

4E ANALYSES AND SUSTAINABILITY INDEX OF LINEAR FRESNEL REFLECTOR

Arif KARABUGA¹, Melik Ziya YAKUT², Zafer UTLU³
Anadolu BIL Vocational School, Istanbul Aydin University, Istanbul, Turkey
Faculty of Technology, Süleyman Demirel University, Isparta, Turkey
Faculty of Engineering, Istanbul Gedik University, Istanbul, Turkey
Corresponding author: Arif KARABUGA, e-mail: arifkarabuga@aydin.edu.tr

REFERENCE NO	ABSTRACT
SOLR-03	This study presents a thermal solar technologies as linear fresnel reflector (LFR), one of the focused solar energy systems is investigated. This system is evaluated under the 4E assessment criteria; Energy, Exergy, Economic and Environment. The energy, exergy, environmental, enviroeconomic, exergoenvironmental, exergoenvironoeconomical analysis and sustainability index of the LFR system is calculated. In addition, energy and exergy losses due to convection and radiation coming from the LFR system is found. If the ambient temperature of the LFR system is 293 K, the energy, exergy, environmental, enviroeconomic, exergoenvironmental, exergenviroeconomic analysis and sustainable index order are 40 %, 1.5617 %, 0.208015 kgCO ₂ /day, 0.003016 \$/day, 0.19447 kgCO ₂ / day, 0.0028199 \$/day and 1.015 respectively, and the sustainability index of this study was found as 1.015.

Keywords:
Energy, Solar Energy, Exergy, Linear Fresnel,

1. INTRODUCTION

When the environmental and economic problems are examined, fossil fuels are seen to be very damaging. One of the proposed alternatives to fossil fuels is renewable energy sources.

About 80% of the world's electricity is generated from fossil energy sources (such as natural gas) and 20% is generated from renewable energy sources (such as hydroelectric, wind, geothermal, solar and other sources) [1].

It is possible to produce two types of energy from solar energy, one of the renewable energy sources. The first type is direct electricity generation systems (PV, PV / T, BIPV) and the second type is thermal energy generation systems (Parabolic systems, solar tower, solar chimney, Fresnel systems) [2].

Thermal energy conversions can be investigated in three categories. These; (i) low temperature, (ii) medium temperature, (iii) high temperature [3]. The linear Fresnel reflector (LFR) allows the production of thermal energy at medium and high temperatures relative to the climate zone. LFR is widely used for simple production, easy maintenance and low cost advantage and

thermal power generation systems [4,5]. Fresnel reflector can also be used as concentrating devices. Figure 1 shows such a configuration, which is made up of smaller flat components. It consists of a number of mirror elements mounted suitably, so that all incident parallel rays of light, after reflection are focussed at a common point. Ideally, mirror elements must be parabolic in shape, but to simplify the manufacturing and assembling problems, flat mirrors are generally used [6]. The LFR systems convert the radiation energy into heat water, vapour energy, cooling with the necessary equipment and electric energy.

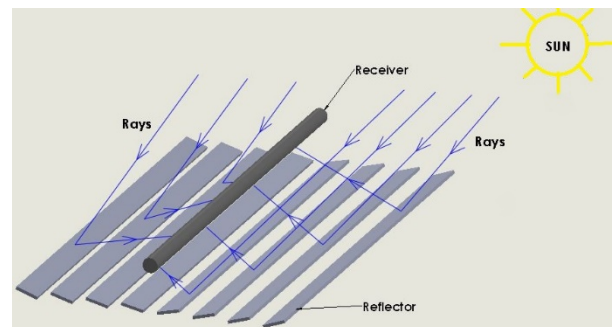


Fig. 1. Fresnel reflectors

LFR systems have many advantage. They are such that; (i) Direct steam production, (ii) It

takes up less space than other solar energy systems, (iii) Low installation cost, (iv) desalination, (v) High pressure and temperature for industrial applications, (vi) Extensive power production tape, from a few kW to MW, (vii) Modules can be added.

