot{E}x_{D,ABED}$	(27)
	(\$/h)	$\dot{E}x_{10} = 0$ $(\dot{C}_6 + \dot{C}_{2.4} + \dot{C}_{10}) + \dot{Z}_{ABED}^{TIC} = (\dot{C}_{2.5} + \dot{C}_7)$ $\dot{C}_{10} = 0$	(28)
 (ABED-AB)	(kW)	$(\dot{E}x_6 - \dot{E}x_7) + (\dot{E}x_{2.4} - \dot{E}x_{2.5}) + \dot{E}x_{10} = \dot{E}x_{D,ABED}$	(29)
	(\$/h)	$\dot{E}x_{10} \neq 0$ $(\dot{C}_6 + \dot{C}_{2.4} + \dot{C}_{10}) + \dot{Z}_{ABED}^{TIC} = (\dot{C}_7 + \dot{C}_{2.5})$ $\dot{C}_{10} \neq 0$	(30)
 (GTMS)	(kW)	$\dot{W}_8 - \dot{W}_9 = \dot{E}x_{D,GTMS}$	(31)
	(\$/h)	$\dot{C}_8 + \dot{Z}_{GTMS}^{TIC} = \dot{C}_9 = c_9 \dot{W}_9$	(32)
(TJE -MIL)	(kW)	$(\dot{E}x_1 + \dot{E}x_3) - \dot{E}x_{Pr,TJE} = \dot{E}x_{C,TJE}$	(33)
	(\$/h)	$(\dot{C}_1 + \dot{C}_3) + \dot{Z}_{TJE}^{TIC} = \dot{C}_{2.5} + \dot{C}_7 = \dot{C}_{kn,TJE} = c_P \dot{E}x_{kn,TJE}$	(34)
(TJE-AB)	(kW)	$(\dot{E}x_1 + \dot{E}x_3 + \dot{E}x_{10}) - \dot{E}x_{Pr,TJE} = \dot{E}x_{C,TJE}$	(35)
	(\$/h)	$(\dot{C}_1 + \dot{C}_3 + \dot{C}_{10}) + \dot{Z}_{TJE}^{TIC} = \dot{C}_{2.5} + \dot{C}_7 = \dot{C}_{kn,TJE} = c_P \dot{E}x_{kn,TJE}$	(36)

2.7. Exergy and Exergoeconomic Performance Metrics

The performance metrics of the TJE respecting exergy, sustainability and exergoeconomic are assigned in Table 5 [6,37,44,49,63].

Table 5. Exergy, sustainability and exergoeconomic performance equations for the TJE.

Description	Unit	Equation	Equation No
Exergy efficiency, ψ	(%)	$\dot{E}x_{Pr} / \dot{E}x_F$	(37)
Sustainability effect factor, SEF	(-)	$1 / (1 - \psi_n)$	(38)
Sustainability cost index, SCI	(\$/GJ)	$c_{Pr}(1 - \psi_n)$	(39)
Unit exergy cost rate of product, c_{Pr}	(\$/GJ)	$\dot{C}_{Pr} / \dot{E}x_{Pr}$	(40)
Economic benefit of amelioration potential rate, $EBAP_n$	(\$/h)	$EBAP_n = c_{Pr,n} \dot{E}xIP = c_{Pr,n} (1 - \psi_n) \dot{E}x_{C,n}$	(41)
Total cost rate of the TJE, $\dot{C}_{TJE}$	(\$/h)	$\dot{C}_{F,TJE} + \dot{Z}_{TJE}^{TIC}$	(42)
Exergy loss cost rate, $\dot{C}_L$	(\$/h)	$c_F \dot{E}x_L$	(43)
Exergy destruction cost rate, $\dot{C}_D$	(\$/h)	$c_F \dot{E}x_D$	(44)
Exergy consumption cost rate, $\dot{C}_C$	(\$/h)	$c_F (\dot{E}x_D + \dot{E}x_L)$	(45)
Relative cost difference, π_n	(%)	$(c_{Pr,n} - c_{F,n}) / c_{F,n}$	(46)
Exergoeconomic factor, ξ_n	(%)	$\dot{Z}_n^{TIC} / (\dot{Z}_n^{TIC} + \dot{C}_{D,n})$	(47)

In accordance with Tables A1 and A2, Tables 6 and 7 demonstrate the rate of exergy, the cost rates of exergy flow and the unit exergy as per the flow state numbers, respectively.

Table 6. Values for the cost rates of exergy flow and unit exergy related to process sections for kerosene fuel use (*: exclusively AB PM).

Location No	Ex (kW)	Ex (GJ/h)	c (\$/GJ)	$\dot{C}$ (\$/h)
0	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00
2	4700	16.92	82.91	1403
2.1	4230	15.23	82.91	1263
2.2	470	1.69	82.91	140
2.3	740	2.66	52.68	140
2.4	720	2.59	54.11	140
2.5	699	2.52	55.78	140
2.5*	1714	6.17	22.74	140
3	16,554	59.59	12.49	745
4	13,258	47.73	44.94	2145
5	7156	25.76	44.94	1158
6	6966	25.08	47.81	1199
7	6746	24.29	52.09	1265
7*	20,164	72.59	38.46	2792
10*	33,941	122	12.49	1527
8	5640	20.30	58.12	1180
9	5583	20.10	59.39	1194
TJE-MIL	5106	18.38	76.45	1405
TJE-AB	8575	30.87	94.97	2932

Table 7. Values for the cost rates of exergy flow and unit exergy related to process sections for hydrogen fuel use (*: exclusively AB PM).

Location No	Ex (kW)	Ex (GJ/h)	c (\$/GJ)	$\dot{C}$ (\$/h)
0	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00
2	4700	16.92	174	2949
2.1	4230	15.23	174	2654
2.2	470	1.69	174	295
2.3	710	2.56	115	295
2.4	690	2.48	119	295
2.5	665	2.39	123	295
2.5*	1677	6.04	48.84	295
3	17,594	63.34	40.81	2585
4	13,349	48.06	112	5376
5	7059	25.41	112	2843
6	6857	24.68	117	2884
7	6551	23.59	125	2950
7*	18,853	67.87	122	8250
10*	36,075	130	40.81	5300
8	5737	20.65	132	2726
9	5583	20.10	136	2740
TJE-MIL	5035	18.13	179	3245
TJE-AB	8228	29.62	288	8545

3. Advanced Exergy and Exergoeconomic Analyses

3.1. Advanced Exergy Analysis

Thanks to traditional exergy analysis, unproductiveness in the process is numerically obtained. Irreversible processes and losses with real development potential can be reduced by implementing advanced exergy analysis. The place and enormity of the sources causing thermodynamic deficiencies can be described via traditional exergy analysis. It also evaluates process sections with the ultimate exergy destruction in general. The efficiency of the system sections can be ameliorated by mitigating the exergy demolition rates inside the sections. A conventional exergy analysis evaluates the process performance beneath certain operating circumstances in order to improve a step or section. However, it cannot take into account the best performance actually available from the system. It is not possible to predict the exergy amelioration capacity without considering section coactions with the conventional exergy analysis methods. These coactions, which cannot be evaluated by traditional exergy analysis, could be analyzed at length by considering the method of advanced exergy analysis [67,68]. Exergy destruction of each section, shown in Figure 3, is allocated to avoidable, unavoidable, exogenous and endogenous fragments.

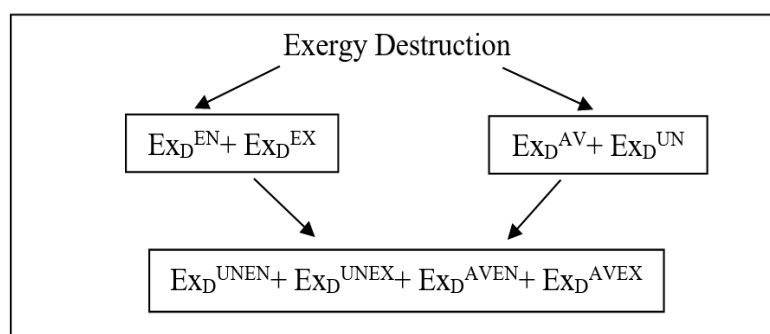


Figure 3. A schematic subdivision of exergy destruction [63].

The destruction respecting the endogenous division involves the section performance taking account that the leftover sections operate in optimum circumstances. The impact of the left-behind sections on the entire process forges the exogenous division of the destruction. The exergy destructions are divided into unavoidable and avoidable parts when considering the disposal capacity of irreversible processes. Though the new technologic improvements are implemented on the systems, the unavoidable division of the sections cannot be eliminated. Nevertheless, the avoidable division can be recovered per technical amelioration. Further analysis of the system can be achieved by combining the $\dot{Ex}_D$ rates. The equations respecting advanced exergy are demonstrated in Table 8 [68–73]:

Table 8. The advanced exergy equations of the process.

