

# Novel thermoenvironmental evaluation criteria and comparing them for an actual heat engine



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## ABSTRACT

In the present study, environmental impact analysis is used for the optimization to an actual heat engine. Four new thermoenvironmental evaluation criteria called as thermoenvironmental function, ecological based thermoenvironmental function, ecologicoenvironmental function and finite time exergoenvironmental criteria are developed and compared with the each other. Ecologicoenvironmental function is used to determine environmental impact at the maximum ecological function. It is defined as the most suitable criteria for an actual heat engine. Because, it has lower irreversibilities compared with others, its work output is equal to 90% of the maximum work and 60% energy efficiency at the optimum point and exergy destruction is lower than others at the optimum point.

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## 1. Introduction

Global warming is a serious threat occurred by greenhouse gas emissions. Greenhouse gasses such as carbon dioxide, methane, nitrous oxide and ozone, trap the heat and cause the earth to get warm. Since the industrial revolution, the greenhouse gas emissions have increased and the effect of the global warming has reached sensible levels. Energy production and conversion systems have the largest share of the greenhouse emissions and environmental analysis has great importance for the design, installation and development of these systems [1].

Eco-indicator 99 is a damage oriented method based on the life cycle analysis and it is used for determining the environmental impacts of systems, processes and product. In this method environmental impacts of systems or processes was named as Eco-indicator and presented at the unit milipoints (mPts). Damage functions approach was developed at the Eco-indicator 99 and three types damage such as human health, ecosystem quality and natural resources was defined [2].

There are several methods for the optimization and design for the heat engines. Finite time thermodynamics (FTT) is a new branch and provides more realistic approach than the classical thermodynamics. Finite time thermodynamics is a powerful tool for performance analysis of the thermal cycles. While classical thermodynamic uses the reversible Carnot engine as an idealized limit, FTT research universal limits including the irreversibilities

[3,4]. The idea of cycle including the external irreversibilities, was introduced by Novikov [5], Curzon and Alborn [6]. Curzon and Alborn developed an endoreversible Carnot cycle which has finite time heat transfer process. In finite time thermodynamics, many optimizing criteria developed and used for different thermodynamics cycles. Ecological function (ECF) is the most widely used one and it is suggested by Angulo Brown. He defined ECF as  $\dot{E} = \dot{W} - T_L \dot{S}_{gen}$  and established that ECF significantly reduces entropy production and improves power production by 10% for Curzon Alborn cycle [7]. Yan [8] arranged this performance evaluation criteria by changing loss power as  $T_0 \dot{S}_{gen}$  and he presented ECF as  $\dot{E} = \dot{W} - T_0 \dot{S}_{gen}$ . The ecological criterion function applied to steady-flow irreversible Carnot power by Cheng and Chen [9]. They investigated effect of the reservoir temperature ratio, the capacitance ratio and the irreversibility coefficient on the ECF. Yan and Lin [10] used the ecological optimization criterion to investigate the optimal performance of a class of irreversible three-heat-source refrigerators, such as absorption refrigerators and adsorption refrigerators. They remarked that using the ecological optimization criterion to investigate the optimal performance of an irreversible three-heat-source refrigerator is more effective and advantageous, in addition, ECF can reduce the amount of energy needed for the refrigerator. Some detailed works included Xia et al. [11], Chen et al. [12] and Zhu et al. [13].

For taking into account the internal irreversibilities in the cycle, Ibrahim et al. [14] presented the “coefficient of irreversibility”. De Vos [15] introduced the thermoeconomic optimization method for the first time by applying of the Novikov plant. Sahin and Kodal

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**Nomenclature**

$B$	environmental impact (MJ/mPts)
$b$	environmental impact point (mPts/kg, (mPts/MJ))
$\dot{E}$	ecological function (kW)
$\dot{E}x_D$	exergy destruction rate (kW)
$\dot{Q}$	heat (kW)
$T$	temperature (K)
$W$	power output (kW)
$x, y$	dimensionless parameters
$z$	sum of the heat conductance (kW/K)

**Subscripts**

$C$	the heat exchange of the cold side
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$E$	heat exchange of the hot side
$H$	heat source
$L$	heat sink
$o$	environmental
$R$	reversible

**Greek letters**

$\alpha$	the heat conductance of the hot side
$\beta$	the heat conductance of the cold side
$\eta$	isentropic/energetic efficiency (%)

[16] report a new kind of finite time thermoeconomic optimization for an endoreversible refrigerator and a heat pump. In the study, cooling load for the refrigerator and the heating load for the heat pump per unit total cost are proposed as objective functions for the optimization. Finite-time exergoeconomic are presented in [17–18]. There are some studies used, FIT, thermoeconomic and exergoeconomic methods in the literature [19–32]. Grosu et al. proposed cost correlations and developed a techno-economic optimization of refrigerating machines based on irreversibilities and cost minimization, since irreversibilities have a direct impact on the operating cost [33]. Another thermoeconomic criterion was submitted by Barranco-Jimenez and Sanchez-Salas [34], it may be called as ecological based thermoeconomic function. It can be called as ecological based thermoeconomic function. This criterion determine the thermoeconomic performance of an heat engine at maximum ecological conditions.

