



Article Sizing Methodology of a Multi-Mirror Solar Concentrated Hybrid PV/Thermal System

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Abstract: The use of a concentrated photovoltaic (CPV) system significantly reduces the required solar cell area that often accounts for the major cost of a PV solar system. A comprehensive performance analysis of a multi-mirror solar concentrated hybrid PV thermal (CPVT) system was conducted. Among different concentrating systems, Linear Fresnel Reflector (LFR) systems are more effective due to their simplicity of operation and low fabrication cost. A mathematical model and the simulation of a CPVT system employing a linear configuration and horizontal absorber is developed here in order to evaluate its performance parameters, using a FORTRAN programing technique. The concentrator system consists of, different width of flat glass mirrors placed under various inclination angles, focusing sunlight on to the PV solar cells mounted along the active cooling system. The effect of focus distance on concentration ratio, collector width, and heat gained by the coolant fluid are investigated. All parameters of the linear Fresnel reflector solar concentrator system are determined and the effect of cooling mass flow rate and cooling inlet temperature upon the system performance is evaluated. With regards to simulation results obtained via the focus distances, the width of mirrors decreased by increasing the number of mirrors, and in turn by increasing the focus distances, this resulted in an increase in CR values. For the specific number of mirrors, concentration ratio increased simultaneously increasing the focus distance; furthermore, increasing the number of mirrors resulted in a reduction in both the width of the mirrors and their inclination angles, and an increase in CR values. The results further confirmed that the total (combined electrical-thermal) efficiency is higher than that of the individual electrical as well as thermal efficiency; reaching approximately 80% and showed no sensitivity to the rises in cooling water temperature for temperature cases under consideration.

Keywords: concentrating system; energy efficiency; hybrid PV/thermal; linear Fresnel reflector

1. Introduction

The present socio-economic and technological climate has seen an ever increasing demand for energy. This increasing and irreversible reliance on energy for industrial and technological advancement has also seen an increase in demands for new, diverse and efficient mechanisms to produce clean and non-pollutant energy sources [1].

Nowadays renewable energy has undergone a rise in popularity; particularly with regards to solar energy. Solar energy has proven to be a promising option to minimize dependence on traditional energy sources such as solid fuel and oil [2,3]. The fossil fuels together constitute almost 87% of the total energy demand of the world [4]. The carbon dioxide emission from burning fossil fuels is believed to be the main factor influencing an alarming rise in the global temperature. Already the harmful effects of climate change can be seen as in rising seas, wildfires, killer cyclones, and extreme weather [4]. Solar energy in particular has proven to possess several proven benefits, namely it is clean, inconsumable, abundant and has a low amount of carbon and harmful emission gases [5,6].

Photovoltaic (PV) is commonly used in the field of renewable energy. It is a direct method for capturing solar radiation from the Sun and directly converting it to direct current (DC) by using semiconductor materials such as silicon.

These semiconductor materials have proven to possess the best characteristics and ability to produce electricity when sunlight hits the surface of a solar cell. Presently PV has achieved more distinctive attention compared to other forms/types of renewable energy sources, particularly in the field of scientific research owing to its versatility of use.

In a comparison to traditional power generation, such as fossil fuels, photovoltaic solar energy has enormous advantages including its reliability, low cost of operation and maintenance, free energy source, clean and high availability source and does not cause any environmental problems/harm via emissions of toxic gases [7].

Concentrating solar radiation for generating electrical power in a PV solar system has made the procedure in concentrator optics specifically for the design of certain geometry of reflectors/lenses for focusing solar radiation on a small surface area of the PV system. Commonly, the cost of the concentrator is lower than that of the PV panels. Consequently, more efforts are aimed at finding mechanisms to reduce the manufacturing cost of these concentrators via the use of several types of solar radiation concentrators for developing low-cost concentrated PV systems [8]. Several existing concentrator systems yield non-uniform focused illumination [9]. The non-uniform solar irradiance will reduce PV system efficiency due to the hot spot effect [10]. In order to produce a concentrated uniform solar radiation, Mills and Morrison [11] proposed a Linear Fresnel Reflector System (LFRS). However, Mills claimed that a low concentration ratio (CR) (<100 sun) is the main drawback of LFRS.

To increase the concentration ratio, and remedy this drawback, a modified LFRS was developed in later secondary studies to be used with a PV system. The results obtained from these analyses indicated that the proposed system improved the distribution of the concentrated solar radiation. LFRS transmission efficiency is low, less than 80%, this may be due to reflections on lens surfaces and lens absorption material [12]. A non-imaging, focusing heliostat has been suggested by Chen [13]. The proposed system has a high CR, this is achieved by overlaying all mirror images to a fixed target. Studies by Amanlou et al. [14] on an air cooled (LCPV/T) solar collector, by transforming the latter into a new diffuser design, uses deflectors to improve the uniformity of air to enhance the PV system efficiency. The reported simulation results indicate that the electrical, thermal and total efficiency were improved by 36%, 42.2% and 40.5%, respectively.

However, experimental results obtained by Karimi et al. [15] on a PV/T solar system, showed that the PV efficiency module had decreased from 10.9% under normal condition to 7.63% under solar concentration, while, the output PV power increased by 28%. Also, the PV/T systems' total efficiency under solar concentration reached up to 46.6% and 53%. Similar, but more theoretically orientated studies on CPV/T solar systems have shown that the total efficiencies of the CPV/T system under the same condition were higher than those of the CPV system [16]. Working on a multifunctional design PV/T solar system, Tian et al. [17] reported that the simulation and experimental results showed that the efficiency of the heat recovery system ranged from 40% to 85% depending on the air velocity and plenum height.

Previous studies by An et al. [18] on linear Fresnel lens solar systems that use a nanofluid as a cooling fluid under optical wide range, reported experimental results for optimum optical cut-in at 620 nm for silicon solar cells for a temperature of nanofluid was 400 °C. The temperature was increased with increasing wave length, and the experimental electrical, thermal and total efficiency reached up to 12.5%, 22.4% and 35%, respectively.

A typical LFRS contains long narrow flat mirrors fixed upon a horizontal plane. These mirrors are sloped at certain angles in order to collect the reflected solar radiation at the absorber. Such absorber can be flat horizontal or any other shape. It is often a tube that contains a heat transfer fluid. Extensive devotion is done for developing LFRS for both thermal and PV systems.

