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PERFORMANCE ANALYSIS AND OPTIMIZATION OF A CONCENTRATED PHOTOVOLTAIC SYSTEM WITH DOUBLE FRESNEL LENSES

ÇİFT FRENSEL LENSLİ BİR YOĞUNLAŞTIRILMIŞ FOTOVOLTAİK SİSTEMİN PERFORMANS ANALİZİ VE OPTİMİZASYONU

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ABSTRACT

In this study, the performance of a CPV system with double Fresnel lenses has been analysed experimentally. In this context, the effects of concentration ratios (C_1, C_2) and f- numbers (f_1, f_2) of primary and secondary lenses and distance between lenses (L_D) on the CPV system performance have been investigated for different configurations. In general, it has been observed that the CPV system performance improves with increasing L_D until it reaches a critical value ($L_{D,crit}$), but it starts to worsen after L_D exceeds $L_{D,crit}$. Besides this, CPV systems with double lenses with a high f_1 value have been seen to perform better than single applications. It has been detected that the performance of the CPV system can be improved by using a secondary Fresnel lens when $f_1 > 0.5$. Beyond these, the ANOVA analyses have been carried out in order to compare the contribution ratio of the optical properties of lens pairs on CPV system performance. It has been observed that C_1 and f_1 are predominantly effective on CPV system performance whereas f_2 has found to have the least contribution ratio. Finally, optimum C_1, C_2, f_1, f_2 and $L_{D,crit}$ have been predicted by genetic algorithm and artificial neural network based studies.

Keywords: Solar energy, CPV system, fresnel lens, ANOVA, neural network

ÖZET

Bu çalışmada, yoğunlaştırıcı optik eleman olarak nokta odaklı Fresnel lens kullanılan çift optik elemanlı bir CPV sistemin performansı deneysel olarak incelenmiştir. Bu kapsamda, birincil ve ikincil optik eleman yoğunlaşma oranları (C_1, C_2), f sayıları (f_1, f_2) ve lensler arası mesafenin (L_D) CPV sistem performansı üzerindeki etkileri tek ve çift Fresnel lensli farklı konfigürasyonlar için araştırılmıştır. Genel olarak, lensler arası mesafe belirli bir kritik değere ($L_{D,crit}$) ulaşıncaya kadar, L_D artışı ile CPV sistem performansının iyileşmekte olduğu ancak L_D'nin kritik değerin üzerine çıktığında sistem performansının kötüleşmeye başladığı gözlenmiştir. Ayrıca, $L_{D,crit}$'in önemli ölçüde Fresnel lens çiftinin optik özelliklerine bağlı olduğu not edilmiştir. Bunun yanı sıra, yüksek f_1 değerine sahip çift Fresnel lensli CPV sistemlerinin, tekli Fresnel lens uygulamalarına göre daha iyi performans sergilediği görülmüştür. $f_1 > 0.5$ olduğunda CPV sisteminin performansının ikincil bir Fresnel lens kullanılarak iyileştirilebileceği tespit edilmiştir. Bunların ötesinde, Fresnel lens çiftlerinin optik özelliklerinin CPV sistem performansına etki oranını karşılaştırmak için deneysel veriler kullanılarak ANOVA analizleri yapılmıştır. ANOVA analizi sonuçları, birincil optik eleman özellikleri C_1 ve f_1'in çift Fresnel lensli CPV sistem performansı üzerinde ağırlıklı olarak etkili olduğunu işaret etmiştir. Öte yandan, diğer parametrelerle karşılaştırıldığında f_2'nin CPV sistem performansı üzerinde en az etkiye sahip olduğu da görülmüştür. Son olarak, genetik algoritma ve yapay sinir ağı temelli çalışmalar ile optimum C_1, C_2, f_1, f_2 and $L_{D,crit}$ tahmin edilmiştir.