Exergy is a useful quantity derived from the second law of thermodynamics and helps to analyse energy and other systems processes [7]. Exergy analysis provides information about the quality and quantity of all inputs and outputs within a system. Exergy analysis helps researchers determine the points at where the quality of energy is lost [8]. Kalogirou et al. [9] have investigated the efficiency of exergy of different type's collectors in different applications. The study has examined in two categories. In the first category, parabolic dish and parabolic trough collectors, focusing on the planar collectors in the second category and without concentrated and non-concentrated have analysed. Adibhatla and Kaushik [10] have performed 4E (Energy, Exergy, Economic and Environmental) analyses of the parabolic trough collector used for preheating the feed water in 500 MWe thermal power plant. As a result, the exergy rate before the improvement of the plant was 38.46% while the solar energy-assisted thermal storage was calculated as 44.60%. Abuska and Sevik [11] have studied the 4E analysis of the flat plate and V-grooved solar air collector, made of aluminium and copper. In this study, different air flow rates (0.01, 0.04, 0.06, 0.08 kg / s) here analysed. As a result, the average thermal efficiency 43-60% and the exergy efficiency to be 6-12% have found.

In this study, 4E (Energy, Exergy, Economic, Environmental) analysis and sustainability index of LFR system were found. The values were investigated from the viewpoint of both energy and exergy.

1.1. System description

There are a few devices, such as a parabolic trough solar collector (PTSC), parabolic dish collector (PDC), solar tower system and linear Fresnel reflector for solar thermal energy

applications. To deliver medium temperature with good efficiency a high-performance solar concentrating solar collector is required. Systems with light structures and low-cost technology for process heat applications to medium temperature could be obtained with linear Fresnel solar collector [12]. LFR is considered as a exchanger, because it converts sunlight energy into thermal energy. LFR systems are suitable for the production of clean water and trigeneration systems by adding necessary equipment. The LFR system focuses the sun's rays through the reflective mirrors and into the absorber tube in the cavity. In this work, there are 10 mirrors in the LFR system. These reflectors follow the sun. Each of the reflectors is 2 meters long and 0.6 meters wide. The radiation value on the mirrors is 545 W/m². The reflectance of the mirrors is 0.95 and the absorbance of the receiver tube is 0.92. The amount of fluid circulated in the system is 0.016 kg / s. The more detailed data and the accepted value of the system is given in Table 1.

Table 1. The system values

The system values	Symbol	Rate
Solar radiation	I	545 W/m ²
Reflectance of the mirror	ρ_{mir}	0.95
Absorber of the receiver	ρ_{rec}	0.92
Emissivity of the receiver	ϵ_{rec}	0.92
Reflector area	A_{ref}	1.22 m ²
Reflector number	A_{n}	10
Receiver area	A_{rec}	0.5026 m ²
Ambient temperature	T_{air}	23°C
Sun temperature	T_{s}	6000 K
Average temperature	T_{avg}	54 °C
Surface temperature	T_{surf}	85 °C
Sky temperature	T_{sky}	10 °C
Water input temperature	T_{in}	20 °C
Specific heat	c_{p}	4187 J/kg °C
Cover area of the glass	A_{gs}	0.722 m ²
Stefan-Boltzmann constant	σ	5.67x10 ⁻⁸ W/m ² K ⁴
Mass flow	\dot{m}	0.016 kg/s
Thermal conductivity	k	0.02851 W/m K
Characteristic length	L	0.3611 m
Kinematic viscosity	ν	1.8372x10 ⁻⁵ m ² /s
Prandtl numbers	Pr	0.7217
Gravity	g	9.81 m/s ²
1/T _{avg}	β	0.00312
Working hours	t	10 h/day
CO ₂ emission value	y_{co2}	6.47x10 ⁻⁶ kg CO ₂ /Wh
Carbone price	c_{co2}	0.0145 \$/kgCO ₂

The circumference of the absorber tube is surrounded by a vacuum glass tube. The purpose of using vacuum glass is to prevent heat transfer to the environment. The absorber tube passes through into of the cavity area. Radiation from the reflector to the absorber pipe may sometimes not come to the pipe due to the locomotion of the sun. Therefore, the rays which do not come into the absorber pipe are struck against the walls of the cavity and are again reflected back to the absorber pipe due to the geometrical structure of the cavity. A schematic representation of the LFR system is given in fig 2.