LFRS has numerous advantages. These include; (*i*) its value for medium-temperature range (100–250 °C) applications [19]; (*ii*) it is fabricated with narrow flat mirrors, and the materials required for fabrication and any other replacement parts are readily available in the market; (*iii*) the planar configuration and the air gap between the adjacent mirrors result in minimal wind loading on the concentrator. Accordingly, LFRS can be installed on a fairly simple cost-support structure [20].

A hybrid CPVT system is a device that converts the energy of solar into bi-generating energy (i.e., electric and thermal energy) [21,22]. The PV panel is laminated above the absorber to produce electrical power. The CPVT collector has an inherent usefulness over other PV and thermal technique than any other widely used concentrating systems.

The significance of this study is that no studies have so far used linear Fresnel reflector mirrors with a horizontal PV/thermal receiver system. Therefore, the focus of analysis of this study is to present a new design of multi-mirror solar concentrated hybrid PV/thermal system, with water as the coolant and presented here as a solution for improving the energy performance. A detailed mathematical model is provided to estimate the system's electrical and thermal performance. Moreover, the effects of some geometrical, glazing, flow rate and other parameters on the thermal and electrical performance will be scrutinized in further detail in the subsequent sections of this article.

2. Theoretical Modelling

2.1. Linear Fresnel Mirror Reflecting Concentrator (LFMRC) System

The structure of Fresnel reflecting mirrors is presented in Figure 1. To simplify the model of LFRC, the following assumptions were considered: (*i*) The use of a Sun tracking system, (*ii*) mirrors are specularly reflecting, and (*iii*) solar irradiance is incident axially. The main parameters of light reflecting mirrors are; inclination angles α_1 , α_2 ... α_i , width of mirrors A_1D_1 , A_2D_2 ... A_iD_i , the aperture of mirrors (plane area) A_1E_1 , A_2E_2 ... A_iE_i , the distance between two mirrors E_1A_2 , E_2A_3 ... $E_{i-1}A_i$, and its position (O_iA_i) on the aperture plane (*XX'*) of the concentrator [23]:

$$\alpha_{i} = \frac{1}{2} \arctan\frac{(a+c) + \sum_{i=1}^{i=m} A_{i-1}A_{i}}{f} = \frac{1}{2} \arctan\frac{(O_{1}A_{i} + a/2)}{f}$$
(1)

where *a* is the width of the solar cell, C is the additional area which can be occupied by the heat transformer (heat sink), f is the focus distance of the concentrator. The position (O_iA_i) value is given by the following equation:

$$O_1 A_i = O_1 A_1 + \sum_{i=1}^{i=m} A_{i-1} A_i$$
(2)

where $(O_1A_1 = a/2 + C)$ and i = 1, 2..., m, where, 'm' is the sum number of mirrors positioned on each side of the reflector base. The width dimension of the first mirror is A_1D_1 , and the line $B'D_1$ represents the reflected ray of solar radiation committed to the extreme ray (C'_1D_1) fallen on the first

mirror upper edge [23]. This ensures that, all solar radiation that is reflected via the first mirror is covered and intercepted by the receiver.



Figure 1. Structure of LFMR solar concentrator.

The main parameters for the second, third and all other mirrors can be determined in a similar manner; hence, the following equations can be utilized for aperture A_iE_i and width A_iD_i of each mirror:

$$A_i E_i = a - \frac{a \tan \alpha_i \tan 2\alpha_i}{1 + \tan \alpha_i \tan 2\alpha_i} = \frac{a}{(1 + (\tan \alpha_i \tan 2\alpha_i))}$$
(3)

and:

$$A_i D_i = \frac{D_i E_i}{\sin \alpha_i} = \frac{(a/\cos \alpha_i)}{(1 + (\tan \alpha_i \tan 2\alpha_i))}$$
(4)

or for simplicity:

$$A_i D_i = \frac{A_i E_i}{\cos \alpha_i} \tag{5}$$

The distance between two neighboring mirrors A_1A_2 , is defined as an important parameter that constitutes the concentrator, and the inclination angles parameter can be obtained from Equation (4). The position and slope of the second mirror would be selected in a way that the reflected solar irradiance does not obstruct the reflected solar irradiance from the 1st mirror. This requires that ray C_2A_2 impinges the lower edge of the 2nd mirror, as illustrated via Figure 1. Subsequently, the reflected rays from the lower edge of the 2nd mirror are reflected on to the upper edge of the 1st mirror, and then to the edge B of the receiver. The required move, linked to the 2nd mirror (E_1A_2) can be found by considering the similar triangles of OBD_1 and $E_1D_1A_2$, and the same procedure can be followed in determining (E_2A_3).

The expression in Equation (6) can be used to determine the areas $E_{i-1}A_i$ for the *i*-th mirror:

$$E_{i-1}A_i = \frac{((a/2 + O_1A_{i-1}) + A_{i-1}D_{i-1}\cos\alpha_{i-1})A_{i-1}D_{i-1}\sin\alpha_{i-1}}{(f - (A_{i-1}D_{i-1}\sin\alpha_{i-1}))}$$
(6)

The location of (O_1A_i) for the *i*-th mirror on the plane (XX') of the concentrator can be determined from the following:

$$O_1 A_i = O_1 A_{i-1} + A_{i-1} D_{i-1} \cos \alpha_{i-1} + E_{i-1} A_i$$
(7)

The aperture width *W* of the concentrator can be expressed as:

$$W = 2\sum_{i=1}^{i=m} (O_1 A_i \cos \alpha_i + E_{i-1} A_i) + 2O_1 A_1$$
(8)

2.2. Concentration Ratio (CR) and Ray Trace Technique

The concentration ratio (*CR*) is defined by summarizing each contribution element of the mirror at a certain point [9]. The local concentration ratio (LCR_i) at any position on the horizontal receiver of any element of the constituent mirror (the *i*th mirror) can be estimated using the following Equation (9) [23,24]:

$$LCR_i = \frac{(A_i D_i \cos \alpha_i)}{a} = \frac{(A_i E_i)}{a}$$
(9)

However, in the case of the flat horizontal absorber, CR can be estimated as follows [25]:

$$CR = 2 \cdot \frac{\sum A_i E_i}{a} = 2 \sum_{i=1}^{i=m} LCR_i = \frac{A_{mirrors}}{A_{absorber}} = \frac{I_{absorber}}{I_{insident}}$$
(10)

where $A_{mirrors}$ and $A_{absorber}$ is the total mirror area (m²) and absorber area (m²), respectively. $I_{insident}$ and $I_{absorber}$ is the solar radiation received by mirrors and absorber (W/m²), respectively.