Description	Unit	Equation	Equation No
Endogenous exergy destruction rate, $\dot{Ex}_{D,n}^{EN}$	(GJ/h)	$\dot{Ex}_{Pr,n}^{RL} \times \left(\frac{\dot{Ex}_D}{\dot{Ex}_{Pr}} \right)_n^{EN}$	(48)
Exogenous exergy destruction, $\dot{Ex}_{D,n}^{EX}$	(GJ/h)	$\dot{Ex}_{D,n}^{EX} = \dot{Ex}_{D,n}^{RL} - \dot{Ex}_{D,n}^{EN}$	(49)
Unavoidable exergy destruction, $\dot{Ex}_{D,n}^{UN}$	(GJ/h)	$\dot{Ex}_{Pr,n}^{RL} \times \left(\frac{\dot{Ex}_D}{\dot{Ex}_{Pr}} \right)_n^{UN}$	(50)

$$\begin{array}{l} \text{Avoidable exergy} \\ \text{destruction, } \dot{E}x_{D,n}^{AV} \end{array} \quad (\text{GJ/h}) \quad \dot{E}x_{D,n}^{AV} = \dot{E}x_{D,n}^{RL} - \dot{E}x_{D,n}^{UN} \quad (51)$$

$$\begin{array}{l} \text{Unavoidable-} \\ \text{endogenous exergy} \\ \text{destruction, } \dot{E}x_{D,n}^{UNEN} \end{array} \quad (\text{GJ/h}) \quad \dot{E}x_{D,n}^{UNEN} = \dot{E}x_{D,n}^{RL} \times \left(\frac{\dot{E}x_D^{UN}}{\dot{E}x_D^{RL}} \times \frac{\dot{E}x_D^{EN}}{\dot{E}x_D^{RL}} \right) = \frac{\dot{E}x_D^{UN} \times \dot{E}x_D^{EN}}{\dot{E}x_D^{RL}} \quad (52)$$

$$\begin{array}{l} \text{Unavoidable-} \\ \text{exogenous exergy} \\ \text{destruction, } \dot{E}x_{D,n}^{UNEX} \end{array} \quad (\text{GJ/h}) \quad \dot{E}x_{D,n}^{UNEX} = \dot{E}x_{D,n}^{RL} \times \left(\frac{\dot{E}x_D^{UN}}{\dot{E}x_D^{RL}} \times \frac{\dot{E}x_D^{EX}}{\dot{E}x_D^{RL}} \right) = \frac{\dot{E}x_D^{UN} \times \dot{E}x_D^{EX}}{\dot{E}x_D^{RL}} \quad (53)$$

$$\begin{array}{l} \text{Avoidable-endogenous} \\ \text{exergy destruction, } \dot{E}x_{D,n}^{AVEN} \end{array} \quad (\text{GJ/h}) \quad \dot{E}x_{D,n}^{AVEN} = \dot{E}x_{D,n}^{RL} \times \left(\frac{\dot{E}x_D^{AV}}{\dot{E}x_D^{RL}} \times \frac{\dot{E}x_D^{EN}}{\dot{E}x_D^{RL}} \right) = \frac{\dot{E}x_D^{AV} \times \dot{E}x_D^{EN}}{\dot{E}x_D^{RL}} \quad (54)$$

$$\begin{array}{l} \text{Avoidable-exogenous} \\ \text{exergy destruction, } \dot{E}x_{D,n}^{AVEX} \end{array} \quad (\text{GJ/h}) \quad \dot{E}x_{D,n}^{AVEX} = \dot{E}x_{D,n}^{RL} \times \left(\frac{\dot{E}x_D^{AV}}{\dot{E}x_D^{RL}} \times \frac{\dot{E}x_D^{EX}}{\dot{E}x_D^{RL}} \right) = \frac{\dot{E}x_D^{AV} \times \dot{E}x_D^{EX}}{\dot{E}x_D^{RL}} \quad (55)$$

3.2. Advanced Exergoeconomic Analysis

The process evaluation in terms of cost is firstly executed via exergoeconomic analysis. Then, the results obtained from traditional exergoeconomic analysis are broken down into unavoidable, endogenous, avoidable and exogenous divisions for further assessment not only for the cost of exergy destruction $\dot{C}_{D,n}$ but also for the cost of investment $\dot{Z}_n^{TIC}$. The cost rates are combined to be assessed for further analysis as avoidable/exogenous-endogenous and unavoidable/exogenous-endogenous divisions. Traditional exergoeconomic analyses are not suitable for evaluating interactions between system steps, since it cannot take into account the optimum efficiency obtained from the system. It is not possible to estimate the EBAP without considering section interactions with traditional exergoeconomic analysis. The cost ratio of endogenous investment $\dot{Z}_n^{EN}$ and the cost rate of endogenous exergy destruction $\dot{C}_{D,n}^{EN}$ are computed assuming that the section under consideration is operating at real working circumstances, while the left behind sections are under theoretical conditions. Evaluating the interactions of all system components on each other and the improvement potential of each section is important for cost improvement. The unavoidable investment cost $\dot{Z}_n^{UN}$ refers to the inevitable cost of the section. $\dot{Z}_n^{UN}$ is the unavoidable cost of the purchased section that cannot be reduced due to the manufacturing restricts [54–62]. A schematic subdivision respecting $\dot{C}_{D,n}$ and $\dot{Z}_n^{TIC}$ are demonstrated in Figure 4.

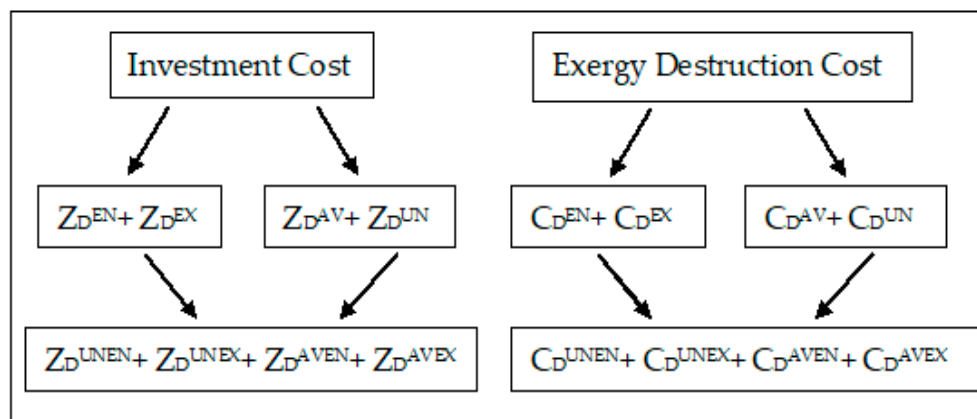


Figure 4. A schematic subdivision respecting the costs of investment and exergy destruction.

The equations respecting the $\dot{C}_{D,n}$ and the $\dot{Z}_n^{TIC}$ are derived and demonstrated in Table 9.

Table 9. Advanced exergoeconomic equations of investment and exergy destruction costs [55].

Investment Cost ($\dot{Z}_n^{TIC}$)	Equation No	Exergy Destruction Cost ($\dot{C}_{D,n}$)	Equation No	Unit
$\dot{Z}_n^{EN} = \dot{E}_{P,n}^{EN} \left(\frac{\dot{Z}}{\dot{E}_P} \right)_n^{RL}$	(56)	$\dot{C}_{D,n}^{EN} = c_{F,n} \cdot \dot{E}_{D,n}^{EN}$	(64)	(\$/h)
$\dot{Z}_n^{EX} = \dot{Z}_n^{RL} - \dot{Z}_n^{EN}$	(57)	$\dot{C}_{D,n}^{EX} = \dot{C}_{D,n}^{RL} - \dot{C}_{D,n}^{EN}$	(65)	(\$/h)
$\dot{Z}_n^{UN} = \left(\frac{TIC^{UN}}{TIC^{RL}} \right)_n \cdot \dot{Z}_n^{RL}$	(58)	$\dot{C}_{D,n}^{UN} = c_{F,n} \cdot \dot{E}_{D,n}^{UN}$	(66)	(\$/h)
$\dot{Z}_n^{AV} = \dot{Z}_n^{RL} - \dot{Z}_n^{UN}$	(59)	$\dot{C}_{D,n}^{AV} = \dot{C}_{D,n}^{RL} - \dot{C}_{D,n}^{UN}$	(67)	(\$/h)
$\dot{Z}_n^{UN,EN} = \dot{E}_{P,n}^{EN} \left(\frac{\dot{Z}}{\dot{E}_P} \right)_n^{UN}$	(60)	$\dot{C}_{D,n}^{UN,EN} = c_{F,n} \cdot \dot{E}_{D,n}^{UN,EN}$	(68)	(\$/h)
$\dot{Z}_n^{UN,EX} = \dot{Z}_n^{UN} - \dot{Z}_n^{UN,EN}$	(61)	$\dot{C}_{D,n}^{UN,EX} = \dot{C}_{D,n}^{UN} - \dot{C}_{D,n}^{UN,EN}$	(69)	(\$/h)
$\dot{Z}_n^{AV,EN} = \dot{Z}_n^{EN} - \dot{Z}_n^{UN,EN}$	(62)	$\dot{C}_{D,n}^{AV,EN} = \dot{C}_{D,n}^{EN} - \dot{C}_{D,n}^{UN,EN}$	(70)	(\$/h)
$\dot{Z}_n^{AV,EX} = \dot{Z}_n^{EX} - \dot{Z}_n^{UN,EX}$	(63)	$\dot{C}_{D,n}^{AV,EX} = \dot{C}_{D,n}^{EX} - \dot{C}_{D,n}^{UN,EX}$	(71)	(\$/h)

4. Results and Discussion

In accordance with Tables A1 and 6, while exergetic and exergoeconomic performance metrics are shown with the use of kerosene in Table 10 for MIL PM, they are demonstrated in Table 11 for AB PM. According to the outcomes for the TJE, while the fuel exergy values were determined to be 16,554 kW (59.59 GJ/h) and 50,495 kW (182 GJ/h) for the MIL and the AB PM, seriatim, the product exergy values were calculated to be 5106 kW (18.38 GJ/h) and 8575 kW (30.87 GJ/h). Hence, the $\dot{E}x_D$ rates were reckoned at 11,447 kW (41.21 GJ/h) and 41,920-kW (151-GJ/h) for the MIL and AB PM, seriatim. The TJE's exergetic efficiency was determined 16.98% and 30.85% for the AB and MIL PM, seriatim [63]. The lowest SEF was reckoned in the CC section with the rate of 2.20 for the MIL PM, while it was computed to be 2.13 in the ABED section for the AB PM. The ultimate SCI were calculated in the CC section with the rate of 20.43 \$/GJ both for the AB and MIL PM. The utmost EBAP was reckoned in the CC as 154 \$/h for the MIL PM, while it was computed with a rate of 644 \$/h for the AB PM. Figure 5 indicates the TJE and its sections' EBAP rates with kerosene fuel use.