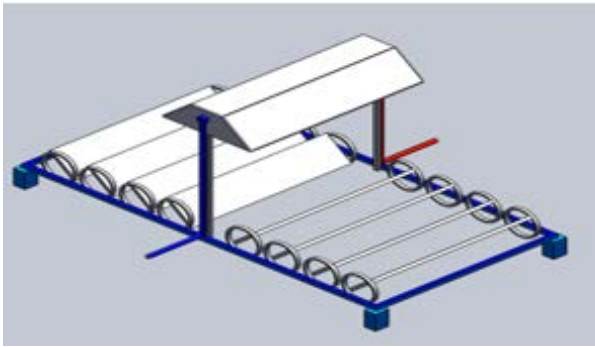


Fig. 2. Schematic representation of linear Fresnel reflector

2. EQUATIONS

In this section have investigated the thermodynamic behaviour of the system. However to determine the amount of thermal energy that is wasted the respective calculations were performed for the inlet and outlet enthalpy, exergy, mass flow rate, solar radiation, energy loss, exergy loss and temperature. For the calculation of these equations, EES program is used for parametric studies and graphical drawings. Input solar radiation rate is found by;

$$\dot{E}n_{solar} = I * \rho_{ref} * \rho_{rec} * \varepsilon_{rec} * A_{ref} * A_n * A_{rec} \quad (1)$$

Where I , ρ_{ref} , ρ_{rec} , ε_{rec} , A_{ref} , A_n are solar radiation, reflectance of the mirror, absorber of the receiver, emissivity of the receiver, reflector area, reflector numbers and receiver area, respectively.

$$\dot{E}n_{solar} = \dot{m} * c_p * (T_{out} - T_{in}) \quad (2)$$

Where \dot{m} , c_p , T_{out} and T_{in} are mass flow of water, specific heat of water, temperature of output water and temperature of input water, respectively.

$$\dot{E}x_{water} = \dot{E}x_{out} - \dot{E}x_{in} \quad (3)$$

Where $\dot{E}x_{water}$, $\dot{E}x_{out}$ and $\dot{E}x_{in}$ are water exergy change, exergy of output water and exergy of input water, respectively.

$$\dot{E}x_{out} = \dot{m} * c_p * \left[(T_{out} - T_{air}) - T_{air} \left(\ln \left(\frac{T_{out}}{T_{air}} \right) \right) \right] \quad (4)$$

Where T_{out} and T_{air} are temperature of output water and ambient temperature, respectively.

$$\dot{E}x_{in} = \dot{m} * c_p * \left[(T_{in} - T_{air}) - T_{air} \left(\ln \left(\frac{T_{in}}{T_{air}} \right) \right) \right] \quad (5)$$

Where T_{in} is temperature of input water. Input solar radiation exergy rate is found by;

$$\dot{E}x_{solar} = \dot{E}n_{solar} \left(1 + \frac{1}{3} \left(\frac{T_{air}}{T_{sun}} \right)^4 - \frac{4}{3} \left(\frac{T_{air}}{T_{sun}} \right) \right) \quad (6)$$

Where T_{sun} is sun temperature. Exergy efficiency of overall system by;

$$\eta_{II} = \frac{\dot{E}x_{water}}{\dot{E}x_{solar}} \quad (7)$$

The sustainability index can be found in the following equation;

$$SI = \frac{1}{1 - \eta_{II}} \quad (8)$$

The energy loss in the system is due to convection and radiation. Total energy loss is found by;

$$\dot{E}n_{loss} = \dot{E}n_{loss,conv} + \dot{E}n_{loss,rad} \quad (9)$$

Where $\dot{E}n_{loss,conv}$ and $\dot{E}n_{loss,rad}$ are energy loss with convection and radiation, respectively.