The equation used to determine the *LCR* on a flat horizontal receiver has been formulated using the ray trace technique and given as:

$$Y = Y_{IP,i} + (X - X_{IP,i}) \tan(90 \pm \xi)$$
(11)

$$X_{P,i} = X_{IP,i} + \frac{F - Y_{IP,i}}{\beta_i}$$
(12)

where ($X_{IP,i}$ and $Y_{IP,i}$) is the (X and Y) coordinate of the intersection point of the cone incident with the *i*-th mirror element. ζ denotes the angular deflection of a beam from incident cone and β_i is the slope of the reflected ray.

2.3. Electrical and Thermal Analyses

Previous work on cooling of photovoltaic cells under concentrated illumination [26] has suggested that the loss of heat from the receiver glass cover is caused by convection and radiation, while any excess heat (useful heat) was removed via the cooling system on the substrate surface. The electrical power output generated by PV module is calculated from the incoming concentrated power (solar radiation) incident on the absorber from the linear Fresnel reflector I_R using Equation (13) [27]:

$$P_{ele} = (I_R \eta_{PV} - P_{PAR}) \eta_{inv} \tag{13}$$

where P_{PAR} is the parasitic power (loss power).

The relationship(s) between PV cell efficiency and cell temperature are calculated using the following Equation (14) [28]:

$$\eta_C = \eta_{Ref} (1 - b(T_C - 25)) \tag{14}$$

where η_C is the calculated efficiency of PV cell at solar cell temperature (T_C), $\eta_{Ref} = 0.097$ is the solar cell efficiency at 25 °C, and *b* is the coefficient for different types of solar cell:

$$\eta_{PV} = \eta_{mod} \eta_C \tag{15}$$

The efficiency of solar cell varies with the concentration ratio (*CR*) and T_C (cell temperature) according to the relation below [29] for the range *CR* \leq 200:

$$\eta_{PV} = \eta_{mod}\eta_C$$

$$= 0.9[0.298 + 0.0142\ln CR + (-0.0007415 + 0.0000697\ln CR)(T_C - 25^{\circ}C)]$$
(16)

Light-to-electricity efficiency can be estimated by using Equation (17):

$$\eta_{ele} = \eta_{Opt} \eta_{PV} \left(1 - \frac{P_{PAR}}{P_{ele}} \right) \eta_{inv} \tag{17}$$

In the examination of thermal processes for active cooling, a few assumptions were made, including steady state conditions, incompressible liquid inside the pipe of collector and with negligible viscous dissipation, no heat loss in the axial direction, and the collector area is relatively small compared to that of the surrounding sky.

In this study, Figure 2 shows the thermal network of energy radiation flowing between the receiver elements of the PV/T and the surroundings. From Figure 2, it can be said that the receiver acts as a control volume by stating the conservation of energy requirement, so that:

$$\dot{E}_{in} - \dot{E}_{out} + \dot{E}_{gen} = \dot{E}_{st} \tag{18}$$

For achieving a thermal equilibrium, the following criteria should be met [30]:

$$I_R - Q_{rad} - Q_{con} - P_{ele} - Q_{cool} - Q_{Ins} + I_{Sky} = 0$$
(19)

where I_R is the incoming solar flux from the collector to the receiver.

The incoming concentrated solar radiation that is received by the PV/T receiver I_R is given by Equation (20):

$$I_R = I_D A_{ac} \eta_{Opt} \tag{20}$$

where I_D is the beam (direct) radiation incident on the mirror collector aperture equaling to a 90% from the total radiation I_T (direct and diffuse) that incident on the collector aperture in (W/m²). The A_{ac} is the actual project area of the mirrors and η_{opt} is the total optical efficiency of the mirrors.

The incident radiation that is absorbed by the PV cells ($Q_{abs-cells}$) is calculated from Equation (21), for transmission and absorption by the product of $\tau \alpha$ (transmission-absorption). The small component of radiation absorbed in the glass cover was eliminated ($1-\alpha_g$):

$$Q_{abs-cell} = I_R A_C(\tau \alpha) (1 - \alpha_g) \tag{21}$$

Correspondingly, the absorbed radiation in the glass cover materials ($Q_{abs-glass}$) accounts for the remaining solar radiation that is not reflected from the glass cover:

$$Q_{abs-glass} = I_R A_g(\tau \alpha) \alpha_g \tag{22}$$

The thermal conversion efficiency can be estimated as in Equation (23) [30]:

$$\eta_{th} = \frac{Q_{cool}}{I_R} \tag{23}$$

The combined heat and PV power (CHP) efficiency is calculated by Equation (24):

$$\eta_{CHP} = \eta_{ele} + \eta_{th} \tag{24}$$

The thermal efficiency obtained from previous equations, can be considered as a reduced temperature function as shown in Equation (25) [30]:

$$T_{red,D} = \frac{(T_{inl} - T_{amb})}{I_D}, \quad or \quad T_{red,T} = \frac{(T_{inl} - T_{amb})}{I_T}$$
 (25)

where; T_{inl} and T_{amb} is the inlet flow and the ambient temperature in °C, respectively. I_D and I_T are the direct radiation and the total radiation (direct and diffuse) incident on the collector.



Figure 2. Thermal network describing a CPVT collector.

The thermal energy absorbed (useful and loss energy) by the receiver (Q_{th}) is calculated from Equations (26) and (27):

$$Q_{th} = Q_{cool} + Q_{th,l} \tag{26}$$

$$Q_{th} = I_R(1 - \eta_{PV}) = Q_{cool} + (Q_{Front} + Q_{Bake})$$
⁽²⁷⁾

Part of this energy is lost from the back and front sides of the absorber (receiver) by both convection and radiation ($Q_{th,l}$), while the rest is transmitted into the coolant (Q_{cool}):

$$Q_{Front} = Q_{Front,conv} + Q_{Front,rad} = h_{con,F}A_F(T_C - T_a) + \varepsilon_F \sigma A_F \left(T_C^4 - T_a^4\right)$$
(28)

The PV panel is covered by an adhesive layer acting as a thermal absorber plate, so that the heat balance among the PV panel and the absorber must be modeled. This can be achieved using Equations (28) and (35).