Environmental evaluation of thermal systems is relatively new. One of this method was presented by Meyer et al. [35] and it is called as the exergoenvironmental analysis. This analysis combined exergy flows with environmental impacts points suggested by Eco-indicator.

In this study, environmental impact analysis is applied for the actual heat engines by using an irreversible Carnot heat engine first time and four new evaluation criteria named as thermoenvironmental function, ecological based thermoenvironmental function, ecologicoenvironmental function and finite time exergoenvironmental criteria are defined for an actual heat engine. Presented thermoenvironmental criteria are adapted and inspired by the thermoeconomic function, ecological based thermo ecological function, ecological function and finite time exergoeconomic function. System is analyzed, results are presented and these results were compared for the each criteria.

**2. Thermodynamic analysis**

In this paper, an irreversible Carnot heat engine is considered and it is investigated by using novel thermoenvironmental criteria. Heat exchange occurred with the infinite heat source and heat sink. Temperature of heat source and heat sink are  $T_H$  and  $T_L$  respectively. Considered system is shown in Fig. 1.

Heat addition to the system is (kW):

$$\dot{Q}_H = \alpha(T_H - T_E) \quad (1)$$

where  $T_E$  is the heat exchange of the hot side temperature,  $\alpha$  is the heat conductance of the hot side (kW/K). Heat rejection from the system is (kW):

$$\dot{Q}_L = \beta(T_C - T_L) \quad (2)$$

where  $T_C$  is the heat exchange of the cold side,  $\beta$  is the heat conductance of the cold side (kW/K). From the first law of the thermodynamics, power output can be described as:

$$\dot{W} = \dot{Q}_H - \dot{Q}_L \quad (3)$$

From the second law of the thermodynamics, Clausius inequality is:

$$\frac{\dot{Q}_H}{T_E} - \frac{\dot{Q}_L}{T_C} \leq 0 \quad (4)$$

This inequality can be converted to equality by defining a dimensionless parameter called internal irreversibility parameter,  $I$  [14].

$$I \frac{\dot{Q}_H}{T_E} = \frac{\dot{Q}_L}{T_C} \quad (5)$$

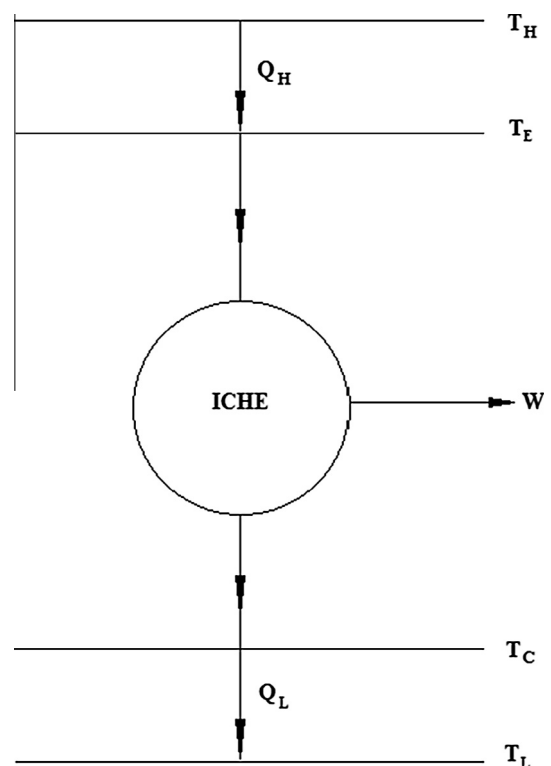


Fig. 1. Schematic of the irreversible Carnot heat engine (ICHE).

Exergy destruction is the measurement of the irreversibilities or lost work in the system and it is equal to environment temperature ( $T_o, K$ ) multiply entropy generation rate (kW/K). Exergy destruction rate (kW) is written as following:

$$ExD = T_o \left( \frac{\dot{Q}_L}{T_L} - \frac{\dot{Q}_H}{T_H} \right) \quad (6)$$

