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# Thermodynamic, thermoeconomic and environmental performance analyses of a commercial aircraft's high bypass turbofan engine

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**Abstract**

Exergetic, exergoeconomic and exergoenvironmental performance analyses of a commercial aircraft's high bypass turbofan engine are studied to predict thermodynamic efficiency of whole engine, exergy cost flow of product and waste exergy, and the environmental damage cost formation of engine emissions emitted to environment. According to this study, the GE90-115 high bypass turbofan engine produces 324.59 GJ/h-kinetic exergy rate while it burns 4.104 kg/s Jet-A fuel. The energy and exergy efficiency values of the engine are estimated to be 51.00% and 48.05%. The fuel cost rate is calculated to be 9632.91 US$/h when the specific fuel exergy cost is found to be 14.24 US$/GJ. The specific product exergy cost is obtained to be 32.23 US$/GJ. However, the total environmental damage cost rate of engine emissions (UHC, CO and NOx) is accounted to be 4552.83 US$/h as long as the specific environmental damage cost is determined to be 14.02 US$/GJ. As a result, the specific exergoenvironmental cost is calculated to be 46.25 US$/GJ for Jet-A fuel.

**Keywords:** Turbofan engine, exergy analysis, exergoeconomic analysis, exergoenvironmental analysis

## 1. INTRODUCTION

Aviation plays a key role in the economic improvement and daily life. It contributes to our quality of life by enabling the movement of people and products all over the globe quickly and safely. The air transport industry has grown rapidly over the years, and this growth is expected to continue [1].

Advancing growth in civil aviation can be attributed to an increasingly globalized society, but at the expense of surges in energy consumption and health threatening pollution. With heightened public environmental awareness, increasing effort is being put into research on issues of aviation-related environmental protection [2]. Aviation sector produces about 2% of total global greenhouse gases (GHG) emissions because aircrafts consumes approximately 2-3% of total fossil fuel consumption in worldwide. If the present increasing rates of air travelling keep on, this tendency is prediction to augment to approximately 3% by 2050 [3].

Two methods are usable to make less environmental influences of aviation sector. One of the methods is to down the exhaust emissions with alternative and clean fuel burnt, and renewable energy consumption [4]. The other method is to peak the thermodynamic efficiency of aircraft propulsion systems hence heightened efficiency values decreases fuel using in aircraft engine for regular thrust or power generation. The most significant criteria in improving the performance of a thermal system are the energetic and exergetic efficiencies. Thermodynamic defiencies of processes are designated and quantified by exergy analysis. Exergy is indicated as maximum useful work potential of a system and it is a measure of the usefulness of energy. Exergy analysis points out the places, amplitudes, and source use of thermodynamic inefficiencies in an energy conversion system [5]. Exergy analysis is helpful for determining the locations and calculating the magnitudes of the

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irreversibilities within a thermodynamic system. Using the result of exergy analysis, the potential for the progression in the performance of the system can be recognized [6].

Exergy analysis can be effectively employed to analyze and optimize energy systems compared with the energy analysis, but it still suffers from several drawbacks such as overlooking the financial and environmental aspects of processes under consideration. In better words, economic and environmental analyses are also essential in order to thoroughly determine the profitability and sustainability of an improvement achieved through the exergy analysis [7].

Besides the effective use of energy sources and valuably, the environmental impacts of a system must be estimated and classified the designing levels for progressing a sustainable process. System owners and designers have been advancing technologies that decrease environmental affects, rise up efficiencies, and lessen fuel consumptions and exhaust emissions. Exergoeconomic analysis is composed of exergy analysis, economic analysis and formation of exergy costs. These analyses are generally carried on the level of system components. Exergy analysis is used for obtaining the waste exergy rates. The economic analysis supplies the cost values associated with the capital investment, operating and maintenance costs of an investigated system. The cost flows of materials and exergy streams in a process are accounted. However, thermodynamic imperfections in all sections of a system are identified (e.g., exergy destruction and loss). Waste exergy and investment costs of a system give usable data in advancing the monetary payment affectivity of the system subcomponent. Exergoeconomic analysis also emphasizes the important points of a system where structural and parametric values can be changed [8].

Climate change politics, such as emitted carbon taxes or emissions tolerations, have been influencing the aviation transportation sector in the recent decade. In this regard, the environmental impact cost flow is presumed to be counted up directly to the payments that should be repaid. In this investigation, environmental analysis methodology covers the environmental harms cost flows and examines the affects of environmental damage cost formation on the cost flow of the system's production [9-10].