Heat balance from the PV panel to the absorber is a conduction heat through the substrate:

$$Q_{ca} = h_{sup} A_{sup} \left(T_C - T_{pl} \right) = Q_{cool} + Q_{ins}$$
⁽²⁹⁾

The overall substrate thermal resistance is found from the individual layers of thermal resistances (adhesive, substrate and solder) and calculated as shown in Equation (30) [31]:

$$h_{sup} = \frac{K_{sup}}{\delta_{sup}} = \left[\frac{\delta_{solder}}{K_{solder}} + \frac{\delta_{material}}{K_{material}} + \frac{\delta_{adhesive}}{K_{adhesive}}\right]^{-1}$$
(30)

The thermal resistance may be minimized by maximizing the glue conductivity (k = 0.9 W/Km) in a layer of 50 µm thick. It is assumed that, the tedlar and EVA layer thickness are 0.1 mm and 0.5 mm with conductivity of k = 0.25 W/Km and k = 0.33 W/Km, respectively. The PV-laminate thermal resistance is calculated as shown in Equation (31) [31]:

$$h_{sup} = \frac{K_{sup}}{\delta_{sup}} = \left[\frac{5 \times 10^{-4}}{0.33} + \frac{1 \times 10^{-4}}{0.25} + \frac{5 \times 10^{-5}}{0.9}\right]^{-1} = 500 \text{ W/Km}^2$$
(31)

The quantity of heat from the absorber cooling plate, and transferred to the coolant fluid is obtained from HE (heat exchanger) relations with constant absorber plate temperature [27]:

$$Q_{cool} = \dot{m} \cdot C_p \cdot (T_{out} - T_{inl}) = h_{cool} \cdot A_{cool} \cdot \Delta T_{LM}$$
(32)

$$\Delta T_{LM} = \frac{(T_{out} - T_{inl})}{\ln\left(\frac{T_{pl} - T_{inl}}{T_{pl} - T_{out}}\right)}$$
(33)

For calculation purposes, these equations can be simplified as in Equations (34) and (35) respectively:

$$Q_{cool} = \dot{m} \cdot C_p \cdot (T_{out} - T_{inl}) = h_{cool} \cdot A_{cool} \cdot \left(T_{pl} - T_m\right)$$
(34)

$$T_m = \frac{(T_{out} - T_{inl})}{2} \tag{35}$$

The coefficient of heat transfer of the convective is estimated, for a laminar flow as:

$$Re < 2300 \rightarrow Nud = 4.364$$
 (36)

Furthermore, calculation of the coefficient of heat transfer is obtained from; $h_{cool} = Nu_d k/d$. where Re_d (Reynolds number) based on the pipe diameter and obtained from; $R_{ed} = 4\dot{m}/\mu\pi d$ and Pr is the Prandtl number. The value of Pr depends on, the mean fluid temperature and thermophysical properties, and is accounted as: $Pr^{2/5} k/\mu^{4/5} = 263.75 + 3.2466 T_m$.

The insulated back surface of the receiver would always be facing the sun, therefore, the back surface of the receiver would be simultaneously exposed to not only un-concentrated solar radiation, but also to convection and radiation losses to the environment. The insulated back surface conduction loss can be obtained from Equation (37) [27]:

$$Q_{ins} = \frac{K_{ins}A_{ins}(T_{pl} - T_{amb})}{\delta_{ins}} = h_{con,in}A_{ins}(T_{ins} - T_{amb}) + \varepsilon_{ins}\sigma A_{ins}\left(T_{ins}^4 - T_{sky}^4\right) - \varepsilon_{ins}A_{ins}I_D$$
(37)

where T_{sky} is the sky temperature obtained from a known relationship Equation (38) [32]:

$$T_{sky} = 0.0552 \times T_{amb}^{1.5} + 2.625 \times N \tag{38}$$

where T_{amb} is the ambient temperature (K); *N* is the sky cloud coverage in octaves. Solving Equations (23)–(38) provides the results for the following:

- The heat rates
- The unknown temperature of solar cell
- The coolant outlet
- The cooling plate
- And the receiver insulated back surface.

A FORTRAN program was developed for the evaluation and sizing of system parameters. The initial conditions that are required in solving the model equations to obtain the value of cell temperature (T_C) at any illumination value are listed in Table 1. It is important to note that q''_{cool} is very large in comparison to q''_{conv} and q''_{rad} in most cases of concentration.

Position (Layer)	Matter	Layer Thickness, t (m)	Material Thermal Conductivity, k (W/m K)	Sum Thermal Resistance $R = \sum_{i} \frac{t_i}{k_i} \text{ (Km}^2/\text{W)}$
Cover glass	Ceria-doped glass	$3 imes 10^{-3}$	1.4	
Adhesive (room temperature vulcanization)	Optical grade silicone	1×10^{-4}	145	
Top half of cell	Silicon	$6 imes 10^{-5}$	145	$R_{g-c} = 2.14 \times 10^{-3}$
Bottom half of cell	Silicon	$6 imes 10^{-5}$	145	0
Solder	Sn:Pb:As	$1 imes 10^{-4}$	50	
Substrate	Aluminum nitride	$2 imes 10^{-3}$	120	$R_{c-s} = 1.91 \times 10^{-5}$
Other Parameter				
Symbol	Description		Value	
T ₀	А	mbient temperature		25 °C
Ε	Hemispherical surface emissivity		0.855	
ηорт	Optical efficiency		0.85	
Σ	Constant of Stephan-Boltzmann		$567.0 imes 10^{-10} \mathrm{W/m^2 K^{-4}}$	
R _{conv}	Convective thermal resistance		$0.2 \mathrm{K} \mathrm{m}^2/\mathrm{W}$	
Α	Cell efficiency constant		55.46×10^{-2}	
В	Cell efficiency constant		$1.84 imes 10^{-4} { m K}^{-1}$	

Table 1. Parameters used in the thermal cooling model.

3. Findings and Analysis

3.1. Characteristics Analysis of an LFRSC System

For exemplifying the design, analysis and performance evaluation process, some numerical calculations were made for the design of the Linear Fresnel Reflector Solar Concentrator (LFRSC) and receiver system design. The obtained LFRSC results are discussed in this section.