First law efficiency:

$$\eta = \frac{\dot{W}}{\dot{Q}_H} \quad (7)$$

Exergy efficiency:

$$\varphi = \frac{\dot{W}}{\dot{W}_R} \quad (8)$$

Ecological function (kW) can be defined as:

$$\dot{E} = \dot{W} - ExD \quad (9)$$

Reversible work per unit time of the system (kW) is difference of exergy input of the system and exergy output from the system and it is described as following:

$$\dot{W}_R = \dot{Q}_H \left( 1 - \frac{T_o}{T_H} \right) - \dot{Q}_L \left( 1 - \frac{T_o}{T_L} \right) \quad (10)$$

environmental impact of the exergy destruction is resulted from the losses in the system.  $b_3$  (mPts/MJ) is the environmental impact of the lost work and it is assumed as:

$$b_3 = (1 - \varphi)b_4 \quad (14)$$

Last criteria is defined as finite time exergoenvironmental criteria. This criteria is expressed as following:

$$B_{FTE} = b_5 W_R - b_4 W \quad (15)$$

where  $b_5$  is the environmental impact of the reversible power output (mPts/MJ). It is assumed as following:

$$b_5 = b_4 / \varphi \quad (16)$$

Using the methodology in Refs. [12,36] and Eqs. (1)–(16) thermodynamic analyses were made.

$$x = \frac{T_E}{T_C}, \quad y = \frac{\alpha}{\beta}, \quad z = \alpha + \beta \quad (17)$$

$$T_E = \frac{T_H I y + T_L x}{(1 + I y)} \quad (18)$$

$$\dot{Q}_H = \frac{z y}{y + 1} \left( \frac{T_H - T_L x}{(1 + I y)} \right) \quad (19)$$

Criteria referred equations between (19) and (22) can be written as following:

$$B = \frac{3.6 T_H T_L (x(T_H - T_L x) + I(T_L x - T_H)) y z}{(3.6 b_4 T_H T_L (T_H x + I T_L x - I T_H - T_L x^2) + 3.6 b_2 T_H T_L x (T_H - T_L x) + b_3 T_o (3.6 I T_H (T_H - T_L x) + 3.6 T_L x (T_L x - T_H))) y z + b_1 m T_H T_L T_o x (1 + I y) (1 + y)} \quad (20)$$

$$B_E = \frac{T_L x (3.6 (T_H^2 + T_H T_o - T_H T_L x - T_L T_o x)) + I T_H (3.6 T_L x (T_L + T_o) - 3.6 T_H (T_L - T_o)) y z}{(3.6 b_4 T_H T_L (T_H x + I T_L x - I T_H - T_L x^2) + 3.6 b_2 T_H T_L x (T_H - T_L x) + b_3 T_o (3.6 I T_H (T_H - T_L x) + 3.6 T_L x (T_L x - T_H))) y z + b_1 m T_H T_L T_o x (1 + I y) (1 + y)} \quad (21)$$

$$B_{EC} = \frac{(3.6 b_4 T_H T_L (T_H x + I T_L x - I T_H - T_L x^2) + b_3 T_o (3.6 I T_H (T_L x - T_H) + 3.6 T_L x (T_L x + T_H))) y z}{T_H T_L x (1 + y) (1 + I y)} \quad (22)$$

$$B_{FTE} = \frac{(3.6 b_4 T_H T_L (I T_H + T_L x^2 - T_H x - I T_L x) + b_5 (3.6 I T_H (T_L x^2 + T_H T_o - T_H T_L - T_L T_o x) + 3.6 T_L x (T_H^2 - T_H T_o - T_H T_L + T_L T_o x))) y z}{T_H T_L x (1 + y) (1 + I y)} \quad (23)$$

Considered criteria are calculated for per hour and MJ by multiplying parameters with 3.6. Thermo-environmental function is:

$$B = \frac{W}{b_1 m + b_2 Q_H + b_3 ExD + b_4 W} \quad (11)$$

where  $m$  is the total mass,  $b_1$  is environmental impact of the components (mPts/kg),  $b_2$  is the environmental impact of the fuel (mPts/MJ),  $b_3$  is the environmental impact of the lost work (mPts/MJ), and  $b_4$  (mPts/MJ), is the environmental impact of the mechanical work. Similarly, ecological based thermoenvironmental function is defined as:

$$B_E = \frac{E}{b_1 m + b_2 Q_H + b_3 ExD + b_4 W} \quad (12)$$

In this approach, it represents to environmental impact of the ecological function. Another new criteria is called as ecologicoenvironmental function. This criteria is can be written as:

$$B_{EC} = b_4 W - b_3 ExD \quad (13)$$

$B_{EC}$  can be thought as the profit rate, since environmental impact of the work output is resulted in the desired product and