To the best of author's experiences, there is no published report and study up to now on the thermodynamic (energy and exergy), thermoeconomic (exergoeconomic) and environmental damage cost performance analyses of a GE90-115B high bypass turbofan engine used on Boing 777 aircraft. Therefore, the goal of this study is to implement the energy, exergy, exergoeconomic and exergo-environmental analyses on a high bypass turbofan engine fueled by Jet-A fuel first time.

## 2. METHODOLOGY

The relations and performance metrics of the energy, exergy, exergoeconomic and environmental damage cost analyzing methodology are identified step by step as following.

### 2.1. Thermodynamic Analysis

Thermodynamic analysis consists of standard aviation performance metrics (specific thrust and specific fuel consumption), energy analysis (first law efficiency and waste energy ratio) and exergy analysis (exergy efficiency, exergetic improvement potential, waste exergy ratio, environmental effect index, ecological effect index, exergetic sustainability factor and sustainable efficiency index).

#### 2.1.1. Standard aviation performance metrics

Specific thrust and specific fuel consumption are well-known standard aviation metrics.

- Specific thrust (*ST*) can be obtained from the ratio of engine power to air mass flow rate as following [11]:

$$ST = \frac{ET}{\dot{m}_a} \tag{1}$$

Where the $ST$, $ET$ and $\dot{m}_a$ denote the specific thrust, the engine thrust and the air mass flow, respectively. The maximum value of *ST* is desired to be maximized in cycle performance. The higher *ST* provides maximum thrust level with a minimum of engine inlet area and minimum air flow rate.

- Specific fuel consumption (*SFC*) is estimated from the ratio of fuel flow rate to engine power as following [11]:

$$SFC = \frac{\dot{m}_F}{ET} \tag{2}$$

Here the $SFC$ and $\dot{m}_F$ represent the specific fuel consumption and fuel mass flow. The minimum *SFC* value is desired to minimize fuel consumption and to maximize cycle performance.

### 2.1.2. Energy analysis

Energy analysis is based on first law of thermodynamics. The energy analysis method supplies the information in regard the energy efficiency, product energy and energy losses form system to the environment, but this analysis does not provide enough detail data about the causes, locations, and types of energy losses rate. The energy balance equation for a steady-state system may be written as [12-15]:

$$\dot{E}_F = \dot{E}_{\mathrm{Pr}} + \dot{E}_{WE} \tag{3}$$

Here $\dot{E}_F, \dot{E}_{\mathrm{Pr}}$ and $\dot{E}_{WE}$ represent the fuel energy rate, product energy rate and waste energy rate. The energy rate of fuel $(\dot{E}_F)$ is obtained from:

$$\dot{E}_F = \dot{m}_F LHV_F \tag{4}$$

Where the $LHV_F$ is lower heating value of fuel. The engine thrust equation for turbojet engine can be estimated from the following momentum equation [12-17]:

$$ET = (\dot{m}V)_{out} - (\dot{m}V)_{in} + A_{out}(P_{out} - P_{in}) \tag{5}$$

Here, the $V$, $A$ and $P$ are velocity, area and pressure at inlet and outlet of engine. The $V_{in}$ is zero if the engine is operated at a rigid position as a ground running or a test cell. Hence the engine power, the exhaust mass rate, the inlet and outlet pressure values and area of exhaust duct are known, the velocity of exhaust duct outlet gases can be counted by eqn. (5). In this regard, the product energy rate of turbofan engine is accounted by [12-17]:

$$\dot{E}_{\mathrm{Pr}} = \dot{m}_{eg} \frac{V_{eg}^2}{2} \tag{6}$$

Where the $\dot{m}_{eg}$ and $V_{eg}$ denote exhaust gases mass flow and velocity. Energetic performance metrics are given as following [12-17]:

- Energy efficiency $(\eta)$ is figured out by:

$$\eta = \frac{\dot{E}_{\mathrm{Pr}}}{\dot{E}x_F} = 1 - \frac{\dot{E}_{WE}}{\dot{E}x_F} \tag{7}$$