The concentrator aperture width *W* is varying and the width of the horizontal receiver (*a*) is constant and equal to 0.125 m. All calculations in this section are conducted with unity of aperture length (L = 1 m).

Figure 3 illustrates the change in tilt angle related to different mirrors and different values of focus distance (F) from 0.4 to 3.2 m. It can be observed that, the mirror tilt angle increases from the mirror at the center of the concentrator to the mirror at the rim. Increases in F values result in a decrease of the tilt angle of each mirror. Moving away from the center of the LFRSC aperture to the rim decreases the mirrors' tilt angle.

The change in the mirrors width A_iD_i for the LFRSC system with a different number of mirrors under consideration and various focusing distances is shown in Figure 4. It can be observed, that moving in the direction of the edge of the LFRSC aperture from the center decreases the width of the mirrors. Moreover, the image width of each mirror must be equal to the receiver width (horizontal receiver) so that the mirror width required is decreased.



Figure 3. Shows the variation in tilt (α_i) of mirror versus the number of mirrors with different focusing distances (*F*) of the concentrator aperture, absorber width *a* = 0.125 m.



Figure 4. Variations in the width of mirror plotted against number of mirrors with different focusing distances (F) of concentrator apparatus, absorber width a = 0.125 m.

It is apparent in Figure 4 (with the horizontal receiver) that, the constituent mirrors' width increases as the focusing distances of the concentrator aperture of the LFRSC increases. These obtained results may be due to the fact that the mirrors' widths were obtained from the dispersion produced on the receiver surface by the reflected radiation from each mirror, which is used in the calculation of the mirror width. The mirror width of LFRSC increases from the center to the rim for each value of focusing distance of concentrator aperture. Accordingly, the width of the constituent mirrors decreases.

However, due to the design limitation in introducing the shift (S) between the successive mirrors to avoid blocking of reflected rays, part of this solar flux incident is lost over the LFRSC system. Thus, the total shifts are a direct measure of total energy loss. Figure 5 shows that the change of shift is related to the different constituent mirrors with F of LFRSC system under design consideration.

For the design, a fast decrease in sum shift (the value of $\sum_{i=1}^{i=m} E_{i-1}A_i$) may initially be noticed, suggesting that the solar radiation losses due to this shift are less than 5% for all values of *F*.



Figure 5. Non-useful collector area plotted against number of mirrors with Different focus distances of concentrator aperture.

Figure 6 demonstrates the concentration ratio (*CR*) change with *F* for the design of LFRSC system. It can be seen that, firstly *CR* increases rapidly with increasing *F* and then becomes approximately constant for F > 1.3 m, this occurs for a number of mirrors totaling no more than 10 mirrors. This is possibly due to the fact that an increase in *F* causes a change in the tilt angle and the width of the mirrors (Figures 3 and 4). From Figure 3, it can be noted that, decreasing slope angle of the mirrors with mirror number $i \ge 6$ higher than for the mirror number of i < 6. Accordingly, the spread image of reflected solar radiation from such mirrors element decreases. Therefore, the required mirror width increases. The total shift also decreases significantly with increasing *F* from 0.4 to 1.0 m, as in Figure 5, hence, two more mirrors are accommodated instead of shift for a given aperture width. Consequently, *CR* increases quickly with increasing *F* from 0.4 to 1.0 m. The mirror sudth increases with an increase in *F* values, and ultimately for F < 1.0 m, the mirror width is reduced. This indicates that the increase in *CR* is constant, and the *CR* becomes constant for accounts of *F* from 1.3 to 3.2 m, particularly for number of mirrors less than tens (i < 10). These figures suggest that the higher values of *F* results in no significant benefits CR changes. For experimental application, the *F* value of LFRSC design can be taken equal to 1.0 m.



Figure 6. Variations in the concentration ratio plotted against focuses distance for different number of mirrors of a concentrator aperture, absorber width a = 0.125 m.

Figure 7 shows the variation in the number of mirrors and aperture width plotted against the CR with a constant focusing distance of the concentrator aperture (F = 1 m), and an absorber width of a = 0.125 m. It appears from Figure 7 that the decay in CR occurs gradually with increasing the total number of mirrors, it also shows that the *CR* increases with an increase in *W*.



Figure 7. Variation in the number of mirrors and aperture width plotted against the concentration ratio with a constant focus distance of the concentrator aperture (F = 1 m), absorber width a = 0.125 m.

The results obtained in Figure 8 illustrate a rapid decrease in CR values with increasing the width a of the absorber, at F = 1.0 m and W = 1.7 m. The resulted distribution of LCR on the horizontal receiver surface, with an absorber width of a = 0.03 m, was obtained by using analytical and ray trace technique for system design, as shown in Figure 9. It can be observed that the obtained *LCR* for both techniques are substantially different.



Figure 8. Variations in the CR plotted against the width *a* of the absorber with focus distance F = 1.0 m, concentrator apparatus width W = 1.7 m.

Figure 9 shows the intercepted ray reflected from a different mirror element on the receiver surface. The shortest width of the ray intercepted on the receiver is assumed to have come from the first mirror. Nevertheless, the intercepted width of all mirror elements (contributing to the LCR) are

over the intercepted width of the 1st mirror. Therefore, regular distribution of LCR to this area is obtained on the receiver surface.

The results from ray trace technique clearly show a large decrease in the uniform distribution of LCR with a large rise in the peak value of LCR. The LCR peak value obtained from the analytical technique is less by around 16%.



Figure 9. Distribution of LCR on the horizontal receiver surface for the aperture (LFRSC) design, absorber width a = 3 cm.

At a constant ($CR \approx 10$) concentration ratio, the dependency of the number of mirrors (*i*) and concentrator width (*W*) on the focus distance (*F*) are plotted and shown in Figure 10. It can be seen that by increasing the focus distance the number of mirrors and concentrator width decreases. This process lasts until the focus distance is about 1.4 m. When the focus distance is more than 1.4 m, no decrease in the number of mirrors and the width *W* has occurred.



Figure 10. Variation number of mirrors and concentrator width with focus distance.

Thus, increasing the focus distance of LFRSC system leads to a reduction in the mirrors inclination angles, increasing the concentration ratio, decreasing the number of mirrors and dimension (width) of the concentrating system.