Optimum values of the considered criteria is calculated by setting zero of their derivatives and obtained values are:

$$x_{opt,B} = \frac{\Gamma - 0.5\sqrt{\Delta}}{\nabla} \quad (24)$$

$$\Gamma = 18 I T_H T_L y z (b_3 T_L T_o - b_3 T_H T_o - b_2 T_H T_L) \quad (25)$$

$$\begin{aligned} \Delta = & (I T_H^2 T_L^2 (I (36 b_2 T_H T_L + b_3 (36 T_H - 36 T_L) T_o)^2 y^2 z^2 \\ & + 20 (b_1 m T_L (1 + (1 + I) y - I y^2) + 18 y z (b_3 (T_L - T_H) T_o) \\ & - b_2 T_H T_L) 5 (b_1 m T_H (1 + (1 + I) y + I y^2) \\ & + 18 I (b_3 (T_L - T_H) T_o - b_2 T_H T_L) y z))) \end{aligned} \quad (26)$$

$$\begin{aligned} \nabla = & (T_L^2 (5 b_1 m T_H (1 + (1 + I) y + I y^2) \\ & + 18 I (b_3 (T_L - T_H) T_o - b_2 T_H T_L) y z)) \end{aligned} \quad (27)$$

$$x_{opt,B_E} = \frac{\Pi - 0.5\sqrt{\Omega}}{\delta} \quad (28)$$

$$\Pi = 18IT_H T_L yz (b_4 T_L T_o + b_3 T_L T_o - b_4 T_H T_o - b_3 T_H T_o - b_2 T_H T_o - b_2 T_H T_L) \tag{29}$$

$$\begin{aligned} \Omega = & (IT_H^2 T_L^2 (ly^2 z^2 (36((b_3 T_H + b_4 T_H - b_3 T_L - b_4 T_L) T_o + b_2 T_H (T_L + T_o)))^2 \\ & + 4(5b_1 m (T_L + T_o)(1 + (1 + l)y + ly^2) + 18yz(b_2 T_H (T_L + T_o) \\ & + (b_3 T_H + b_4 T_H - b_3 T_L - b_4 T_L) T_o))(5b_1 m (T_H + T_o)(1 + (1 + l)y + ly^2) \\ & + 18lyz((b_3 T_L + b_4 T_L - b_3 T_H - b_4 T_H) \\ & T_o - b_2 T_H (T_L + T_o)))))) \end{aligned} \tag{30}$$

$$\Theta = (T_L^2 (5b_1 m (T_H + T_o)(1 + (1 + l)y + ly^2) + 18lyz((b_3 T_L + b_4 T_L - b_3 T_H - b_4 T_H) T_o - b_2 T_H (T_L + T_o)))) \tag{31}$$

$$x_{opt, B_{EC}} = \frac{T_H}{T_L} \sqrt{\frac{I(b_2 T_L + b_3 T_o)}{(b_2 T_H + b_3 T_o)}} \tag{32}$$

$$x_{opt, B_{FTE}} = \frac{T_H}{T_L} \sqrt{\frac{I(b_4 T_L - b_5 (T_o + T_L))}{(b_4 T_H - b_5 (T_o + T_H))}} \tag{33}$$

Dimensionless parameters are used in this study and investigated parameters are expressed as following:

$$b = Bb_4, \quad b_E = B_E b_4, \quad b_{EC} = \frac{B_{EC}}{W_{max} b_4}, \quad b_{FTE} = \frac{B_{FTE}}{W_{max} b_4},$$

$$w = \frac{W}{W_{max}} \quad \text{and} \quad exd = \frac{ExD}{ExD_{max}}$$

### 3. Results and discussion

Results obtained from the calculation are shown in Figs. 2–10. Assumptions and parameters used in the calculations can be seen in Table 1.

Variation of parameters with  $x$  can be seen in Figs. 2–4. Firstly,  $b$  and  $b_E$  are searched. Both of them change logarithmically, they increase until their maximum (optimum points) and then they begin to decrease. Optimum point for the  $b$  is at the  $x = 2.29$  and maximum value at this point is 1.422.  $b_E$  reaches its optimum point at the  $x = 2.97$  and it is equal to 0.973. While we investigate the  $b_{EC}$  and  $b_{FTE}$ , it can be seen that  $b_{EC}$  has the similar trend with  $b$  and  $b_E$ . Its maximum is obtained at the  $x = 2.62$  and maximum value is equal to 2.404.  $b_{FTE}$  has different tendency compared with others.

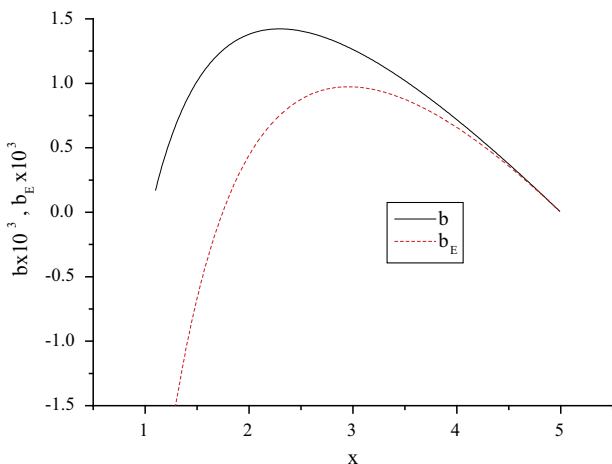


Fig. 2. Variations of the dimensionless thermoenvironmental and ecological based thermoenvironmental functions with  $x$ .