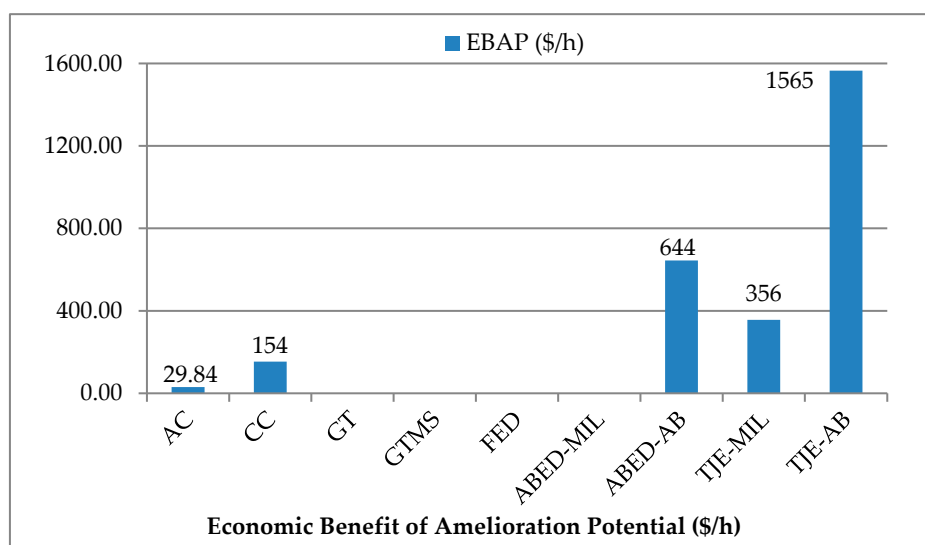


Figure 5. Economic profit of amelioration potential (EBAP) with JP-8 fuel usage.

The overall SEF of the engine was computed 1.20 and 1.45 for AB and MIL PM, seriatim, while SCI was reckoned with the rates of 78.84 and 52.86 \$/GJ. In accordance with the ameliorated potential of the system, the EBAP was determined to be 356 and 1565 \$/h for MIL and AB PM, seriatim. The maximum $\dot{Z}^{TIC}$ was calculated with the rate of 209 \$/h in AC section, whereas it was reckoned at 13.76 \$/h in the GTMS section with the minimum rate for both aforementioned modes. As per Table 6, $\dot{C}_{TJE}$ was reckoned at 1405 \$/h for the MIL PM, while it was calculated to be 2932 \$/h for AB PM. According to Figure 6, the π and the ζ of the entire process were determined 512% and 56.20% for the MIL PM, whereas they were computed 660% and 25.95% for the AB PM, seriatim. The cost ratios and the indicators of the sustainability and exergy related to the engine sections are demonstrated below.

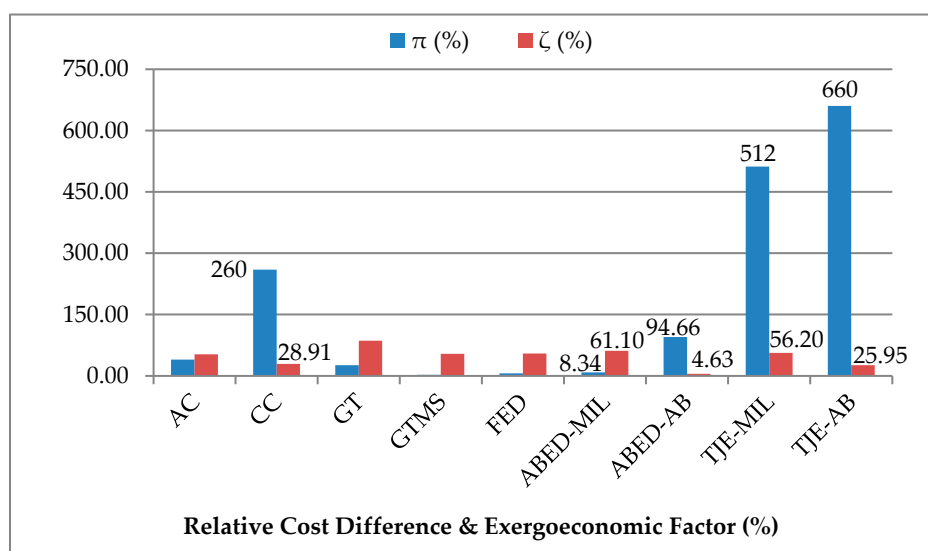


Figure 6. Relative cost difference (π) and exergoeconomic factor (ζ) with JP-8 fuel usage.

With respect to Table 10, the maximum unit fuel cost rate was calculated in the AC section, which had a rate of 59.39 \$/GJ, while it was reckoned at 12.49 \$/GJ for the entire engine. Moreover, the AC section had the ultimate unit product cost with the rate of 82.91 \$/GJ, while it was calculated to be 76.45 \$/GJ for the whole engine. The utmost $\dot{C}_C$ and the π were determined at 338 \$/h and 260% in the CC section, seriatim, while they were reckoned at 515 \$/h and 512% for the whole engine. Therewithal, CC section had the minimum ζ with 28.91%.

Table 10. Results for exergy, exergoeconomic and sustainability performance indicators for MIL PM with kerosene fuel use.

SEC.	$\dot{E}x_F(\text{kW})$	$\dot{E}x_{Pr}(\text{kW})$	$\dot{E}x_C(\text{kW})$	$\Psi(\%)$	SEF(—)	SCI(\$/GJ)	EBAP(\$/h)	$c_F(\$/\text{GJ})$	$c_{Pr}(\$/\text{GJ})$	$\dot{C}_C(\$/\text{h})$	$\dot{Z}^{TIC}(\$/\text{h})$	$\pi(\%)$	$\zeta(\%)$
AC	5583	4700	883	84.19	6.32	13.11	29.84	59.39	82.91	189	209	39.60	52.57
CC	16,554	9028	7525	54.54	2.20	20.43	154	12.49	44.94	338	138	260	28.91
GT	5833	5640	193	96.69	30.23	1.92	1.06	46.24	58.12	32.12	193	25.69	85.71
FED	7895	7686	209	97.35	37.70	1.28	0.91	45.66	48.40	34.43	41.29	5.99	54.53
ABED	7686	7445	241	96.86	31.84	1.65	1.32	48.40	52.43	42.06	66.07	8.34	61.10
GTMS	5640	5583	57.13	98.99	98.73	0.60	0.12	58.12	0.35	11.95	13.76	2.20	53.52
Total Destruction Rate	-	-	9109	-	-	-	-	-	-	410	-	-	-
Total Losses Rate	-	-	2338	-	-	-	-	-	-	105	-	-	-
TJE	16,554	5106	11,447	30.85	1.45	52.86	356	12.49	76.45	515	661	512	56.20

Table 11. Results for exergy, exergoeconomic and sustainability performance indicators for AB PM with kerosene fuel use.

SEC.	$\dot{E}x_F(\text{kW})$	$\dot{E}x_{Pr}(\text{kW})$	$\dot{E}x_C(\text{kW})$	$\Psi(\%)$	SEF(—)	SCI(\$/GJ)	EBAP(\$/h)	$c_F(\$/\text{GJ})$	$c_{Pr}(\$/\text{GJ})$	$\dot{C}_C(\$/\text{h})$	$\dot{Z}^{TIC}(\$/\text{h})$	$\pi(\%)$	$\zeta(\%)$
AC	5583	4700	883	84.19	6.32	13.11	29.84	59.39	82.91	189	209	39.60	52.57
CC	16,554	9028	7525	54.54	2.20	20.43	154	12.49	44.94	338	138	260	28.91
GT	5833	5640	193	96.69	30.23	1.92	1.06	46.24	58.12	32.12	193	25.69	85.71
FED	7895	7686	209	97.35	37.70	1.28	0.91	45.66	48.40	34.43	41.29	5.99	54.53
ABED	41,606	21,878	19,728	52.58	2.11	17.65	644	19.12	37.23	1360	66.07	94.66	4.63
GTMS	5640	5583	57.13	98.99	98.73	0.60	0.12	58.12	0.35	11.95	13.76	2.20	53.52
Total Destruction Rate	-	-	28,595	-	-	-	-	-	-	1286	-	-	-
Total Losses Rate	-	-	13,324	-	-	-	-	-	-	599	-	-	-
TJE	50,495	8575	41,920	16.98	1.20	78.84	1565	12.49	94.97	1886	661	660	25.95

With respect to Table 11, the ultimate unit fuel cost rate was calculated in the AC section, which had a rate of 59.39 \$/GJ, while it was reckoned at 12.49 \$/GJ for the entire engine. Moreover, the AC section had the ultimate unit product cost with a rate of 82.91 \$/GJ, while it was calculated to be 94.97 \$/GJ for the entire engine. The utmost $\dot{C}_C$ was determined at 1360 \$/h in the ABED section, while it was reckoned at 1886 \$/h for the whole engine. In addition, ABED section had the minimum ζ with 4.63%.