3.2. Receiver Design and Performance Results

With the set of equations obtained for active cooling, the receiver performance of different designs is estimated against of the T_{red} (reduced temperature). The constant and ambient conditions which are used in the simulations are shown in Table 1, whilst Table 2 presents the thermal and electrical performances at zero T_{red} (where, $T_{inl} = T_{amb} = 35$ °C) and flow rate of $\dot{m} = 0.015$ kg/m² s. The thermal and electrical efficiency curves are displayed in Figures 11 and 12, respectively. From Figures 11 and 12 pertaining to the uncovered receiver, clearly show that the poorest performance occurred at an equal ambient and inlet coolant temperatures ($T_{red} = 0$), this obtained result is most probable due to large thermal losses. In contrast, the receivers with one or two glass hoods have shown a greater performance under these conditions. Hence, it can be said that, the receiver with two glass hoods is more suitable for high thermal applications. However, the drawback here is that the electrical efficiency falls significantly. This is possibly due to the presence of a second cover, whilst, the thermal efficiency increases slightly with the reduced temperature. These simulation results in Figures 11 and 12 also indicate that the single glass cover receiver would be preferable over other designs, because, the lesser the cover number the lesser the thermal efficiency, but, higher electric efficiency will be obtained.

Table 2. Thermal and electrical performance at zero T_{red} ($T_{amb} = T_{inl}$) for different configuration.

Receiver Type	Efficiency (%)		
	Thermal	Electric	
PV module	-	9.68	
Conventional thermal collector	83.12	-	
PV/T-collector 0 glass cover	52.50	9.68	
PV/T-collector 1 glass cover	58.12	8.87	
PV/T-collector 2 glass covers	58.12	8.12	



Figure 11. Thermal efficiency against reduced temperature for various designs.



Figure 12. Electrical efficiency against reduced temperature for various designs.

3.3. Concentrator Photovoltaic/Thermal (CPVT) Collector

The results of the developed simulation program shown in this section are for a CPVT collector which uses a linear Fresnel reflector, and under a direct insolation value of 1000 W/m^2 . The variation in the collector area depends on the electrical power generation requirements. The performance of the CPVT collector which is considered in the simulation is without any loading.

The developed simulation program is used to investigate and obtain results for the parameters of a CPVT collector with absorber widths of 0.1, 0.12, 0.16, 0.2 m. Figure 13 shows that, in general, the length of a CPVT system increases with increasing the power requirement, also the width of a CPVT receiver increases with increasing the required electric power and it decreases with increasing of focus distance (*F*). Figure 13a–d were obtained at a fixed length of specified power requirement, where the width of the collector decreases with increasing the width of the receiver. For a specified receiver width and at the lowest value of focus distance, the figure shows that the width of the collector is very wide compared with that of collector width at a higher focus distance. These results indicate that the lower the value of the focus distance the higher the number of mirrors required, and this is because the angle of mirrors for lower focusing distance would be higher than the angle of mirrors for higher focus distance.



Figure 13. Cont.



Figure 13. The length and the width of CPVT collector plotted against the required power with different focus distances, (**a**–**d**) different receiver width.

The simulation results for the dependence of *CR* on the required electric power of a CPVT collector with various focus distances (*F*) are presented in Figure 14a–d. The concentration ratio increases with increasing the electrical power requirement and focus distance. Thus, increasing the focusing distance of the CPVT collector, results in the reduction of inclination angles for the mirrors, furthermore, it is apparent that at a lower power requirement the inclination of concentration ratio is higher than that of inclination of a concentration ratio for higher required power. Figure 14a–d for the specified required power, also suggest that the *CR* of the collector decreases with increasing width of the receiver.



Figure 14. The concentration ratio of a CPVT collector plotted against the required power with different focus distances, (**a**–**d**) different receiver width.

The increase in thermal energy to the required power in a linear relationship is presented in Figure 15a–d, which show plots of the thermal energy (Q_{th}) for the CPVT collector versus power requirement with various focus distances. The objective of using the thermal process is to cool the solar cell, particularly where a concentration condition exists, and these plots indicate that for a specified power requirement the thermal energy increases with increasing the focus distance (*F*). The results for various receiver widths in Figure 15 show a thermal energy decrease with increasing receiver width.



Figure 15. The thermal energy of a CPVT collector plotted against the required power with various focus distance, (**a**–**d**) different receiver width.

The results of heat gain (Q_{gain}) energy, cooling heat energy (Q_{cool}) for the circulating water versus the power required with various focus distance and receiver width are illustrated in Figure 16a–d. From Figure 16, it is evident that the energy gain increases with increasing the power requirement and focusing distance for a certain level of required power. The effect of changing focus distances on the heat gain is clearly minimal, especially for the lowest value of required power, and this relationship is linear. For different receiver width, it can be seen that, as the receiver width increases the energy losses are increased, as shown in Figure 16, thus, the energy gain decreases with increasing receiver width. The heat gain by the circulating water can be used for, domestic uses, and industrial processes (cleaning, heating, absorber refrigerator, distillation), without incurring added cost to the system.



Figure 16. Gain energy of a CPV/T collector plotted against the required power with different focus distance, (**a**–**d**) different receiver width.

Figure 17a–d show the important effective temperature in the CPVT collector versus that of mass flow rate for cooling water at a zero reduced temperature ($T_{amb} = T_{inl}$). The simulation results in Figure 17 show plots for the cell, outlet cooling water temperature curves, different temperature curve for the cell and outlet cooling, and the different temperature curve for outlet and inlet cooling. These results clearly show that the decrease in the cell and outlet cooling water temperature is accompanied by an increase in the flow rate. The temperature difference between outlet and inlet coolant is reduced with increases in the flow rate. The important temperature difference between the cell and outlet cooling water increases with an increase in the flow rate, and this increase should be in the range that does not cause cell failure. The plotted curves in Figure 17a–d for the effective temperature at different required power, show that all are increased with increasing of required power, this increase is possibly due to the increase in the concentration area.



Figure 17. Cont.



Figure 17. Effective temperatures of a CPVT collector plotted against the mass flow rate for the same focus distance and receiver width, (**a**–**d**) different required power.