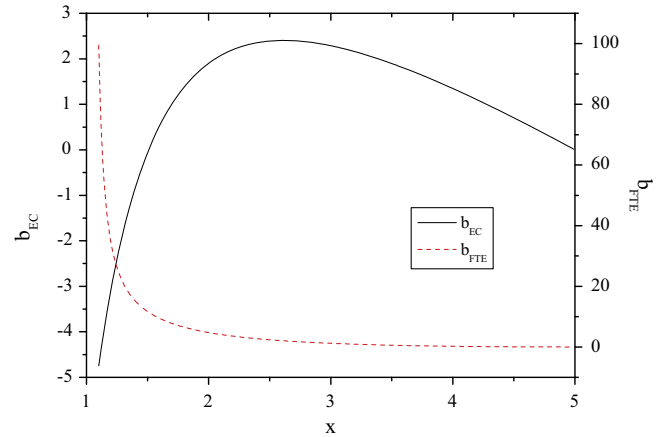


Fig. 3. Variations of the ecologicoenvironmental and finite time exergoenvironmental functions due to the  $x$ .

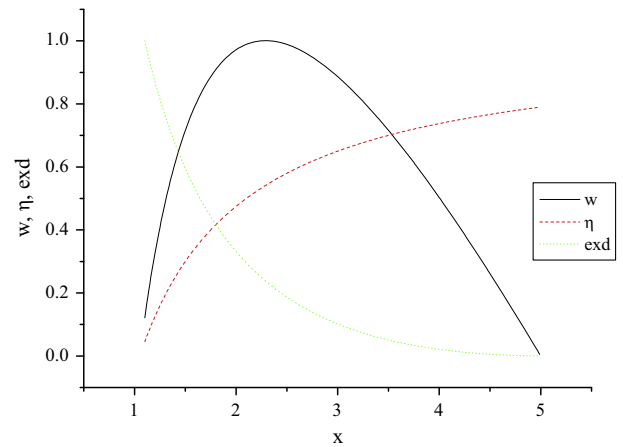


Fig. 4. Work, efficiency and exergy destruction as a function of  $x$ .

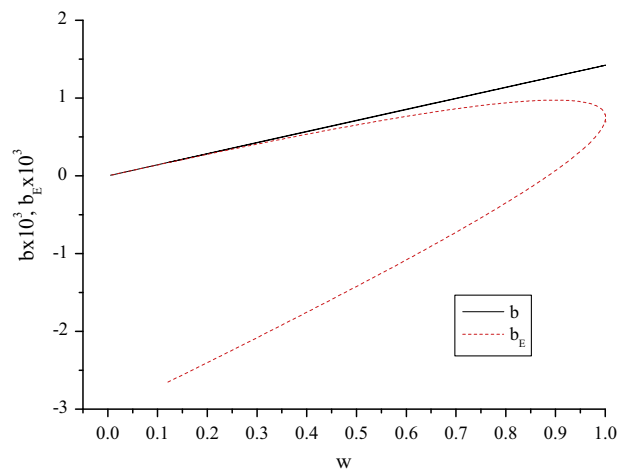


Fig. 5. Variations of the dimensionless thermoenvironmental and ecological based thermoenvironmental, functions versus the work.

It reduces logarithmic without any extremum point with  $x$ . Negative values for the  $b_E$  and  $b_{EC}$  mean that exergy destruction rate at these points are greater than the work output. Finally, parameters of  $w$ ,  $\eta$  and  $exd$  are examined.  $w$  reaches its maximum at the  $x = 2.29$ ,  $\eta$  and  $exd$  have no maximum or minimum,  $\eta$  rises up with  $x$ , while  $exd$  reduces according to the  $x$ .

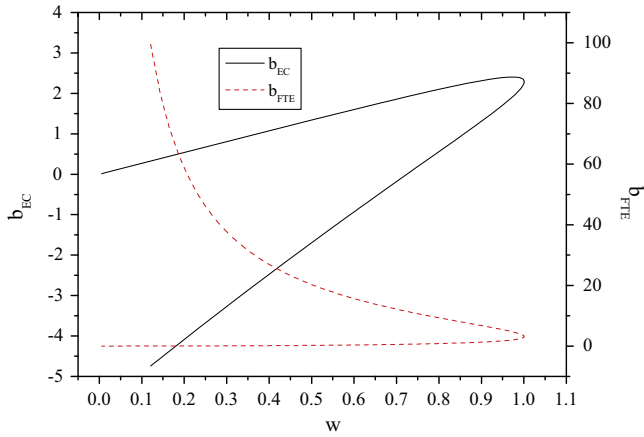


Fig. 6. Variations of the ecogicoenvironmental and finite time exergoenvironmental functions versus the work.