In accordance with Tables A2 and 7, while exergetic and exergoeconomic performance metrics are shown with the use of hydrogen in Table 12 for MIL PM, they are demonstrated in Table 13 for AB PM. According to the outcomes for the TJE, while the fuel exergy values were determined to be 17,594 kW (63.34 GJ/h) and 53,669 kW (193 GJ/h) for the MIL and AB PM, seriatim, the product exergy rates were calculated to be 5035 kW (18.13 GJ/h) and 8228 kW (29.62 GJ/h). Hence, the $\dot{E}x_D$ rates were reckoned at 12,559 kW (45.21 GJ/h) and 45,441 kW (164 GJ/h) for MIL and AB PM, seriatim. The TJE's exergetic efficiency was determined at 15.33% and 28.62% for the AB and MIL PM, seriatim [63]. The lowest SEF was reckoned in the CC section with a rate of 2.08 for the MIL PM, while it was computed to be 1.89 in the ABED section for the AB PM. The ultimate SCI were calculated in the CC section with a rate of 53.89 \$/GJ for the MIL PM, while it was computed at 61.17 \$/GJ for AB PM. The utmost EBAP was reckoned in the CC with a rate of 600 \$/h for the MIL PM, while it was computed to be at a rate of 2372 \$/h for the AB PM. Figure 7 indicates the EBAP of the TJE and its sections with the usage of H₂ fuel.

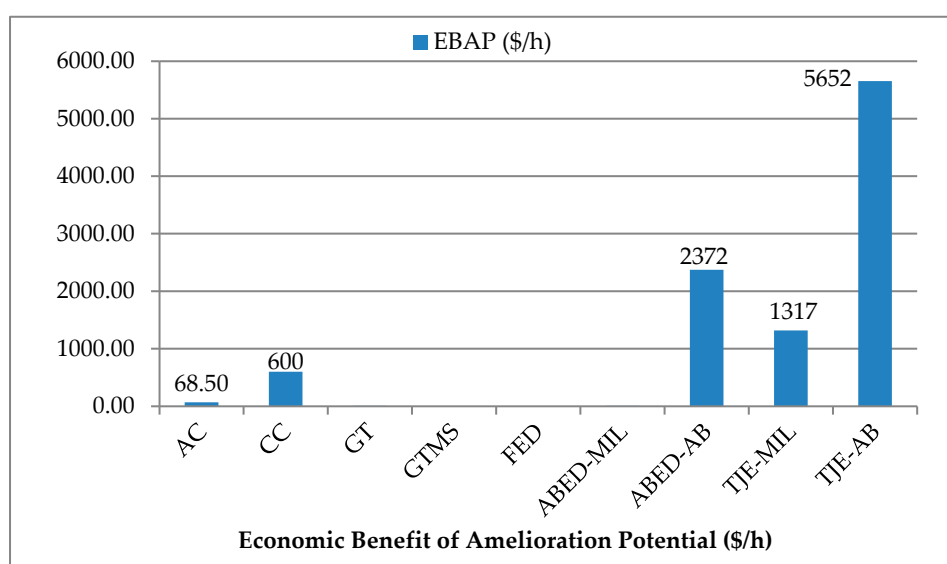


Figure 7. Economic benefit of amelioration potential (EBAP) with H₂ fuel usage.

The overall SEF of the engine was computed to be 1.18 and 1.40 for AB and MIL PM, seriatim, while SCI was reckoned with rates of 128 and 244 \$/GJ. In accordance with the ameliorated potential of the system, the EBAP was determined to be 1317 and 5652 \$/h for MIL and AB PM, seriatim. The maximum $\dot{Z}^{TIC}$ was calculated with a rate of 209 \$/h in the AC section, whereas it was reckoned at 13.76 \$/h in GTMS section with the minimum rate for both aforementioned PMs. As per Table 7, $\dot{C}_{TJE}$ was reckoned at 3245 \$/h for MIL PM, while it was calculated to be 8545 \$/h for AB PM. As per Figure 8, the π and the ζ of the entire system were determined to be 339% and 26.37% for the MIL PM, whereas they were computed to be 607% and 9.01% for the AB PM, seriatim. The cost rates and the indicators of sustainability and exergy related to engine sections are demonstrated in Figure 8.

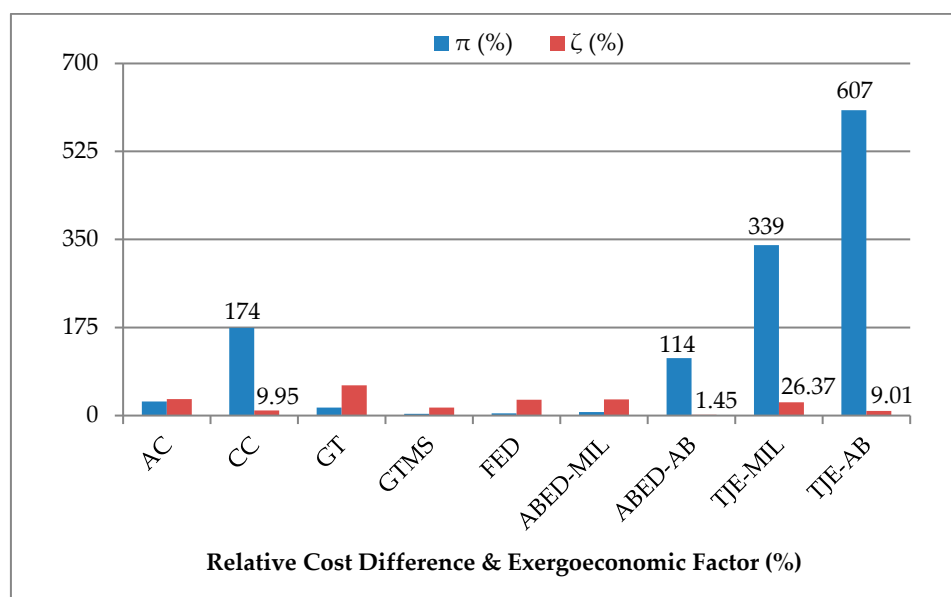


Figure 8. Relative cost difference (π) and exergoeconomic factor (ζ) with H_2 fuel usage.

With respect to Table 12, the ultimate unit fuel cost rate was calculated in the AC section, which had a rate of 136 \$/GJ, while it was reckoned at 40.81 \$/GJ for the entire engine. Moreover, the AC section had the ultimate unit product cost with a rate of 174 \$/GJ, while it was calculated to be 179 \$/GJ for the whole engine. The utmost $\dot{C}_C$ and the π were determined to be 1245 \$/h and 174% in the CC section, seriatim, while they were reckoned at 1845 \$/h and 339% for the whole engine. Therewithal, the CC section had the minimum ζ with 9.95%.

Table 12. Results for exergy, exergoeconomic and sustainability performance indicators for MIL PM with hydrogen fuel use.

SEC.	$\dot{E}x_F(\text{kW})$	$\dot{E}x_{Pr}(\text{kW})$	$\dot{E}x_C(\text{kW})$	$\psi(\%)$	SEF(—)	SCI(\$/GJ)	EPiP(\$/h)	$c_F(\text{\$/GJ})$	$c_{Pr}(\text{\$/GJ})$	$\dot{C}_C(\text{\$/h})$	$\dot{Z}^{TIC}(\text{\$/h})$	$\pi(\%)$	$\zeta(\%)$
AC	5583	4700	883	84.19	6.32	27.56	68.50	136	174	433	209	27.85	32.57
CC	17,594	9119	8475	51.83	2.08	53.89	600	40.81	112	1245	138	174	9.95
GT	6050	5737	313	94.82	19.32	6.83	6.65	114	132	129	193	15.78	59.99
FED	7769	7546	223	97.13	34.88	3.36	2.58	112	117	90	41.29	4.31	31.46
ABED	7546	7216	330	95.62	22.84	5.47	6.09	117	125	139	66.07	6.75	32.19
GTMS	5737	5583	154	97.31	37.16	3.67	1.97	132	136	73.37	13.76	3.28	15.80
Total Destruction Rate	-	-	10,378	-	-	-	-	-	1525	-	-	-	-
Total Losses Rate	-	-	2181	-	-	-	-	-	320	-	-	-	-
TJE	17,594	5035	12,559	28.62	1.40	128	1317	40.81	179	1845	661	339	26.37

Table 13. Results for exergy, exergoeconomic and sustainability performance indicators for AB PM with hydrogen fuel use.