$$\dot{E}n_{loss,conv} = hA_{gs}(T_{surf} - T_{air}) \quad (10)$$

Where h , A_{gs} and T_{surf} are heat transfer coefficient, heat transfer surface area of glass cover and the glass cover surface temperature, respectively.

$$h = \frac{kNu}{L} \quad (11)$$

Where k and L are thermal conductivity and characteristic length, respectively.

$$Nu = \left[0.6 + \frac{0.387(Ra)^{1/6}}{\left\{ 1 + \left(\frac{0.559}{Pr} \right)^{9/16} \right\}^{8/27}} \right]^2 \quad (12)$$

Where Ra and Pr are Rayleigh number and Prandtl number, respectively.

$$Ra = \frac{g\beta(T_{surf}-T_{air})D^3}{\nu^2} Pr \quad (13)$$

Where g , D and ν^2 are gravity, diameter of glass cover and kinematic viscosity, respectively.

$$\dot{E}n_{loss,rad} = \varepsilon\sigma A_{gs}(T_{surf}^4 - T_{sky}^4) \quad (14)$$

Where ε , σ and T_{sky} are emissivity, Stefan-Boltzmann constant and sky temperature, respectively.

Exergy loss is as energy loss and total exergy loss is found by;

$$\dot{E}x_{loss} = \dot{E}x_{loss,conv} + \dot{E}x_{loss,rad} \quad (15)$$

Where $\dot{E}x_{loss,conv}$ and $\dot{E}x_{loss,rad}$ are exergy loss with convection and radiation, respectively.

$$\dot{E}x_{loss,conv} = \dot{E}n_{loss,conv} \left(1 - \frac{T_{air}}{T_{surf}} \right) \quad (16)$$

$$\dot{E}x_{loss,rad} = \dot{E}n_{loss,rad} \left(1 - \frac{T_{air}}{T_{surf}} \right) \quad (17)$$

The exergy destruction rate of the system can be found in the following equation;

$$\dot{E}x_{dest} = \dot{E}x_{in} + \dot{E}x_{solar} - \dot{E}x_{out} - \dot{E}x_{loss} \quad (18)$$

The environmental analysis of the system can be found in the following equation [13];

$$x_{CO2} = y_{CO2} \dot{E}n_{solar} t_{working} \quad (19)$$

Where y_{CO2} and $t_{working}$ are carbon dioxide emission value and working hours of the system. The enviroeconomic analysis of the system can be found in the following equation [13];

$$Ec_{CO2} = x_{CO2} c_{CO2} \quad (20)$$

Where c_{CO2} is carbon dioxide price. The exergoenvironmental analysis of the system can be found in the following equation [13];

$$x_{exCO2} = y_{CO2} \dot{E}x_{solar} t_{working} \quad (21)$$

The exergoenvironmental analysis of the system can be found in the following equation [13];

$$Ec_{exCO2} = x_{exCO2} c_{CO2} \quad (22)$$

An exergoeconomic analysis reveals the origin, magnitude and location of cost of thermodynamic inefficiencies in energy conversion systems.

3. RESULT and DISCUSSION

In THIS STUDY, the thermodynamic analysis of LFR system is done. The values obtained as a result of the calculations made are showed in table 2.

In the calculations of the absorber pipe, the Ra number was found to be $3.749e^7$, which is the small from boundary value of 10^{12} in the literature. Therefore, the Nusselt number formula given in equation 12 have used.