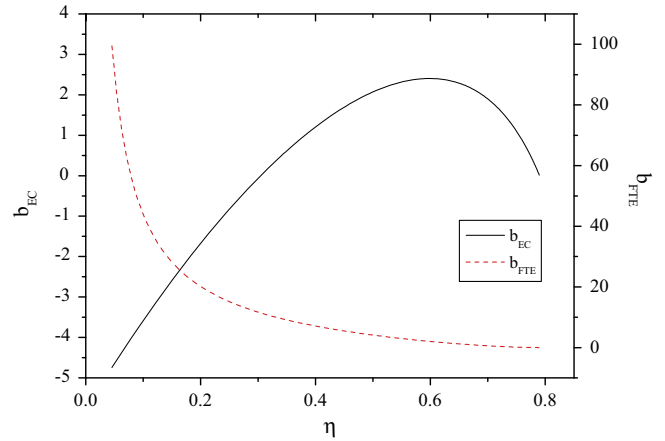


Fig. 9. Variations of the ecogicoenvironmental and finite time exergoenvironmental functions with the efficiency.

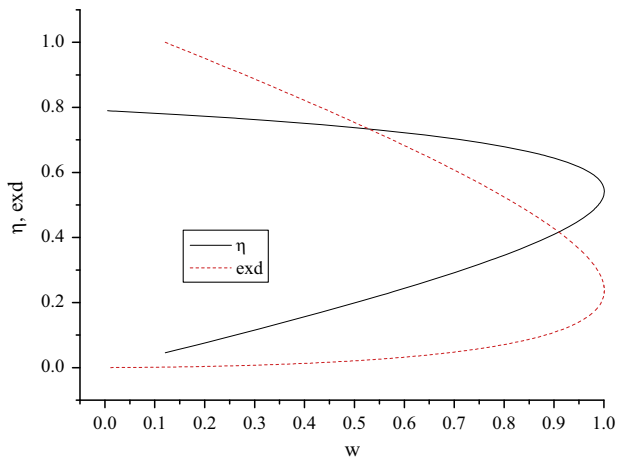


Fig. 7. Variations to the efficiency and exergy destruction respect to the work.

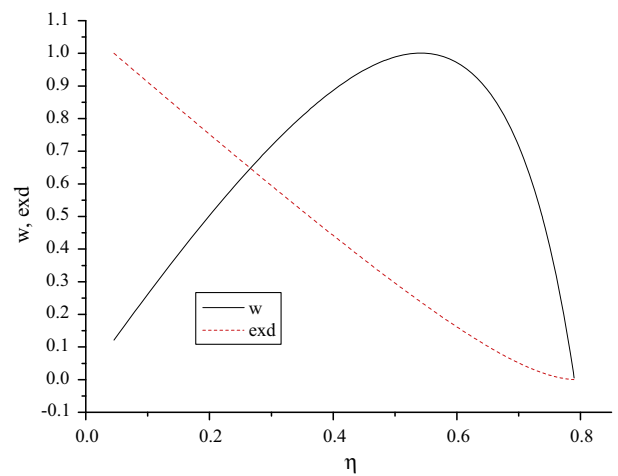


Fig. 10. Variation of the work and exergy destruction with efficiency.

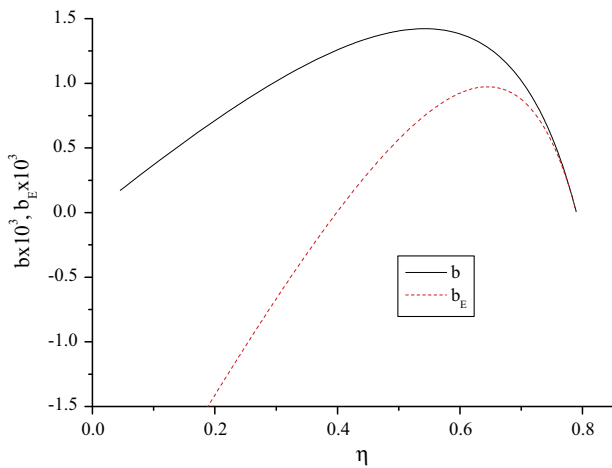


Fig. 8. Variations of the thermoenvironmental and ecological based thermoenvironmental functions with the efficiency.

Fig. 5 shows the variations of  $b$  and  $b_E$  with  $w$ . At maximum  $b$ , work output gets its maximum.  $w$  is equal to 0.90 at the maximum  $b_E$ . Similarly, Fig. 6 is shown changes of the  $b_{EC}$  and  $b_{FTE}$  with the  $w$ . According to the results,  $w$  is equal to 0.97 for the maximum  $b_{EC}$ .

Table 1  
Parameters used in the analysis ([2]).