SEC.	$\dot{E}x_F(\text{kW})$	$\dot{E}x_{Pr}(\text{kW})$	$\dot{E}x_C(\text{kW})$	$\psi(\%)$	SEF(—)	SCI(\$/GJ)	EPiP(\$/h)	$c_F(\text{\$/GJ})$	$c_{Pr}(\text{\$/GJ})$	$\dot{C}_C(\text{\$/h})$	$\dot{Z}^{TIC}(\text{\$/h})$	$\pi(\%)$	$\zeta(\%)$
AC	5583	4700	883	84.19	6.32	27.56	68.50	136	174	433	209	27.85	32.57
CC	17,594	9119	8475	51.83	2.08	53.89	600	40.81	112	1245	138	174	9.95
GT	6050	5737	313	94.82	19.32	6.83	6.65	114	132	129	193	15.78	59.99
FED	7769	7546	223	97.13	34.88	3.36	2.58	112	117	90	41.29	4.31	31.46
ABED	43,596	20,530	23,066	47.09	1.89	61.17	2372	53.99	116	4488	66.07	114	1.45
GTMS	5737	5583	154	97.31	37.16	3.67	1.97	132	136	73.37	13.76	3.28	15.80
Total Destruction Rate	-	-	33,113	-	-	-	-	-	-	4865	-	-	-
Total Losses Rate	-	-	12,327	-	-	-	-	-	-	1811	-	-	-
TJE	53,669	8228	45,441	15.33	1.18	244	5,652	40.81	288	6676	661	607	9.01

With respect to Table 13, the ultimate unit fuel cost rate was calculated in the AC section, which had a rate of 136 \$/GJ, while it was reckoned at 40.81 \$/GJ for the entire engine. Moreover, the AC section had the ultimate unit product cost with a rate of 174 \$/GJ, while it was calculated to be 288 \$/GJ for the entire engine. The ultimate π was assigned in the CC and ABED sections as 174% and 114%, seriatim. The ultimate $\dot{C}_C$ was determined 4488 \$/h in the ABED section, while it was reckoned at 6676 \$/h for the whole engine. At the same time, ABED had the minimum ζ with 1.45%.

The comparative consequences of this research according to Figure 9 with the J85-GE-CAN-15 TJE research [49] are discussed as follows:

The $\dot{C}_F$, the c_{pr} and the $\dot{C}_C$ of J85-GE-CAN-15 TJE engine were determined to be 1482 \$/h, 121 \$/GJ and 1040 \$/h for MIL PM, respectively, while they were reckoned as 4079 \$/h, 133 \$/GJ and 3150 \$/h for AB PM with kerosene fuel utilization. Moreover, while the SEF were calculated to be 1.42 and 1.29 for the MIL and AB PM, seriatim, the SCI were reckoned at 85.26 and 103 \$/GJ. As per Figure 9, the results indicate that the J85-GE-5H TJE for the present study is more cost effective than the J85-GE-CAN-15 TJE.

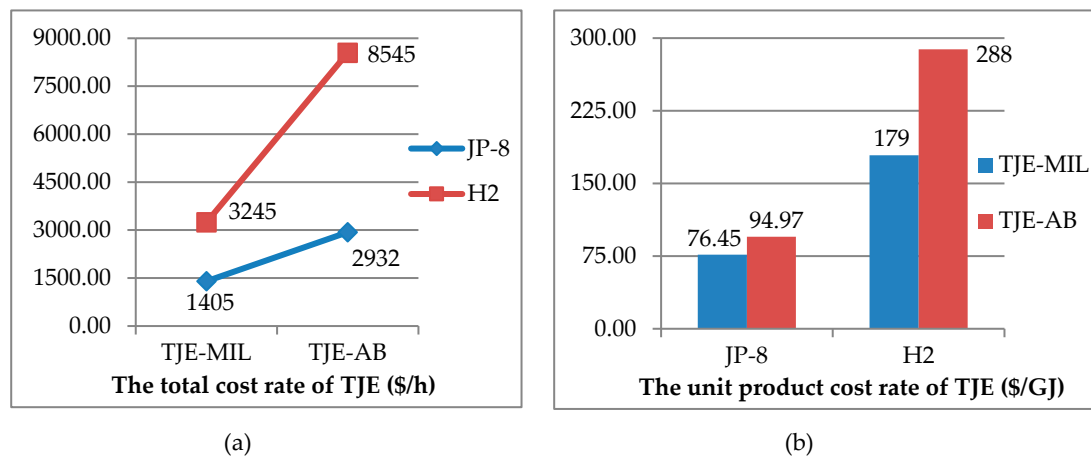


Figure 9. (a) The TJE's total cost rate; (b) The TJE's unit product cost rate.

From another research perspective, as per [52], the $\dot{C}_F$, the c_{pr} and the $\dot{C}_C$ of the (J69-T-25A) TJE engine were determined to be 1144 \$/h, 355 \$/GJ and 980 \$/h, respectively, with H₂ fuel use. Although the exergetic efficiency of the J69 TJE was less than the one in this study, the J85-GE-5H TJE's $\dot{C}_{TJE}$ was reckoned higher than the J69 TJE due to the higher rates of the $\dot{C}_F$ and the $\dot{Z}^{TIC}$ comparatively. In accordance with Table 9, the outcomes of the exergoeconomic analysis are confirmed with the results of the advanced exergoeconomic analysis. While the advanced investment costs are demonstrated in Table 14, the exergoeconomic destruction costs are indicated in Table 15 for JP-8 usage.

Table 14. Results for advanced investment costs for kerosene use.

SEC.	$\dot{Z}^{TIC}(\$/h)$	$\dot{Z}^{UN}(\$/h)$	$\dot{Z}^{AV}(\$/h)$	$\dot{Z}^{EX}(\$/h)$	$\dot{Z}^{EN}(\$/h)$	$\dot{Z}^{UNEN}(\$/h)$	$\dot{Z}^{UNEX}(\$/h)$	$\dot{Z}^{AVEN}(\$/h)$	$\dot{Z}^{AVEX}(\$/h)$
AC	209	178	31.38	31.34	178	151	26.64	26.68	4.70
CC	138	110	27.53	12.62	125	100	10.10	25.01	2.52
GT	193	173	19.27	12.00	181	163	10.80	18.07	1.20
FED	41.29	35.10	6.19	5.12	36.17	30.74	4.35	5.43	0.77
ABED-MIL	66.07	52.85	13.21	9.05	57.02	45.61	7.24	11.40	1.81
ABED-AB	66.07	52.85	13.21	11.15	54.92	43.94	8.92	10.98	2.23
GTMS	13.76	12.39	1.38	0.94	12.82	11.54	0.85	1.28	0.09
TJE-MIL	661	562	99	65	596	506	55.33	89.21	9.75
TJE-AB	661	562	99	97	564	479	82.36	84.45	14.51

Table 15. Results for advanced exergy destruction costs for kerosene utilization.

SEC.	$\dot{C}_D$ (\$/h)	$\dot{C}_D^{UN}$ (\$/h)	$\dot{C}_D^{AV}$ (\$/h)	$\dot{C}_D^{EX}$ (\$/h)	$\dot{C}_D^{EN}$ (\$/h)	$\dot{C}_D^{UNEN}$ (\$/h)	$\dot{C}_D^{UNEX}$ (\$/h)	$\dot{C}_D^{AVEN}$ (\$/h)	$\dot{C}_D^{AVEX}$ (\$/h)
AC	189	154	34.36	28.28	160	130	24.00	30.08	4.28
CC	338	329	9.34	31.04	307	299	30.31	8.61	0.74
GT	32.12	19.48	12.64	2.00	30.12	18.15	1.33	11.97	0.67
FED	34.43	22.51	11.92	4.27	30.16	19.62	2.89	10.54	1.38
ABED-MIL	42.06	23.35	18.70	5.76	36.30	19.97	3.38	16.33	2.38
ABED-AB	1360	1152	208	231	1129	955	197	174	33.79
GTMS	11.95	6.52	5.43	0.82	11.14	6.04	0.47	5.09	0.34
TJE-MIL	515	380	134	146	369	343	37.48	26.36	108
TJE-AB	1886	1127	759	788	1098	962	165	136	623

With respect to Table 3, the $\dot{Z}_{TJE}^{TIC}$ of TJE was 661 \$/h for both PM with kerosene use. The major fragments of this rate were determined to be 209 \$/h in the AC and 193 \$/h in the GT sections. As per Table 14 for JP-8 utilization, $\dot{Z}_{TJE}^{AV}$ and $\dot{Z}_{TJE}^{UN}$ were calculated within the same rate as 98.96 \$/h and 562 \$/h for both PM, seriatim. The maximum $\dot{Z}^{AV}$, determined in the AC, was 31.38\$/h. The ultimate $\dot{Z}^{UN}$, found out in the AC, was 178 \$/h, since it had the highest unavoidable equipment cost in the entire engine. The $\dot{Z}_{AC}^{UN}$ of the AC was the aggregate of $\dot{Z}_{AC}^{UNEN}$ with a rate of 151 \$/h and $\dot{Z}_{AC}^{UNEX}$ with a rate of 26.64 \$/h.

On the other hand, the utmost endogenous investment cost $\dot{Z}^{EN}$, occurring in the GT section, was 181 \$/h. The percentage of $\dot{Z}_{GT}^{EN}$ was 31.55% of the $\dot{Z}_{TJE}^{EN}$ (564 \$/h) and 26.92% of the $\dot{Z}_{TJE}^{TIC}$. The great $\dot{Z}^{EN}$ was computed because of major $\dot{E}x_D^{EN}$. Therefore, the exogenous investment cost $\dot{Z}^{EX}$ was reckoned to be less than the $\dot{Z}^{EN}$. While the TJE had $\dot{Z}_{TJE}^{EN}$ with rates of 596 and 564 \$/h for the MIL and AB PM, seriatim, it had $\dot{Z}_{TJE}^{EX}$ within rates of 65.08 and 96.87 \$/h. The more exergy destruction and loss occur in the engine, the more endogenous investment cost becomes. The major fragments of the $\dot{Z}^{EX}$ indicated in Table 14 were assigned 31.34 \$/h in the AC and 12.62 \$/h in the CC sections. The results show that the AC had a noticeable impact on the CC section, while the CC section had a similar impact on the AC section. Additionally, the ultimate $\dot{Z}^{AVEX}$ was calculated to be 4.70 and 2.52 \$/h in the AC and CC sections, seriatim, while the $\dot{Z}^{AVEN}$ was calculated to be 26.68 \$/h and 25.01 \$/h.