- Waste energy ratio $(\alpha)$ is computed by:

$$\alpha = \frac{\dot{E}_{WE}}{\dot{E}_F} = 1 - \eta \tag{8}$$

### 2.1.3. Exergy analysis

In comparison with energy analysis, exergy analysis method gives effective and useful information for determining the locations, sources, sizes and magnitudes of thermodynamic inefficiencies within an energy conversion system or process. The exergy balance equation for an energy conversion system is given as:

$$\dot{E}x_F = \dot{E}x_{\mathrm{Pr}} + \dot{E}x_{WEx} \tag{9}$$

Here $\dot{E}x_F, \dot{E}x_{\mathrm{Pr}}$ and $\dot{E}x_{WEx}$ symbolize the fuel exergy rate, product exergy rate and waste exergy rate. The chemical exergy stream $(\dot{E}x_{CH,F})$ of fuel is estimated by [13-15, 17-18]:

$$\dot{E}x_{CH,F} = (\dot{m}LHV\xi)_F \tag{10}$$

The lower heating value (*LHV*) of the Jet-A fuel is assumed to be 43080 kJ/kg [19]. The $\xi$ expresses the fuel exergy property of liquid fuel. The $\xi$ is obtained to be 1.06124 for Jet-A jet engine fuel $(C_{11.6}H_{22})$ from the following equation [13-14, 17-18]:

$$\xi \cong 1.04224 + 0.011925\frac{b}{a} - \frac{0.042}{a} \tag{11}$$

The kinetic exergy rate as product exergy of turbofan engine is accaunted from[12-17]:

$$\dot{E}x_{\mathrm{Pr}} = \dot{m}_{eg} \frac{V_{eg}^2}{2} \tag{12}$$

Exergetic performance metrics are foud out from following relations [13-15, 17, 20-25]:

- Exergy efficiency $(\psi)$:

$$\psi = \frac{\dot{E}x_{\mathrm{Pr}}}{\dot{E}x_F} = 1 - \frac{\dot{E}x_{WEx}}{\dot{E}x_F} \tag{13}$$

- Exergetic improvement potential $(ExIP)$:

$$\dot{E}xIP = (1-\psi)\dot{E}x_{WEx} \tag{14}$$

- Waste exergy ratio $(\beta)$:

$$\beta = \frac{\dot{E}x_{WEx}}{\dot{E}x_F} = 1 - \psi \tag{15}$$

- Environmental effect factor $(EEF)$:

$$EEF = \frac{\beta}{\psi} \tag{16}$$

- Ecological effect factor $(EcoEF)$:

$$EcoEF = \frac{1}{\psi} \tag{17}$$

- Exergetic sustainability index $(ESI)$:

$$ESI = \frac{1}{EEF} \tag{18}$$

- Sustainable efficiency factor:

$$SEF = \frac{1}{1-\psi} \quad (19)$$

### 2.2. Thermoeconomic analysis

Thermoeconomic analysis consists of economic analysis, exergoeconomic analysis and exergoeconomic performance metrics.

#### 2.2.1. Economic analysis

The economic analysis includes the hourly levelized cost rate of total capital investment $\left(\dot{Z}^{TCI}\right)$, the hourly levelized cost rate of operation and maintenance processes $\left(\dot{Z}^{OM}\right)$, the hourly levelised cost rate of total cost formation $\left(\dot{Z}^{tot}\right)$, and the hourly levelized cost rate of jet fuel $\left(\dot{C}_F\right)$. In order to obtain $\dot{Z}^{TCI}_{sys}$, the hourly levelized cost methodology is selected for this study. The steps of this methodology are given as following [6, 9-10, 25-28];

- The present worth of the turbofan engine $\left(PW_{sys}\right)$ :

$$PW_{sys} = TCI_{sys} - SV_{sys} PVF(i,n) \quad (20)$$

Where $TCI$ is the total capital investment of engine system.

- The salvage value $\left(SV_{sys}\right)$:

$$SV_{sys} = TCI_{sys}\pi \quad (21)$$

- The present value factor $\left(PVF\right)$:

$$PVF = \frac{1}{(1+i)^n} \quad (22)$$

Here the $i$ and $n$ imply interest rate and life time of system.

- The annual capital cost $\left(ACC_{sys}\right)$:

$$ACC_{sys} = PW_{sys} CRF(i,n) \quad (23)$$

- The recovery factor of capital $\left(CRF\right)$ :

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (24)$$

- The hourly levelised cost rate of total capital investment $\left(\dot{Z}^{TCI}_{sys}\right)$ for the engine:

$$\dot{Z}^{TCI}_{sys} = \frac{ACC_{sys}}{\tau} \quad (25)$$

Where the $\tau$ stands for the annual operation hours of engine.