Table 2. Calculated value

Parameter	Rate	Unit
$\dot{E}n_{solar}$	2775	W
$\dot{E}n_{loss}$	537.6	W
$\dot{E}n_{loss,conv}$	148.3	W
$\dot{E}n_{loss,rad}$	389.4	W
x_{CO2}	0.1795	kgCO ₂ /day
Ec_{CO2}	0.002603	\$/day
$\dot{E}x_{solar}$	2592	W
$\dot{E}x_{water}$	151.8	W
$\dot{E}x_{in}$	1.128	W
$\dot{E}x_{out}$	152.9	W
$\dot{E}x_{loss}$	92.84	W
$\dot{E}x_{loss,conv}$	25.62	W
$\dot{E}x_{loss,rad}$	67.27	W
$\dot{E}x_{dest}$	2347	W
η_{II}	0.05855	%
SI	1.062	-
x_{exCO2}	0.1677	kgCO ₂ /day
Ec_{exCO2}	0.002432	\$/day

Exergy losses in the system due to ambient temperature are showed in fig. 3. The increase in ambient temperature results in a reduction in loss of exergy in the cavity area.

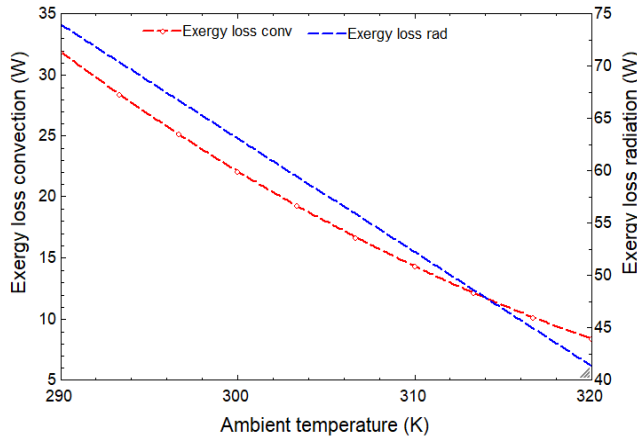


Fig. 3. Exergy losses due to ambient temperature

Exergy destruction and total exergy loss in the LFR system due to ambient temperature are showed in fig. 4. Exergy losses (radiation and convection) in the system have observed to decrease with the increase in the ambient temperature.

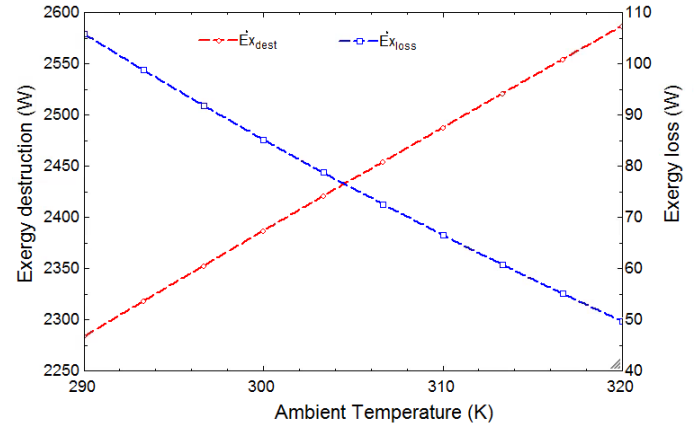


Fig. 5. Exergy destruction and total exergy loss due to ambient temperature

Exergy efficiency and exergy of output water in the LFR system due to ambient temperature are showed in fig. 5. The increase in ambient temperature causes loss of exergy, but increases the exergy destruction in the system.

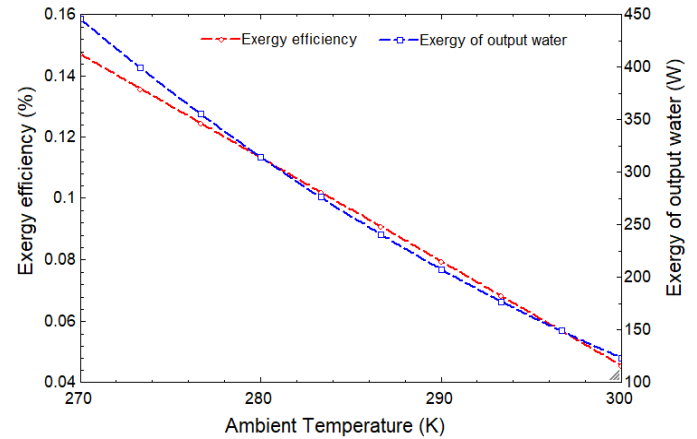


Fig. 5. Exergy efficiency and exergy of output water values due to ambient temperature