In accordance with Tables A3 and A4, the advanced exergoeconomic cost rates are displayed in Table 15. The TJE's avoidable exergy demolition cost rates $\dot{C}_D^{AV}$ were reckoned at 134 \$/h and 759 \$/h for MIL and AB PM, seriatim. The maximum part of the $\dot{C}_D^{AV}$ was determined in the AC as 34.36 \$/h for the MIL PM, while it was computed in the ABED with a rate of 208 \$/h for the AB PM. The ultimate unavoidable exergy destruction cost rate $\dot{C}_D^{UN}$ was found out in the CC with a value of 329 \$/h for MIL PM, while it was reckoned in the ABED with a rate of 1152 \$/h for AB PM. The $\dot{C}_D^{UN}$ division of the CC was the aggregate of $\dot{C}_D^{UNEX}$ and $\dot{C}_D^{UNEN}$ with rates of 30.31 and 299 \$/h, seriatim, for MIL PM, whereas it was the aggregate of 96.85 and 955 \$/h for AB PM. The unavoidable cost rates cannot be reduced because of manufacturing restraints.

On the other hand, the ultimate endogenous exergy demolition cost $\dot{C}_D^{EN}$, occurring in the CC, was 307 \$/h. The ultimate $\dot{C}_D^{EN}$ was reckoned because of the combustion process. Hence, the exogenous exergy demolition cost $\dot{C}_D^{EX}$ was computed less than the $\dot{C}_D^{EN}$. While the TJE had $\dot{C}_{D,TJE}^{EN}$ with rates of 369 and 1098 \$/h for the MIL and AB PM, seriatim, the TJE engine had $\dot{C}_{D,TJE}^{EX}$ within rates of 146 and 788 \$/h. The maximum division of the $\dot{C}_D^{EX}$ was determined in the CC with a rate of 146 \$/h for the MIL PM, whereas it was computed in the ABED with a rate of 788 \$/h for the AB

PM. The $\dot{C}_D^{EX}$ came about in the related section because of the irreversible processes happened in the other sections. The mutual coactions among the engine sections can be figured out by breaking down the destruction cost rates into the exogenous divisions. The utmost avoidable-exogenous exergy destruction cost rate $\dot{C}_D^{AVEX}$ was calculated in the AC with a value of 4.28 \$/h for MIL PM, while it was reckoned in the ABED with a rate of 33.79 \$/h for the AB PM. At the same time, the ultimate avoidable-endogenous exergy demolition cost rate $\dot{C}_D^{AVEN}$ was reckoned in the AC with a value of 30.08 \$/h for MIL PM, while it was reckoned in the ABED with a rate of 174 \$/h for the AB PM. As per the outcomes, the $\dot{C}_D^{AVEX}$ could be reduced by implementing structural ameliorations to the entire system. The $\dot{C}_D^{AVEN}$ part could be mitigated by ameliorating the yield of the investigated section. When taking into account the usage of H₂, the advanced investment costs are demonstrated in Table 16 and the exergoeconomic destruction costs are displayed in Table 17.

Table 16. Results for advanced investment costs for H₂ utilization.

SEC.	$\dot{Z}^{TIC}(\$/h)$	$\dot{Z}^{UN}(\$/h)$	$\dot{Z}^{AV}(\$/h)$	$\dot{Z}^{EX}(\$/h)$	$\dot{Z}^{EN}(\$/h)$	$\dot{Z}^{UNEN}(\$/h)$	$\dot{Z}^{UNEX}(\$/h)$	$\dot{Z}^{AVEN}(\$/h)$	$\dot{Z}^{AVEX}(\$/h)$
AC	209	178	31.38	28.38	181	154	24.12	27.12	4.26
CC	138	110	27.53	13.98	124	98.93	11.18	24.73	2.80
GT	193	173	19.27	30.61	162	146	27.55	16.21	3.06
FED	41.29	35.10	6.19	4.02	37.27	31.68	3.42	5.59	0.60
ABED-MIL	66.07	52.85	13.21	8.70	57.37	45.89	6.96	11.47	1.74
ABED-AB	66.07	52.85	13.21	12.31	53.76	43.01	9.85	10.75	2.46
GTMS	13.76	12.39	1.38	1.26	12.50	11.25	1.13	1.25	0.13
TJE-MIL	661	562	99	70.64	590	502	60.05	88.38	10.58
TJE-AB	661	562	99	71.42	589	501	60.72	88.27	10.70

Table 17. Results for advanced exergy destruction costs of TJE and sections for H₂ utilization.

SEC.	$\dot{C}_D(\$/h)$	$\dot{C}_D^{UN}(\$/h)$	$\dot{C}_D^{AV}(\$/h)$	$\dot{C}_D^{EX}(\$/h)$	$\dot{C}_D^{EN}(\$/h)$	$\dot{C}_D^{UNEN}(\$/h)$	$\dot{C}_D^{UNEX}(\$/h)$	$\dot{C}_D^{AVEN}(\$/h)$	$\dot{C}_D^{AVEX}(\$/h)$
AC	433	354	78.86	58.77	374	305	49.61	69.70	9.16
CC	1245	1201	44.12	126	1119	1080	121	38.94	5.18
GT	129	86.98	41.53	20.41	108	71.22	15.76	36.88	4.65
FED	89.97	56.68	33.29	8.76	81.21	50.35	6.33	30.86	2.43
ABED-MIL	139	76.60	62.60	18.33	121	64.43	12.17	56.44	6.16
ABED-AB	4488	3709	779	840	3648	3007	703	641	138
GTMS	73.37	41.46	31.91	6.72	66.65	37.64	3.82	29.01	2.90
TJE-MIL	1845	1398	447	483	1362	1249	149	113	334
TJE-AB	6676	4175	2501	2599	4077	3499	676	578	1923

According to Table 3, the $\dot{Z}_{TJE}^{TIC}$ of TJE was 661 \$/h for both modes with H₂ use. The great portion of this rate were determined to be 209 \$/h in the AC and 193 \$/h in the GT sections; the minor portions were found to be 13.76 \$/h in the GTMS and 41.29 \$/h in the FED sections. As per Table 16 for H₂ usage, $\dot{Z}_{TJE}^{AV}$ and $\dot{Z}_{TJE}^{UN}$ were calculated within the same rates as 98.96 \$/h and 562 \$/h for both PM, seriatim. The maximum $\dot{Z}^{AV}$ was found out in the AC with a rate of 31.38 \$/h, while the utmost $\dot{Z}^{UN}$ was determined in the AC with a value of 178 \$/h. The $\dot{Z}_{AC}^{UN}$ of the AC was the aggregate of $\dot{Z}_{AC}^{UNEN}$ with a rate of 154 \$/h and $\dot{Z}_{AC}^{UNEX}$ with a rate of 24.12 \$/h. The unavoidable divisions cannot be mitigated on account of technological restraints. On the other hand, the utmost $\dot{Z}_{GT}^{EN}$ computed in the AC to be 181 \$/h. The higher the $\dot{E}x_{D,n}^{EN}$ occurred, the more $\dot{Z}^{UN}$ became. Hence, the $\dot{Z}^{EX}$ was determined less. While the TJE had $\dot{Z}_{TJE}^{EN}$ with rates of 596 and 564 \$/h for both PM, seriatim, the TJE engine had $\dot{Z}_{TJE}^{EX}$ within the rates of 65.08 and 96.87 \$/h. The major fragments of the $\dot{Z}^{EX}$ indicated in Table 16 were assigned 30.61 \$/h in the GT and 28.38 \$/h in the AC sections. The results show that

the GT had a noticeable impact on the AC section, while the AC had a similar effect on the GT section. In addition, the $\dot{Z}^{AVEX}$ rates were calculated to be 4.26 and 2.80 \$/h in the AC and CC sections, seriatim, while the $\dot{Z}^{AVEN}$ rates were reckoned at 27.12 and 24.73 \$/h.

In accordance with Tables A5 and A6, the $\dot{C}_D$ were demonstrated in Table 17. The TJE's $\dot{C}_D^{AV}$ were 447 and 2501 \$/h for MIL and AB PM, seriatim. The maximum part of the $\dot{C}_D^{AV}$ was determined in the AC with a rate of 78.86 \$/h for the MIL PM, whereas it was computed in the ABED with a rate of 779 \$/h for the AB PM. The ultimate $\dot{C}_D^{UN}$ in the CC was found to have a value of 1201 \$/h for MIL PM, while it was reckoned in the ABED with a rate of 3709 \$/h for AB PM. The $\dot{C}_D^{UN}$ fragment of the CC was the aggregate of $\dot{C}_D^{UNEX}$ with a rate of 121.27 \$/h and $\dot{C}_D^{UNEN}$ with a rate of 1080 \$/h for MIL PM, whereas it was the aggregate of $\dot{C}_D^{UNEX}$ with a rate of 703 \$/h and $\dot{C}_D^{UNEN}$ with a rate of 3007 \$/h in ABED for AB PM.