Anahtar Kelimeler: Güneş enerjisi, CPV sistem, fresnel lens, ANOVA, yapay sinir ağı

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INTRODUCTION

"The world is not inherited from their ancestors, people borrowed it from their children," says a wise saying. However, human beings have been using fossil fuels for many years in order to provide the energy, which is the most basic need, by ignoring the damages they may cause to the world. As is known, fossil fuels contain carbon, and when they are burned to generate energy, they release carbon dioxide. Today's scientists have revealed that carbon dioxide creates a greenhouse effect on the world and causes global climate change. For this reason, in today's world, energy is not only a basic requirement of human beings but also one of the most primary issues that needs to be solved. This situation has focused attentions on the development of new, clean and renewable energy technologies. One of these technologies is photovoltaic systems that directly generate electrical energy using solar energy. However, the seasonal variation of solar energy density depending on geographical conditions causes the yields of these applications to remain at limited levels. Therefore, in recent years, it has been observed that studies on this area have focused on the development of new applications for improving the efficiency of photovoltaic systems (Xie et. al, 2011; Yadav et. al, 2013). Among these applications, "Concentrated Photovoltaic Systems (CPV)" stands out, where the sun's rays are focused on a specific target using optical elements such as lenses or mirrors. However, CPV systems have a very complex structure, since their performance depends on many parameters such as focusing distance, geometrical and optical concentration ratio, optical efficiency of the lens and solar radiation flux. Therefore, studies to investigate the performance of CPV systems under different operating conditions are very important. There are many different studies in the literature aimed at improving the performance of CPV systems. According to the using optical element type, it is possible to be classified these studies into two main groups as Fresnel lens and mirror. One of the first applications in the literature regarding with using Fresnel lens in CPV systems is Harmon's (1977) experimental study, in which optical efficiency was investigated for different concentration ratio. It was determined that the lens has sufficient optical efficiency at low concentration rates, but the optical efficiency of the lens decreases by 20-80 % as the focus distance decreases, especially at high concentrations. In another pioneer study that the economic feasibility of CPV systems were investigated depending on their photovoltaic cell yields, optical efficiency and cost per unit area was conducted by James and Williams. (1978). It has been highlighted that the change in solar energy density over time decreases the efficiency of photovoltaic cells and thus the cost per unit cell area increases. In addition to this, it was stated that it would be possible to benefit from CPV systems more effectively by using appropriate solar tracking systems. It has been also pointed out that solar energy density, optical transmissivity, unit cell area cost and solar tracking systems are the most critical parameters for Fresnel lens type CPV systems. In the following years, interest in CPV systems has increased and many studies on CPV systems have been implemented in the 1980s. These studies generally focused on solar tracking systems, cooling technologies for solar cells, high concentration systems and different imaging Fresnel lens shapes (Nakata et. al, 1980; Shepard and Chan, 1981; Moffat and Scharlack, 1982). It is possible to observe that since the 1990s, research on CPV systems with Fresnel lenses has reached a certain level and has started to stand out in many different areas from space applications (Grilikhes et. al, 1996; Rumyantsev et. al, 2002) to terrestrial applications (Kemmoku et. al, 2003). Essentially, an ideal CPV system is desired to concentrate sunlight uniformly onto the photovoltaic cell. However, the main problem of CPV systems is that it can generate non-uniform solar radiation intensity on the photovoltaic cell depending on the optical properties such as the focal length of the optical element and the geometric concentration ratio (Segev and Kribus, 2013). For this reason, many different methods have been developed in order to provide more uniform solar radiation intensity on the photovoltaic cell in CPV systems. The most important of these methods is the use of secondary optical elements (Tien and Shin, 2016). In the literature, there are many studies conducted using secondary optical elements with different optical properties in order to obtain a more uniform solar radiation intensity (Victoria et. al, 2009; Chen and Su, 2010; El Himer et. al, 2012; Chen and Chiang, 2015; Tien and Shin, 2016; Renzi et. al, 2017; Şahin and Yılmaz, 2019). In these studies, CPV systems with double optical elements, generally consisting of different optical element pairs, were examined and it was noticed that the use of secondary optical element significantly improved the system performance. Although Fresnel lenses are lower in cost and easier to apply compared to other optical elements, it is observed that there are not enough studies on CPV systems with double Fresnel lenses in the current literature. Besides, there is no clear answer to the question of which optical parameters are more critical on the performance of CPV system with double Fresnel lenses. This gap in the current literature is the main motivation for this study. The main purpose of this study is to experimentally investigate the effects of concentration ratio, f-number and distance between lenses on the performance of CPV systems, which consist of pairs of point-focused Fresnel lenses with different optical properties. With the help of the experimental findings, it is also aimed to make statistical predictions based on the ANOVA method in order to determine the importance order of the related parameters. Finally, it also purposed the optical properties and distance between lenses are optimized by artificial neural network coupled with genetic algorithm to maximise the performance of CPV system.