The environmental and exergenvironmental values in the LFR system depending on the change in radiation value are showed in fig. 6. The increase in the ambient temperature caused both the exergy of output water and the system to decrease in exergy efficiency. This case that the environmental temperature (dead-state temperature) is effective on the efficiency of exergy.

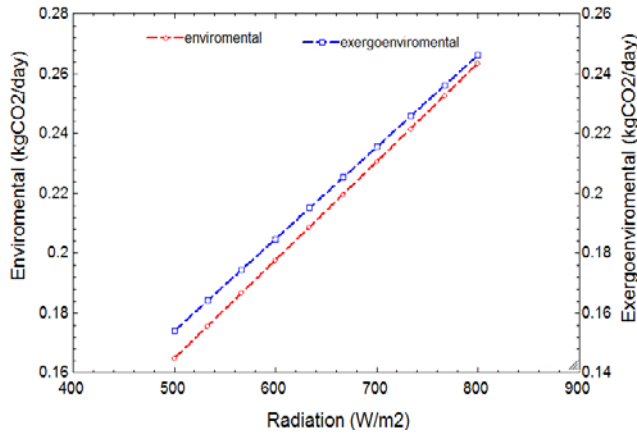


Fig. 6. Environmental and exergoenvironmental values due radiation

Due to the increase in the intensity of radiation, the increase in the environmental and exergoenvironmental values has occurred.

4. CONCLUSIONS

As a result of the study, 4E analysis and sustainability index of LFR system are calculated.

- The exergy efficiency and sustainability index of the systems are found 0.05855 and 1.0162, respectively.
- As a result of the analysis, the energy and exergy loss are found 537.6 W and 92.89 W, respectively.
- The environmental and exergoenvironmental values of the system are found, 0.1795 kgCO₂/day and 0.1677 kgCO₂/day, respectively.
- The enviroeconomic and exergoenvironomic values of the system are found, 0.002603 \$/day and 0.002432 \$/day, respectively.
- When the heat loss analysis is examined, it is calculated that the heat loss is in the cavity region and the heat loss have the maximum by radiation.
- A detailed analysis of the absorber pipe and cavity geometry should be performed to reduce energy loss.

Nomenclature

I	Solar Radiation (W/m ²)
LFR	Linear Fresnel Reflector
A_{ref}	Reflector Area (m ²)
A_n	Reflector Number
A_{rec}	Receiver Area (m ²)

A_{gs}	Glass Cover Area (m ²)
T_{air}	Ambient Temperature (K)
T_s	Sun Temperature (K)
T_{avg}	Average Temperature (K)
T_{surf}	Surface Temperature (K)
T_{sky}	Sky Temperature (K)
T_{in}	Water input Temperature (K)
T_{out}	Water output Temperature (K)
L	Characteristic Length (m)
Pr	Prandtl Number
Ra	Rayleigh Number
E_n	Energy (W)
E_x	Exergy (W)
SI	Sustainability Index
\dot{m}	Mass Flow (kg/s)
t	Working Hours
γ_{CO_2}	CO ₂ Emission Value (kgCO ₂ /day)
C_{CO_2}	Carbon Price (\$/day)

Greek Letters

η	Exergy Efficiency (%)
σ	Stefan-Boltzmann Constant (W/m ² K ⁴)
ν	Kinematic Viscosity (m ² /s)
ρ_{mir}	Reflectance of the mirror
ϵ_{rec}	Emissivity of the Receiver

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