On the other hand, the ultimate $\dot{C}_D^{EN}$, determined in the CC, was 1119 \$/h. The TJE had $\dot{C}_{D,TJE}^{EN}$ rates of 1362 and 4077 \$/h for the MIL and AB PM, seriatim, while it had $\dot{C}_{D,TJE}^{EX}$ rates of 483 and 2599 \$/h. The maximum fragment of the $\dot{C}_D^{EX}$ was determined in the CC with a rate of 126 \$/h for the MIL PM, while it was computed in the ABED with a rate of 840 \$/h for the AB PM. The ultimate $\dot{C}_D^{AVEX}$ was calculated in the AC with a value of 9.16 \$/h for MIL PM, while it was reckoned in the ABED to be a rate of 138 \$/h for the AB PM. At the same time, the maximum $\dot{C}_D^{AVEN}$ was reckoned in the AC as 69.70 \$/h for MIL PM, while it was reckoned in the ABED as 641 \$/h for the AB PM. According to the outcomes, the $\dot{C}_D^{AVEX}$ rates could be mitigated by increasing the whole of the TJE's yield. The $\dot{C}_D^{AVEN}$ rates could be minified by ameliorating the efficiency of the investigated section.

5. Conclusions

J85-GE-5H TJE was evaluated completely considering exergoeconomic and advanced exergoeconomic analyses with kerosene and hydrogen fuels usage. Primarily, sustainability, exergoeconomic and advanced exergoeconomic analyses of the TJE were fulfilled utilizing kerosene fuel with respect to real engine working circumstances. The aforementioned analyses were then perused parametrically in terms of using H₂ fuel. After all, the outcomes reckoned for both fuel uses were collated in terms of cost effectiveness assessment of the TJE. The main conspicuous sequels related to the current research were stated below:

- The $\dot{C}_F$ rates were calculated to be 745 and 2271 \$/h for the MIL and AB PM with kerosene use, seriatim, while they were obtained as 2585 and 7885 \$/h with H₂ use.
- The $\dot{C}_D$ rates with JP-8 were determined 515 \$/h for the MIL PM and 1886 \$/h for the AB PM. By considering the use of hydrogen, the $\dot{C}_D$ for the MIL PM was 1845 \$/h, whereas it was 6676 \$/h for the AB PM.
- The C_{Pr} rates were determined as 76.45 \$/GJ and 94.97 \$/GJ with kerosene use, seriatim, while they were computed as 179 \$/GJ and 288 \$/GJ with H₂ use.
- The $\dot{C}_{TJE}$ rates were reckoned to be 1405 \$/h for the MIL PM and 2932 \$/h for the AB PM. By considering the usage of hydrogen, the $\dot{C}_{TJE}$ were 3245 \$/h and 8545 \$/h, seriatim.
- The EBAP values were computed to be 356 \$/h and 1565 \$/h for the MIL and AB PM with kerosene use, seriatim, while they were reckoned as 1317 \$/h and 5652 \$/h with H₂ use.
- The ζ rates were computed as 56.20% and 25.95% for the MIL and AB PM with kerosene use, seriatim. By taking into account the use of H₂, the ζ were 26.37% and 9.01%.
- The π rates were calculated to be 512% for the MIL PM and 660% for the AB PM. By considering the use of hydrogen, the π were 339% and 607%, seriatim.

- The SEF values were determined to be 1.45 and 1.20 for the MIL and AB PM with kerosene use, seriatim, while they were calculated 1.40 and 1.18 with H₂ use.
- The SCI values were determined to be 52.86 and 78.87 \$/GJ for the MIL and AB PM, seriatim, whereas they were reckoned 128 and 244 \$/GJ with H₂ use.
- The $\dot{C}_D^{UN}$ rates were calculated as 380 and 1127 \$/h for MIL and AB PM with kerosene use, seriatim, while they were determined as 1298 and 4175 \$/h with H₂ use. Moreover, the $\dot{C}_D^{UNEN}$ rate had the highest $\dot{C}_D$ for both fuel utilizations. Hence, the tract has low amelioration aptness.
- The $\dot{Z}_{TJE}^{UN}$ and the $\dot{Z}_{TJE}^{AV}$ rates were reckoned with values of 562 and 98.96 \$/h, seriatim, for both fuel uses.
- The $\dot{Z}_{TJE}^{EN}$ rates were computed as 596 and 564 \$/h for MIL and AB PM with kerosene use, seriatim, while they were reckoned as 590 and 589 \$/h with H₂ use.
- The $\dot{Z}_{TJE}^{EX}$ rates were calculated 65.08 and 96.87 \$/h for MIL and AB PM with kerosene use, seriatim, while they were reckoned to be 70.64 and 71.42 \$/h with H₂ use.
- The $\dot{C}_D^{EN}$ rates were computed as 369 and 1098 \$/h for MIL and AB PM with kerosene use, seriatim, whereas they were determined as 1362 and 4077 \$/h with H₂ use.
- The $\dot{C}_D^{EX}$ rates were computed to be 146 and 788 \$/h for MIL and AB PM with kerosene use, seriatim, while they were determined as 483 and 2599 \$/h with H₂ use.
- As the $\dot{C}_D^{EN}$ rates were computed higher than the $\dot{C}_D^{EX}$ rates, the coactions between the sections were low.
- The $\dot{C}_D^{AV}$ rates were computed as 134 and 759 \$/h for MIL and AB PM with kerosene use, seriatim, while they were determined as 447 and 2501 \$/h with H₂ use. Moreover, the $\dot{C}_D^{AVE}$ had a smaller $\dot{C}_D$ rate than the $\dot{C}_D^{AVE}$ cost rate in the whole tract not only for kerosene use but also for H₂ use.

Between the system sections, the CC and ABED had the maximum $\dot{C}_D$, $\dot{C}_D^{UN}$, SCI, π and EBAP rates for both fuel usages, whereas they had the minimum ζ and SEF rates. These results demonstrated that the primary factor bringing about an increase in the cost rates was the high demolition cost values of the CC and ABED sections because of the imperfections that happened in the combustion process. Meanwhile, the utmost avoidable investment costs were determined in the AC, CC and GT sections, whereas the utmost avoidable exergy destruction costs were reckoned in the ABED, AC and CC sections because of the relatively great exergy destructions rates. When the analyses are examined in terms of the internal state of the section, it was revealed that the potential for improvement depended mostly on sections. Hence, the endogenous demolition cost rate was larger than the exogenous demolition cost rate. The results were also similar for the cost rates of investment in terms of advanced analysis. The aforementioned analyses indicated that the sections were in the boundary of thermodynamic restraints as per the $\dot{Z}^{UNEN}$ and the $\dot{C}_D^{UNEN}$ rates and had to be produced to obtain better performance not only in thermodynamic efficiency but also in cost effectiveness. Therefore, the researchers have been studying to enhance the performance of TJE by implementing innovations such as three-dimensional (3D) print manufacturing technologies, which lessen the labor, material and development cost rates drastically.

Consequently, the engine operated less cost effective with the use of H₂ because of the increase in $\dot{C}_D$. Moreover, it was less sustainable due to the lower efficiency. Although the renewable energy sources will take the place of oil resources in the future, there has to be done to pave the way of production technologies to alter the challenges both in efficiency and cost effectiveness in gas turbine systems.

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Nomenclature

$\dot{ACC}$	yearly capital cost rate (\$/yr)
c	unit exergy flow cost (\$/GJ)
c_p	specific heat capacity (kJ/(kg·K))
$\dot{C}$	exergy flow cost rate (\$/h)
CRF	cost recovery factor (-)
$\dot{E}$	energy rate (kW or GJ/h)
$\dot{E}_{BAP}$	economic benefit of amelioration potential rate (\$/h)
$\dot{E}_x$	exergy rate (kW or GJ/h)
$\dot{FC}$	yearly fuel cost rate (\$/yr)
FP	fuel price (\$/kg)
i	interest rate (%)
LHV	lower heating value of fuel (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
n	lifetime (yr)
$OM \dot{C}$	yearly operation and maintenance cost (\$/yr)
P	pressure (kPa)
PVF	present value factor (-)
PW	present value (\$)
$\dot{Q}$	heat transfer rate (kW or GJ/h)
RC	ratio of the purchase cost of the section to the investment cost (%)
SCI	sustainability cost index (\$/GJ)
SEF	sustainability effect factor (-)
SV	salvage value (\$)
SVR	salvage value rate (%)
T	temperature (°C or K)
TIC	total investment cost (\$)
V	velocity (m/s)
$\dot{W}$	work rate or power (kW or GJ/h)
$\dot{Z}$	hourly investment cost rate (\$/h)

Greek Letters

ψ	exergy (second law) yield (%)
τ	yearly operation hour (h/yr)
π	relative cost difference (%)
ζ	exergoeconomic factor (%)

Subscripts

$ABED$	afterburner exhaust duct
AC	air compressor
C	consumption
CC	combustion chamber

<i>D</i>	destroyed, destruction
<i>F</i>	fuel
<i>FED</i>	forward exhaust duct
<i>GT</i>	gas turbine
<i>GTMS</i>	gas turbine mechanic shaft
<i>in</i>	inlet
<i>kn</i>	kinetic exergy
<i>l</i>	losses
<i>n</i>	<i>n</i> -th section
<i>out</i>	outlet
<i>P</i>	pressure
<i>Pr</i>	product
<i>T</i>	temperature
<i>TJE</i>	turbojet engine
0	reference state
1,2,3,...8,9,10	location numbers of sections
Superscripts	
<i>AV</i>	avoidable
<i>AVEN</i>	avoidable-endogenous
<i>AVEX</i>	avoidable-exogenous
<i>EN</i>	endogenous
<i>EX</i>	exogenous
<i>IC</i>	investment cost
<i>OM</i>	operation and maintenance cost
<i>RL</i>	real
<i>UN</i>	unavoidable
<i>UNEN</i>	unavoidable-endogenous
<i>UNEX</i>	unavoidable-exogenous
<i>TIC</i>	total investment cost
Abbreviations	
<i>AB</i>	afterburner
<i>AC</i>	air compressor
<i>ABED</i>	afterburner exhaust duct
<i>CC</i>	combustion chamber
<i>CFCO</i>	continuous flow continuous open
<i>FED</i>	forward exhaust duct
<i>GT</i>	gas turbine
<i>GTMS</i>	gas turbine mechanic shaft
<i>MIL</i>	military
<i>PM</i>	process mode
<i>SCI</i>	sustainability cost index
<i>SEF</i>	sustainable effect factor
<i>SEC</i>	section
<i>SPECO</i>	specific exergy cost method
<i>TJE</i>	turbojet engine

Appendix A

Table A1. Values for energy rate, exergy rate, mass flowrate, pressure and specific heat capacity for the system sections for JP-8 fuel utilization (*: solely for Afterburner (AB) process mode) [63].