Parameter	Unit	Value
$T_H$	K	1500
$T_L$	K	300
$T_o$	K	298.15
$l$	-	1.05
$y$	-	1
$z$	kW/K	10
$^*b_1$	mPts/kg	17
$^*b_2$	mPts/MJ	0.067
$^*b_4$	mPts/MJ	0.17
$m$	kg	10,000

However,  $b_{FTE}$  has no extremum point, its maximum is at the  $x = 1.1$  (at the beginning) and the work output is 0.12 at this point. As it shown in Fig. 7,  $\eta$  and  $exd$  have similar trends with  $b_{FTE}$  and same results are correct for them too.

Figs. 8–10 show the change of parameters with  $\eta$ . At the maximum  $b$  and  $b_E$ ,  $\eta$  gets 0.54 and 0.65 respectively.  $b_E$  reaches its optimum at the  $x = 2.62$  and  $\eta$  is equal to 0.60 at this point.  $b_{FTE}$  has the maximum efficiency at  $x = 4.99$  that is the maximum  $x$ , because it has no extremum point. Same results are valid for the  $exd$  too. Finally, at the maximum  $w$  efficiency value is equal to 0.54.

When  $exd$  is investigated at the optimum points for the considered criteria following results are obtained:

- $exd$  obtains 0.24 and 0.17 for optimum  $b$  and  $b_E$ .
- At maximum  $b_{EC}$  and  $w$ ,  $exd$  values are equal to 0.16 and 0.24 respectively.
- For the  $b_{FTE}$ ,  $exd$  reduces with decreasing  $b_{FTE}$ .

According to the results, it can be said that  $b_{EC}$  the most advantageous criteria for the thermal system. Because, the work output at the maximum point is equal to 90 percentage of the maximum work, its energy efficiency is 60% and finally,  $exd$  is the minimum comparing values with others criteria's maximum point.

#### 4. Conclusion

Four different and novel thermoenvironmental based methods are investigated and compared with each other. An irreversible Carnot heat engine is chosen as system and it is investigated by using referred four methodology. According to the results, it can be said that  $B_{EC}$  is the most convenient method to evaluate a thermal cycles. Because, it can be applied with a little loss in the work output comparing at the optimum point with other methods, however, its energy efficiency is 60% importantly high and exergy destruction rate (irreversibilities) are lower than others. This means that in the optimum  $B_{EC}$ , irreversibilities (or entropy generation) is really lower and that's why, losses in the system or environmental impacts of the system reduces. Finally, these thermoenvironmental approaches should be analyzed for each system considered and results should be interpreted carefully to applications of designing low environmental harmful thermal systems.