Simulation plots for different effective temperature in the CPVT collector versus the mass flow rate of the cooling water at a zero reduced temperature ($T_{amb} = T_{inl}$) for a certain required power (500 W) and different focus distance (F) are shown in Figure 18a–c. These figures indicate an increase in the effective temperature as a result of increasing focus distances. This increase in the focus distance leads to increases in the concentrating area, most probably due to the increase in the incoming radiation flux that is received by the receiver.



Figure 18. Effective temperatures of a CPVT collector plotted against the mass flow rate for the same required power and receiver width, (**a**–**c**) various focus distances.

The conversion efficiency of the CPVT collector that uses a linear Fresnel reflector for electrical, thermal, and total efficiency is calculated and presented in Figure 19 for steady state conditions. The outlet flow temperature (T_{out}) is an independent parameter that can be controlled by varying flow rate. In Figures 19 and 20, the coolant outlet temperature was controlled by varying the mass flow rate with constant inlet cooling temperature.

The temperature of PV cells is 11–30 °C higher than that of the outlet cooling fluid temperature, it is known that photovoltaic cells typically work at temperatures below 100 °C as commercially available silicon cells. However, the operation at higher temperatures is possible for more sophisticated multi-junction cells with high *CR*. This may be acceptable, by increasing the amount of thermal energy in order to be used for other applications.



Figure 19. The variation of the CPVT collector mass flow rate, Electrical, Thermal, and CTE efficiencies with the coolant outlet temperature (constant $T_{inl} = 35 \degree$ C).



Figure 20. Variation of the mass flow rate, electrical and useful thermal powers with the cooling outlet water temperature (at constant $T_{inl} = 35$ °C).

Figure 19 shows that by decreasing the mass flow rate, the outlet temperatures are increased. Consequently, the electric efficiency could reach a value of 18.6% at temperatures of 50 °C, and progressively decrease at higher temperatures. Therefore, the residual energy of more than 60% is recovered as 'useful' energy in the cooling fluid. This energy is considered to be additional energy in increasing the total system efficiency (Figure 19). It is important to note that the energy losses in the pipes between the LFRSC receiver (PVT) and the consumer have not been taken into account.

The CPVT system with constant inlet cooling temperature of 35 °C and an outlet water temperature of 50 °C is obtained at a mass flow rate of 0.02 kg/sec, as shown in Figure 20. This figure also shows a value of 324 W for the output electrical power (P_{ele}) of the collector, and the useful output thermal (Q_{th}) value of 1090 W. This means that the total efficiency has reached a value of 80%, without indicating any sensitivity to changes in temperature or the mass flow rate.

The results for the conversion efficiencies, coolant outlet temperature versus the cooling inlet water temperature at a constant mass flow rate of (0.01 kg/sec) are shown in Figure 21. The CPV/T system electrical efficiency has reduced from 20% at 25 °C cooling inlet water temperature to around 10% at 250 °C. The overall electrical efficiency of the system is less than the cell efficiency where it comprises losses of the optics, module and inverter. The thermal efficiency of CPVT system simultaneously increases as the cooling inlet water temperature increases despite higher thermal energy losses to the surroundings. Therefore, the energy that has not been converted into electricity is often recovered in the form of heat.



Figure 21. The variation of the CPVT collector coolant inlet temperature, electric, thermal, and CTE efficiencies with the coolant outlet temperature (constant $\dot{m} = 0.01$ kg/sec).

The electrical and thermal energies for a constant flow rate of 0.01 kg/sec for the cooling system, as illustrated by Figure 22, shows that, at a cooling inlet temperature of 50 °C and an outlet cooling temperature of 80 °C, the electrical power (P_{ele}) and thermal useful power output (Q_{th}) of the system are 320 W and 1098 W, respectively.



Figure 22. The variation of the CPV/T collector coolant outlet temperature, electric and useful thermal powers with the cooling inlet water temperature (constant $\dot{m} = 0.01$ kg/sec).

The CPVT system results indicate that it is suitable for the required range of temperatures, the low operational temperature range is quite appropriate for domestic applications and space household heating. The useful thermal energy that is generated by low grade temperature has no effect on the electrical efficiency. However, operation of the CPVT system at temperatures of around 100 °C is suitable for different applications such as, absorption refrigeration with single stage, desalination and other similar industrial applications. An operation with a high temperature of around 150 °C is suitable with double effect absorption refrigeration and organic Rankine power cycle. These results also suggest that the outlet temperature of the CPV/T collector serves as a major parameter that connects the CPV/T system to the thermal applications.

Figure 23 shows the efficiencies of conversion from solar flux to electrical, useful thermal and combined electrical-thermal (CET) versus the outlet cooling temperature, T_{out} , for a *CR* of 18 and beam flux of 900 W/m².

The calculated efficiency of the CPV/T system for a rise in temperature (difference between outlet and inlet of cooling water temperature) of 15 °C and 30 °C, indicates that it is a suitable method to study the system performance with different thermal applications. The two cases of temperature rise show approximately similar results. These results show the susceptibility of the CPV/T receiver performance to this factor is low. The cell temperature was 11–30 °C greater than the temperature of cooling water outlet, and the electrical efficiency of the CPVT receiver was reduced from 19% to 15% at cooling water outlet temperatures of 42 °C to 150 °C, respectively. Simultaneously, the thermal efficiency incremented from around 58% to 65% as the cooling water temperature increases from 42 °C to 150 °C. The total (combined electrical-thermal) efficiency is higher than that of the individual electrical as well as thermal efficiency; reaching approximately 80% and showed no sensitivity to the rises in cooling water temperatures.



Figure 23. The variation of the CPVT collector electric, thermal and CTE efficiencies with the cooling outlet water temperature (constant $\dot{m} = 0.01$ kg/sec and fixed $\Delta T_{coolant} = 15$ °C and 30 °C).

Figure 24 represents the results for the concentration ratio and the width of a CPVT collector versus the focus distance with different power requirements. This figure shows that increasing CR leads to a decrease in the width of the system with an increasing of focus distance for different required electric power. It can be seen that the width is decreasing strongly for small values of *F* and it is almost constant for higher $F^{\underline{S}}$ (from 1.5 to 3.0 m). Hence, it can be concluded that, with the use of these dependent optimal parameters (*CR*, *F*, and *W*) of the system can be defined for the purpose of obtaining a sufficient *CR* with use of low values of focus distance and width.