- The hourly levelised cost rate of operating and maintanence $\left(\dot{Z}^{OM}_{sys}\right)$ for the turbofan engine:

$$\dot{Z}^{OM}_{sys} = \frac{OMC_{sys}}{\tau} \quad (26)$$

Where the $OMC$ represents the yearly overhaul and maintanence cost rate of the engine.

- Additionally, the levelized hourly cost rate $\left(\dot{C}_F\right)$ of jet fuel is determined by:

$$\dot{C}_F = 3600 \dot{m}_F FSP \quad (27)$$

Where the $FSP$ is the fuel selling price.

#### 2.2.2. Exergoeconomic analysis

The target of exergoeconomic analyzing methodology is to comprehend the cost generation process and to predict the cost flow of product generated by the turbofan engine system in this study. Several methods for the exergy cost calculation are recommended in the open literature. But, the Specific Exergy Costing (SPECO) method is widely used for researchers and the SPECO method is chosen for this work. The general cost formation balance relation of the turbofan engine system can be written as following [6, 9-10, 25-28]:

$$\dot{C}_{F,sys} + \dot{Z}^{tot}_{sys} = \dot{C}_{\mathrm{Pr},sys} \quad (28)$$

Where the $\dot{C}$ denotes the total hourly cost rate while the $\dot{Z}^{tot}_{sys}$ represents the hourly levelized total cost flow of the system.

The $\dot{Z}^{tot}_{sys}$ is obtained from [6, 9-10, 25-28];

$$\dot{Z}^{tot}_{sys} = \dot{Z}^{TCI}_{sys} + \dot{Z}^{OM}_{sys} \quad (29)$$

#### 2.2.3. Exergoeconomic performance metrics

To compare with the exergoeconomic performances of investigated systems, some performance metrics are developed and used. The exergoeconomic performance metrics are average cost per unit exergy of fuel $\left(c_F\right)$ and product $\left(c_{\mathrm{Pr}}\right)$ which are explained as [6, 9-10, 25-28]:

$$c_F = \frac{\dot{C}_F}{\dot{E}x_F} \tag{30}$$

$$c_{\Pr} = \frac{\dot{C}_{\Pr}}{\dot{E}x_{\Pr}} \tag{31}$$

Relative cost difference $(\phi)$ is described based on explanation of average cost per unit exergy of fuel and product of the system or component. The relative cost difference is predicted by [6, 9-10, 25-28]:

$$\phi = \frac{c_{\Pr} - c_F}{c_F} \tag{32}$$

This parameter denotes the variety between the average cost of products and fuels which is due to the exergy destruction and the investment cost. The exergoeconomic factor is related to waste exergy (destruction and losses) and the total hourly levelized cost rate. The waste exergy cost flow $(\dot{C}_{WEx})$ and exergoeconomic factor $(\varphi)$ are estimated by [6, 9-10, 25-28]:

$$\dot{C}_{WEx} = c_F \dot{E}x_{WEx} \tag{33}$$

$$\varphi = \frac{\dot{Z}^{tot}}{\dot{Z}^{tot} + \dot{C}_{WEx}} \tag{34}$$

Where the $\dot{C}_{WEx}$ is the cost rate of waste exergy. The exergoeconomic factor $(\varphi)$ is a performance tool for comparing the importance of an investigating system's investment cost flow with the waste exergy cost flow associated with the system.

### 2.3. Environmental analysis

#### 2.3.1 Environmental damage cost analysis

Environmental damage cost formation consists of the sum of all pollutant damage cost rates stemming from emissions such as carbon monoxide (CO), carbon dioxide ($CO_2$), nitrogen dioxide ($NO_2$), sulfur dioxide($SO_2$), particular materials (PM), volatile organic compounds (VOC), unburned hydrocarbons (UHC). The environmental cost rate is occured by multiplying emissions' flow rates by their corresponding unit damage cost of each emission.