#### References

- [1] EPA. United States Environmental Protection Agency, Sources of Greenhouse gas emissions. <<http://www.epa.gov/climatechange/ghgemissions/sources/industry.html>>.
- [2] Goedkoop M, Spriensma R. The Eco-indicator 99: a damage oriented method for life cycle impact assessment. Methodology report, Amersfoort, Netherlands; 2000. <<http://www.pre.nl>>, July 2015.
- [3] Chen J. The maximum power output and maximum efficiency of an irreversible Carnot heat engine. *J Phys D Appl Phys* 1994;27(6):1144–9.
- [4] Grosu L, Feidt M, Benelmir R. Study of improvement of the performance coefficient of machines operating with three reservoirs. *Int J Exergy* 2004;1:147–62.
- [5] Novikov II. The efficiency of atomic power stations. *J Nucl Energy* 1958;11:25–8.
- [6] Curzon F, Ahlborn B. Efficiency of a Carnot engine at maximum power-output. *Am J Phys* 1975;43:22–4.
- [7] Angulo-Brown F. An ecological optimization criterion for finite-time heat engines. *J Appl Phys* 1991;69:7465–9.
- [8] Yan Z. Comment on ecological optimization criterion for finite-time heat-engines. *J Appl Phys* 1993;73:3583.
- [9] Cheng C, Chen C. The ecological optimization of an irreversible Carnot heat-engine. *J Phys D: Appl Phys* 1997;30:1602–9.
- [10] Yan Z, Lin G. Ecological optimization criterion for an irreversible three-heat-source refrigerator. *Appl Energy* 2000;66:213–24.
- [11] Xia D, Chen L, Sun F. Universal ecological performance for endoreversible heat engine cycles. *Int J Ambient Energy* 2001;27:15–20.
- [12] Chen L, Sun F, Wu C. Thermo-economics for endoreversible heat-engines. *Appl Energy* 2005;81:388–96.
- [13] Zhu X, Chen L, Sun F, Wu C. Exergy based ecological optimization for a generalized irreversible Carnot refrigerator. *J Energy Inst* 2006;79:42–6.
- [14] Ibrahim OM, Klein SA, Mitchell JW. Optimum heat power cycles for specified boundary conditions. *J Eng Gas Turb Power* 1991;113:514–21.
- [15] De Vos A. Endoreversible economics. *Energy Convers Manage* 1997;38:311–7.
- [16] Sahin B, Kodal A. Finite time thermoeconomic optimization for endoreversible refrigerators and heat pumps. *Energy Convers Manage* 1998;40:951–60.
- [17] Wu C, Chen L, Sun F. Effect of the heat transfer law on the finite-time, exergoeconomic performance of heat engines. *Energy* 1996;21:1127–34.
- [18] Wu C, Chen L, Sun F. Effect of the heat transfer law on the finite-time, exergoeconomic performance of Carnot heat pump. *Energy Convers Manage* 1998;39:579–88.
- [19] Kodal A, Sahin B, Yilmaz T. Effects of internal irreversibility and heat leakage on the finite time thermoeconomic performance of refrigerators and heat pumps. *Energy Convers Manage* 2007;41:607–19.
- [20] Durmusoglu Y, Ust Y. Thermodynamic optimization of an irreversible regenerative closed Brayton cycle based on thermoeconomic performance criterion. *Appl Math Model* 2014;38:5174–86.
- [21] Ahmadi MH, Ahmadi MA. Thermodynamic analysis and optimization of an irreversible Ericsson cryogenic refrigerator cycle. *Energy Convers Manage* 2015;89:147–55.
- [22] Sadatsakkak SA, Ahmadi MH, Bayat P, Pourkiaei SM, Feidt M. Optimization density power and thermal efficiency of an endoreversible Braysson cycle by using non-dominated sorting genetic algorithm. *Energy Convers Manage* 2015;93:31–9.
- [23] Ahmadi MH, Ahmadi MA, Mehrpooya M, Sameti M. Thermo-ecological analysis and optimization performance of an irreversible three-heat-source absorption heat pump. *Energy Convers Manage* 2015;90:175–83.
- [24] Ahmadi MH, Ahmadi MA, Sadatsakkak SA. Thermodynamic analysis and performance optimization of irreversible Carnot refrigerator by using multi-objective evolutionary algorithms (MOEAs). *Renew Sustain Energy Rev* 2015;51:1055–70.
- [25] Ahmadi MH, Ahmadi MA. Thermodynamic analysis and optimization of an irreversible radiative-type heat engine by using non-dominated sorting genetic algorithm. *Int J Ambient Energy* 2014. <http://dx.doi.org/10.1080/01430750.2014.977>.
- [26] Rajesh A, Kaushik SC, Kumar R, Arora R. Multi-objective thermo-economic optimization of solar parabolic dish Stirling heat engine with regenerative losses using NSGA-II and decision making. *Int J Electr Power Energy Syst* 2016;74:25–35.
- [27] Liao T, Lin J. Optimum performance characteristics of a solar-driven Stirling heat engine system. *Energy Convers Manage* 2015;97:20–5.
- [28] Yaqi L, Yaling H, Weiwei W. Optimization of solar-powered Stirling heat engine with finite-time thermodynamics. *Renew Energy* 2011;36:421–7.
- [29] Naserian MM, Farahat S, Sarhaddi F. Finite time exergy analysis and multi-objective ecological optimization of a regenerative Brayton cycle considering the impact of flow rate variations. *Energy Convers Manage* 2015;103:790–800.
- [30] Yang B, Chen L, Ge Y, Sun F. Exergy performance optimization of an irreversible closed intercooled regenerative Brayton cogeneration plant. *Arabian J Sci Eng* 2014;39:6385–97.
- [31] Ahmadi MH, Sayyaadi H, Mohammadi AH, Barranco-Jimenez MA. Thermo-economic multi-objective optimization of solar dish-Stirling engine by implementing evolutionary algorithm. *Energy Convers Manage* 2013;73:370–80.
- [32] Ahmadi MH, Ahmadi AA, Bayat R, Ashouri M, Feidt M. Thermo-economic optimization of Stirling heat pump by using non-dominated sorting genetic algorithm. *Energy Convers Manage* 2015;91:315–22.
- [33] Grosu L, Benelmir R, Feidt M. Technico-economic simulation and optimization of a compression refrigerating machine. *Energy Convers Manage J* 1999;40:1651–60.
- [34] Barranco-Jimenes MA, Sanchez-Salas N. Effect of combined heat transfer on the thermoeconomic performance of an irreversible solar-driven heat engine at maximum ecological conditions. *Rev Mex Fis* 2013;59:179–86.
- [35] Meyer L, Tsatsaronis G, Buchgeister J, Schebek L. Exergoenvironmental analysis for evaluation of the environmental impact of energy conversion systems. *Energy* 2009;34:75–89.
- [36] Chen L, Zhu X, Sun F, Wu C. Exergy-based ecological optimization for a generalized irreversible Carnot heat-pump. *Appl Energy* 2007;84:78–88.