Figure 24. Concentration ratio and the width of a CPVT collector plotted against the focus distance with different power required.

4. Comparison Validation

The thermal, electrical and total efficiencies of the proposed system are compared with those obtained by different related studies [33–40]. Commonly, every system has own advantages and disadvantages compared with other systems but the main goal is to increase the electrical and thermal efficiency without more increasing in the total cost of the system. Figure 25 shows comparison among present system and other different studies. The total efficiency for different systems ranged from 36% to 98%. However, for different CPVT systems, higher total efficiency achieved dependent on system design and optical efficiency. CPVT systems with different designs can also meet the thermal and electric demand in building and industrial sector. This is because, the CPVT systems have some challenges to become wide spread such as low density of energy, high locational and dependency of the environment.



Figure 25. Comparison of CPVT system efficiency of the present study against different studies.

5. Conclusions

This study conducted a comprehensive performance analysis of a multi-mirror solar concentrated integrated photovoltaic/thermal (CPVT) system. The integrated CPVT system utilizes the linear Fresnel reflector mirror technique that relies on high-performance technology at a low cost. The results obtained from this study suggest that this system works across a wide scale of temperatures dependent on the thermal application. The obtained simulation results from the FORTRAN program with its attention to specific focus distances, showed that the more mirrors used the higher the inclination angles of the mirrors and vice versa.

Moreover, for specific focus distances, the width of mirrors has decreased with increasing the number of mirrors, while increases in focus distance results in an increase in CR values. For the specific number of mirrors, concentration ratio increased simultaneously increasing the focus distance; furthermore, increasing the number of mirrors has resulted in a reduction in both the width of mirrors as well as inclination angles, and an increase in CR values.

Ultimately, the design of the Fresnel mirror reflector concentration system found that the focus distance should be between 1 m to 2.5 m. For a chosen constant focus distance equal to one meter and receiver width of the CPVT system equal to 12.5 cm, the CR= 6 is obtained with 4 mirrors, and if CR = 24, then the required number of mirrors is 18. The total width of the LFRSC system in the two cases was found to be 1 m and 4.5 m.

The simulation results for the electrical and thermal power of 324 W, 320 W and 1090 W, 1098 W can be obtained for flow rates of 0.02 kg/s and 0.01 kg/s, with a cooling water temperature rise of 15 °C, and 30 °C, respectively. Finally, values of 18%, 62% and 80% were obtained for the electrical, thermal and combined efficiencies.

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Abbreviations

Nomenclature

а	Receiver width, (m)
Α	Area, (m ²)
AD	Width of mirror, (m)
A _{ap}	Apparatus area, (m ²)
A _{ac}	Mirror actual area, (m ²)
A_{PV}	Photovoltaic (cell) area, (m ²)
A_R	Receiver area, (m ²)
c _p	Specific heat, (J/K. kg)
CR	Concentration ratio, (#)
D	Tube diameter, (m)
Gr	Grashof number, (#)
h	Specific enthalpy, (J/kg)
hc	Heat transfer coefficient for convection, (W/K m ²)
Н	Height of insulation air layer, (m)
Ι	Radiation flux intensity, (W/m^2)
I _R	Receiver flux intensity, (W/m^2)
I _D	Direct radiation flux intensity, (W/m^2)
k	Thermal conductivity, (W/K m)
k _b	Boltzmann's constant, ($1.381 \times 10^{-23} \text{ J/K}$)
kT/q	Thermal voltage, (0.02586 V at (300 K))
L	Characteristic length, (m)

Lap	Apparatus length, (m)
L _c	Length of receiver surface, (m)
L_{PV}	Photovoltaic (Cell) length, (m)
m	Mass flow rate of fluid, (kg/sec)
Nu	Nusselt number, (#)
P _{ele}	Electric output power, (W)
Pr	Prandtl number, (#)
Q _{cool}	Thermal heat transfer to the water (gain heat), (W)
Q_{th}	Thermal output power, (W)
Q _{rad}	Thermal heat loss due to radiation, (W)
Qabs-cells	Radiation absorbed by the solar cells, (W)
Qabs-glass	Radiation absorbed in the glass-silicone cover, (W)
Q _{ins}	Thermal heat transfer through the insulation, (W)
Qcon	Thermal heat loss due to convection, (W)
Ra	Rayleigh number, (#)
Re	Reynolds number, (#)
Т	Temperature, (K)
T _{amb}	Ambient temperature, (K)
T _{inl}	Inlet flow temperature, (K)
T_m	Mean Fluid temperature, (K)
T _{out}	Outlet flow temperature, (K)
T_{red}	Reduced temperature, (K m ² /W)
Uloss	Overall loss coefficient, (W/m K)
υ	Velocity, (m/s)
W	Apparatus width, (m)
W_{PV}	Photovoltaic (Cell) width, (m)
Greek Symbols	i
α	Absorption, and the mirror angle
δ	Thickness of layer, (m)
ε	Emissivity coefficient, (#)
η_{CTE}	Combined thermal and electric efficiency, (#)
η_{Th}	Thermal efficiency, (#)
η_{ele}	Electrical efficiency, (#)
θ	Angle of incidence of radiation (the angle between
	the sun and the zenith)
λ	wavelength
μ	Dynamic viscosity, (kg/m.sec)
ν	Kinematic viscosity = μ/ϱ , (m ² /sec)
σ	Stefan-Boltzmann constant, $(5.67 \times 10^{-6} \text{ W/m}^2 \cdot \text{K}^4)$
τα	Transmission-absorption coefficient, (#)
τ_{PV}	Transmission coefficient for layers above PV, (#)
Subscripts/Sup	erscripts
ар	apparatus
ac	actual
amb	ambient
С	cell
ca	trom cells to absorber
crit	critical
D	Direct
ele	electric
เทข	inverter
opt	optical
max	maximum
K	Keceiver

Abbreviations

CPV	Concentrated Photovoltaic
CPV/T	Concentrated hybrid Photovoltaic/Thermal
CPC	Compound parabolic concentrator
CST	Concentrating Solar Thermal
FPPV	Flat-Plate Photovoltaic
LFRSC	Linear Fresnel reflector solar concentrator
LFMRC	Linear Fresnel Mirror Reflecting Concentrator
PV	Photovoltaic
PV/T	Photovoltaic/Thermal

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