The cost flow of exhaust emissions for the considered system can be calculated by [9-10, 25, 29-31]:

$$\dot{C}_{env} = c_{CO}\dot{m}_{CO} + c_{NO_X}\dot{m}_{NO_X} + c_{UHC}\dot{m}_{UHC} \tag{35}$$

Where the $\dot{C}$ is the environmental damage cost rate of GHG emission, the $c_{UHC}, c_{CO}$ and $c_{NO_x}$ are the specific costs of UHC, CO, $NO_x$ avoided $\dot{m}_{UHC}, \dot{m}_{CO}$ and $\dot{m}_{NO_x}$ are the mass flow rate of UHC, CO and $NO_x$-emissions. In accordance with the ECO-COST 2007 Life Cycle Assessment (LCA) data for emissions and material depletion, the specific damage cost values $(c)$ of the UHC, CO and $NO_x$ are listed to be 4.388 \$/kg , 0.176 \$/kg and 6.871 \$/kg [9-10, 25, 29-30]:

#### 2.3.2 Exergoenvironmental cost analysis

In this study, the exergo-environmental cost formation $(\dot{C}_{exen})$ equals to the sum of the exergoeconomic cost flow $(\dot{C}_{ex})$ and environmental damage cost flow $(\dot{C}_{env})$. The exergoenvironmental cost rate can be accounted by [9-10, 25, 31]:

$$\begin{aligned}\dot{C}_{exen} &= \dot{C}_{ex} + \dot{C}_{env} = \left(\dot{C}_F + \dot{Z}^{TIC} + \dot{Z}^{OM}\right) + \dot{C}_{env} \\ &= \left(\dot{C}_F + \dot{Z}^{tot}\right) + \dot{C}_{env}\end{aligned} \tag{36}$$

The specific exergoenvironmental cost $(c_{exen})$ of the engine product can be estimated from [9-10, 25, 31]:

$$c_{exen} = \frac{\dot{C}_{exen}}{\dot{E}x_{\Pr}} \tag{37}$$

## 3. ENGINE DATA AND METARIAL

### 3.1. Engine technical data

The GE90 series turbofan engine was developed and built for the Boeing 777 commercial aircrafts by General Electric. It is a part of high-bypass turbofan aircraft engines family. The GE90 engines have the thrust ratings ranging from 330 to 510 kN. It entered service with British Airways in November 1995. The GE90-115B high bypass turbofan engine is currently the world's largest and the most powerful turbofan engine. It has been used on Boing 777-200, -200ER,-200LR,-300/-300ER versions and 777F.
The main components and sections of GE90-115B engine are illustrated in Figure 1. Technical data can be listed as following [32]:

- Type: high bypass turbofan engine with axial flow and twin-shaft
- Length: 7.290 m
- Diameter**:** overall: 3.429 m; fan: 3.251 m
- Dry weight: 8283 kg

- Compressor section:
  - ✓ 1 stage axial swept fan with wide chord
  - ✓ 4 stages low pressure compressor
  - ✓ 9 stages high pressure compressor
- Combustion Section:
  - ✓ Dual annular combustor
  - ✓ Low $NO_x$ emission
- Turbine Section:
  - ✓ 2 stages axial high pressure turbine
  - ✓ 6 stages axial low pressure turbine
- Control system:
  - ✓ Full Authority Digital Engine Control
- Performances:
  - ✓ Maximum TO thrust at SL: 514 kN
  - ✓ Air flow rate:1461 kg/s
  - ✓ Fuel consumption:4.104 kg/s
  - ✓ Bypass ratio: 8.9:1
  - ✓ Overall pressure ratio: 42:1
  - ✓ Thrust-to-weight ratio: approx. 6.3:1

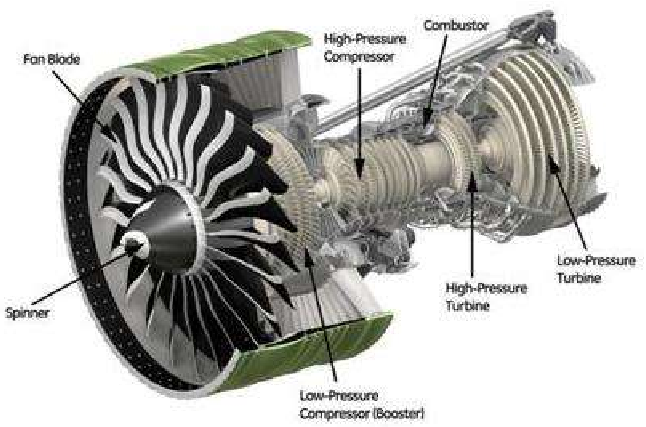


Figure 1. Cutaway of GE90-115B engine

### 3.2. Engine economical data

For economical analysis, the economical data of the engine are given as following:

- Total Capital Investment Cost of engine $(TCI)$ :16,000,000.00 US$ [33]
- Engine overhaul and maintenance cost $(OMC)$ :800,000.00 US$ [34]
- Engine operation hours $(\tau)$ in a year: 3000 h [34]
- Interest rate $(i)$: 10%
- Engine life time $(n)$:30 yr
- Engine salvage ratio $(\pi)$: 15%

Using these data; the present worth $(PW)$, present value factor $(PVF)$, capital recovery factor $(CRF)$, annual capital cost $(ACC)$, hourly levelized total capital investment cost rate $(\dot{Z}_{sys}^{TCI})$, hourly levelized operating and maintenance cost rate of the system $(\dot{Z}_{sys}^{OM})$ and total hourly levelized total cost rates of engine $(\dot{Z}_{sys}^{tot})$ are estimated to be 15862459.0 US$, 0.05731, 0.1061, 1682678.0 US$/yr, 560.893 US$/h, 266.667 US$/h, and 827.559 US$/h, respectively.

### 3.3. Fuel data

Jet engine, turbofan engine, turboprop and turboshaft engine used on commercial aviation consumes Jet-A/-A1 as a fuel. The LHV of the Jet-A fuel is 43080 kJ/kg [19]. The chemical exergy of Jet-A fuel is calculated to be 45718.03 kJ/kg from eqn. (11). Fuel selling price $(FSP)$ of Jet-A is announced as 0.652 US$/kg [35]. The hourly fuel cost rate $(\dot{C}_F)$ of the engine is computed to be 9632.91 US$/h while the engine consumes 4.104 kg/s Jet-A fuel for takeoff operation mode at sea level.

### 3.4. Emission data

The exhaust emission rate emitted from GE90 series engines excepting GE90-115B were estimated by National Pollutant Inventory Group in Australia [36]. For GE-115B turbofan engine running takeoff operation at sea level; the emission values of the unburned hydrocarbons (UHC), carbon monoxide (CO), and nitrogen oxides ($NO_x$) are derived from GE90-92B turbofan engine as 0.621 kg/h, 2.313 kg/h and 861.008 kg/h, respectively.

## 4. RESULTS AND DISCUSSION

### 4.1. Results of thermodynamic analysis

The GE-90-115B engines 514 kN while it engine consumes 1461 kg/s-air flow. In this regard, the specific thrust is calculated to be 0.352 kN/kg/s. On the other hand, the specific fuel consumption is estimated to be 0.00798 kg/(kN.s) since the engine consumes 4.104 kg/s Jet-A fuel.

The engine generates 324.586 GJ/h- kinetic energy rate as a product when it consumes 636.481 GJ/h- fuel energy rate. In this case, the energy efficiency of the engine is obtained to be 51.0% while the waste energy ratio is found to be 49.0%.

The GE90-115 engine produces 324.586 GJ/h- kinetic exergy rate when it consumes 675.457 GJ/h- fuel exergy rate. In this situation, the exergy efficiency of the engine is accaunted to be 48.05% when the waste exergy ratio is figured out to be 51.95%. The energy and exergy rates and efficiencies of the engine are illustrated in Figure 2.

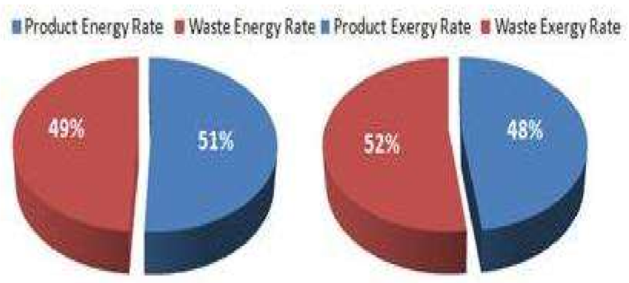


Figure 2. Product and waste energy and exergy rates and efficiency values of the engine

The some exergetic performance metrics are indicated in Fig. 3. According to Fig.3, the exergetic improvement potential of the engine is retrived to be 182.26 GJ/h while the environmental effect factor, ecological effect factor, exergetic sustainability index and sustainable efficiency factor are estimated to be 1.081, 2.081, 0.925 and 1.925, respectively.