State No.	Fluid type	$\dot{m}(\text{kg/s})$	P(kPa)	T(K)	$c_p(\text{kJ/kg} \cdot \text{K})$	$\dot{E}(\text{kW})$	$\dot{E}_x(\text{kW})$
0	Air	0.00	101	288	1.00375	0.00	0.00
1	Air	18.12	101	288	1.00375	0.00	0.00
2	Air	18.12	719	572	1.04401	5583	4700
2.1	Air	16.31	719	572	1.04401	5024	4230
2.2	Air	1.81	719	572	1.04401	558	470
2.3	Air	1.81	182	943	1.12946	1405	740
2.4	Air	1.81	179	932	1.12735	1380	720
2.5	Air	1.81	175	920	1.12477	1350	699
2.5*	Air	1.81	175	1,563	1.13501	2691	1714
3	Military fuel	0.36	245	298	-	15,593	16,554
4	Combustion gas	16.67	683	1177	1.23710	19,454	13,258
5	Combustion gas	16.67	182	943	1.18586	13,811	7156
6	Combustion gas	16.67	179	932	1.18345	13,568	6966
7	Combustion gas	16.67	175	920	1.18055	13,277	6746
7*	Combustion gas	17.41	175	1,563	1.38960	32,784	20,164
10*	Afterburner fuel	0.74	245	298	-	31,972	33,941
8	Mechanical work	-	-	-	-	5640	5640
9	Mechanical work	-	-	-	-	5583	5583

Table A2. Values for energy rate, exergy rate, mass flowrate, pressure and specific heat capacity for the system sections for H₂ fuel utilization (*: solely for AB process mode) [63].

State No.	Fluid Type	$\dot{m}(\text{kg/s})$	P(kPa)	T(K)	$c_p(\text{kJ/kg} \cdot \text{K})$	$\dot{E}(\text{kW})$	$\dot{E}_x(\text{kW})$
0	Air	0.00	101	288	1.00375	0.00	0.00
1	Air	18.12	101	288	1.00375	0.00	0.00
2	Air	18.12	719	572	1.04401	5583	4700
2.1	Air	16.31	719	572	1.04401	5024	4230
2.2	Air	1.81	719	572	1.04401	558	470
2.3	Air	1.81	182	923	1.12550	1359	710
2.4	Air	1.81	179	912	1.12319	1332	690
2.5	Air	1.81	175	894	1.11934	1289	665
2.5*	Air	1.81	175	1532	1.14204	2647	1677
3	Military fuel	0.13	245	298	-	15,593	17,594
4	Combustion gas	16.44	683	1156	1.27884	19,550	13,349
5	Combustion gas	16.44	182	923	1.22356	13,813	7059
6	Combustion gas	16.44	179	912	1.22086	13,552	6857
7	Combustion gas	16.44	175	894	1.21645	13,125	6551
7*	Combustion gas	16.71	175	1532	1.38537	30,629	18,853
10*	Afterburner fuel	0.27	245	298	-	31,972	36,075
8	Mechanical work	-	-	-	-	5737	5737
9	Mechanical work	-	-	-	-	5583	5583

Table A3. Results for endogenous, exogenous, unavoidable and avoidable exergy demolition of the TJE and its sections for the MIL process mode for JP-8 utilization [63].

SEC.	$\dot{E}_D^{RL}(\text{kW})$	$\dot{E}_D^{UN}(\text{kW})$	$\dot{E}_D^{AV}(\text{kW})$	$\dot{E}_D^{EX}(\text{kW})$	$\dot{E}_D^{EN}(\text{kW})$	$\dot{E}_D^{UNEN}(\text{kW})$	$\dot{E}_D^{UNEX}(\text{kW})$	$\dot{E}_D^{AVEN}(\text{kW})$	$\dot{E}_D^{AVEX}(\text{kW})$
AC	883	722	161	132	750	610	112	141	20.01
CC	7525	7318	208	690	6835	6644	674	191	16.34
GT	193	117	75.95	12.02	181	109	8.00	71.93	4.02
FED	209	137	72.50	25.98	183	119	17.59	64.11	8.39
ABED	241	134	107	33.06	208	115	19.42	93.71	13.64
GTMS	57.13	31.15	25.98	3.90	53.23	28.89	2.26	24.34	1.64
TJE	9109	8459	650	897	8212	7,626	833	586	64.04

Table A4. Results for endogenous, exogenous, unavoidable and avoidable exergy demolition of TJE and sections for the AB process mode for JP-8 utilization [63].

SEC.	$\dot{E}_D^{RL}(\text{kW})$	$\dot{E}_D^{UN}(\text{kW})$	$\dot{E}_D^{AV}(\text{kW})$	$\dot{E}_D^{EX}(\text{kW})$	$\dot{E}_D^{EN}(\text{kW})$	$\dot{E}_D^{UNEN}(\text{kW})$	$\dot{E}_D^{UNEX}(\text{kW})$	$\dot{E}_D^{AVEN}(\text{kW})$	$\dot{E}_D^{AVEX}(\text{kW})$
AC	883	722	161	132	750	610	112	141	20.01
CC	7525	7318	208	690	6835	6644	674	191	16.34
GT	193	117	75.95	12.02	181	109	8.00	71.93	4.02
FED	209	137	72.50	25.98	183	119	17.59	64.11	8.39

ABED	19,728	16,727	3001	3329	16,399	13,867	2859	2532	469
GTMS	57.13	31.15	25.98	3.90	53.23	28.89	2.26	24.34	1.64
TJE	28,595	25,052	3544	4193	24,403	21,378	3673	3024	520

Table A5. Results for endogenous, exogenous, unavoidable and avoidable exergy demolition of TJE and sections in advanced exergy evaluation for the MIL process mode for H₂ utilization [63].

SEC.	$\dot{Ex}_D^{RI}(\text{kW})$	$\dot{Ex}_D^{UN}(\text{kW})$	$\dot{Ex}_D^{AV}(\text{kW})$	$\dot{Ex}_D^{EX}(\text{kW})$	$\dot{Ex}_D^{EN}(\text{kW})$	$\dot{Ex}_D^{UNEN}(\text{kW})$	$\dot{Ex}_D^{UNEX}(\text{kW})$	$\dot{Ex}_D^{AVEN}(\text{kW})$	$\dot{Ex}_D^{AVEX}(\text{kW})$
AC	883	722	161	120	763	621	101	142	18.66
CC	8475	8174	300	861	7614	7349	826	265	35.24
GT	313	212	101	49.74	263	174	38.40	89.87	11.34
FED	223	140	82.43	21.69	201	125	15.67	76.41	6.02
ABED	330	182	149	43.50	287	153	28.88	134	14.62
GTMS	154	87.25	67.16	14.14	140	79.22	8.03	61.05	6.11
TJE	10,378	9518	860	1110	9269	8500	1018	768	91.99

Table A6. Results for endogenous, exogenous, unavoidable and avoidable exergy demolition of TJE and sections in advanced exergy evaluation for the AB process mode for H₂ utilization [63].

SEC.	$\dot{Ex}_D^{RI}(\text{kW})$	$\dot{Ex}_D^{UN}(\text{kW})$	$\dot{Ex}_D^{AV}(\text{kW})$	$\dot{Ex}_D^{EX}(\text{kW})$	$\dot{Ex}_D^{EN}(\text{kW})$	$\dot{Ex}_D^{UNEN}(\text{kW})$	$\dot{Ex}_D^{UNEX}(\text{kW})$	$\dot{Ex}_D^{AVEN}(\text{kW})$	$\dot{Ex}_D^{AVEX}(\text{kW})$
AC	883	722	161	120	763	621	101	142	18.66
CC	8475	8174	300	861	7614	7349	826	265	35.24
GT	313	212	101	49.74	263	174	38.40	89.87	11.34
FED	223	140	82.43	21.69	201	125	15.67	76.41	6.02
ABED	23,066	19,083	3,982	4297	18,769	15,469	3614	3299	68
GTMS	154	87.25	67.16	14.14	140	79.22	8.03	61.05	6.11
TJE	33,113	28,419	4694	5363	27,750	23,816	4603	3934	760

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