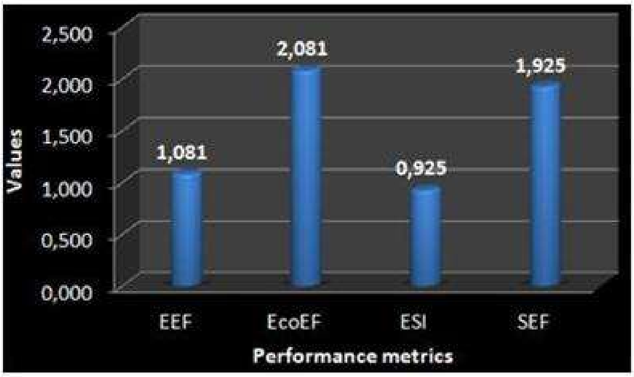


Figure 3. Exergetic performance indicators

### 4.2. Results of thermoecomic analysis

The total hourly levelized capital investment and O&M cost rates of engine $\left(\dot{Z}_{sys}^{tot}\right)$ are estimated to 827.559 US$/h during the hourly fuel cost rate $\left(\dot{C}_F\right)$ of the engine is computed to be 9632.91 US$/h. Because the engine consumes it consumes 675.457 GJ/h- fuel exergy rate, the specific fuel exergy cost is accounted to be 14.26 US$/GJ.

The engine product cost rate is found to be 10460.47 US$/h for engine product. Since the GE90-115 engine produces 324.586 GJ/h-kinetic exergy rate, the specific product exergy cost is determined to be 32.23 US$/GJ.

When the exergoeconomic performance metrics are analyzed, the relative cost difference and exergoeconomic factor are calculated to be 125.98% and 70.23%, respectively.

### 4.3. Results of environmental analysis

The environmental damage cost rates of UHC, CO and $NO_x$ are calculated to be 2.095 USA$/h, 0.312 US$/h and 4550.43 US$/h, respectively. Therefore, the total environmental damage cost rate $\left(\dot{C}_{env}\right)$ is obtained to be 4552.83 USA$/h. So the GE90-115 engine produces 324.586 GJ/h-kinetic exergy rate, the specific environmental damage cost is obtained to be 14.03 US$/GJ.

The exergoenvironmental cost rate of the engine product $\left(\dot{C}_{exen} = \dot{C}_{ex} + \dot{C}_{env}\right)$ is estimated to be 15013.40 US$/h. In this case, the specific exergoenvironmental cost is obtained to be 46.25 US$/GJ. The specific cost values and exergoeconomic performance metrics are demonstrated in Figure 4.

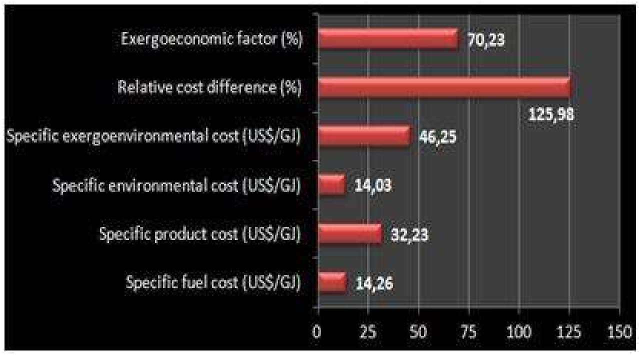


Figure 4. The specific cost values and exergo-economic performance metrics of the engine

## 5. CONCLUSION

Exergetic, exergoeconomic and environmental analyses of a high bypass turbofan engine used on commercial aircraft are investigated for determining the magnitudes of the irreversibilities within a the system, exergy cost formation rates of product and waste exergy, and the environmental damage cost rate of engine emissions. Main remarkable results of this study are summarized as following:

- The specific thrust is calculated to be 0.352 kN/kg/s while specific fuel consumption is estimated to be 0.00798 kg/(kN.s)

- The energy and exergy efficiency values of the engine are estimated to be 51.00% and 48.05%.
- The environmental effect factor, ecological effect factor, exergetic sustainability index and sustainable efficiency factor are estimated to be 1.081, 2.081, 0.925 and 1.925, respectively
- The specific product exergy cost is obtained to be 32.23 US$/GJ when the specific fuel exergy cost is found to be 14.24 US$/GJ.
- The specific exergoenvironmental cost is calculated to be 46.25 US$/GJ as long as the specific environmental damage cost is determined to be 14.02 US$/GJ.

This study is beneficial for researchers who want to work on similar systems and issues. For a future work, the exergetic, exergoeconomic and environmental performances of this engine's major components will be analyzed.

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