MATERIAL AND METHODS

Experimental Apparatus

In this study, the performance parameters of a CPV system with double concentrator optical elements with different optical properties were investigated experimentally. For this purpose, a CPV system consisting of a lighting unit, two-piece of concentrator optical elements and a multi-junction photovoltaic cell was designed (Fig. 1). Eight point-focus PMMA Fresnel lenses with different optical properties were used as optical elements in the experimental study, and the optical properties of lens were specified in Table 1. In the designed CPV system, $(10\ mm x 10\ mm)$ 3C42 type triple junction $(InGaP - InGaAs - Ge)$ a photovoltaic cell belonging to Azur Space Company was used (Fig.1). The experiments were carried out under indoor test condition. In order to simulate solar radiation, a lighting unit consisting of Philips tungsten-halogen bar lamps with 1000 W and projector was designed (Fig. 1), as in many studies in the literature (Tawfik et. al, 2018). Vernier PYR-BTA pyranometer was used to measure the solar radiation flux coming from the lighting unit onto the photovoltaic cell. The lighting unit has also a PLC-based control unit that works synchronously with the pyranometer and ensures that the CPV system remains constant at the required solar radiation level. In order to determine the performance parameters of the CPV system, the current-voltage $(I - V)$ and power-voltage $(P - V)$ characteristics of the photovoltaic cell were measured using the PROVA 210 solar module analyzer.

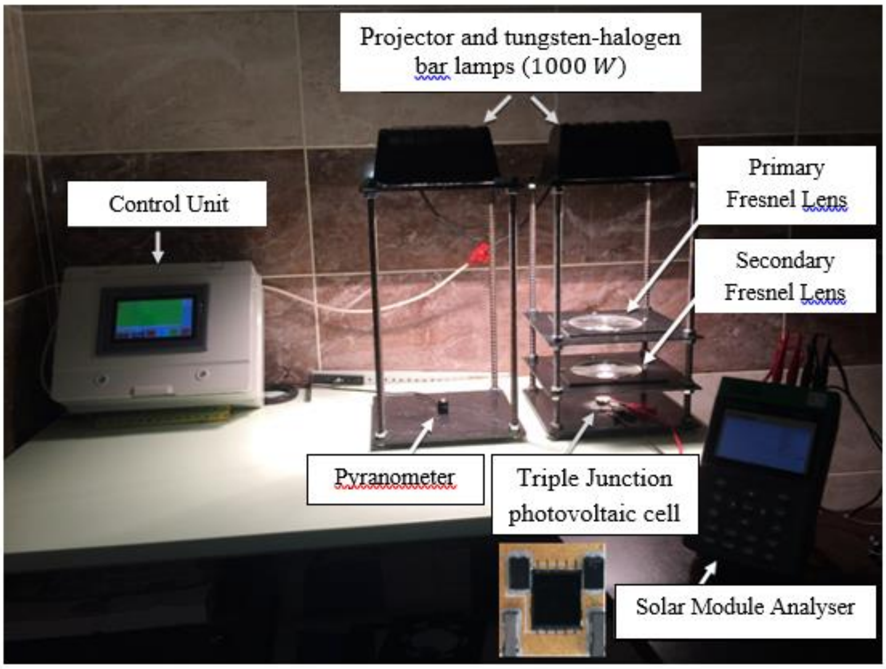


Figure 1. Experimental Setup and Equipment

Table 1. Optical Properties of the Fresnel Lenses Used in the Study

Fresnel lens	Diameter (Ø) (mm)	Focal length* (F_L) (mm)	Concentration** ratio (C)	*f* – number***
F1	150	140	176.7	0.9
F2	150	100	176.7	0.7
F3	150	70	176.7	0.5
F4	100	90	78.5	0.9
F5	100	70	78.5	0.7
F6	100	50	78.5	0.5
F7	52	35	21.2	0.7
F8	52	25	21.2	0.5

* Optimum distance from the lens to the photovoltaic cell, ** ratio of lens area to photovoltaic cell area, *** ratio of lens focal length to lens diameter.

Indoor Tests

Indoor tests were carried out under $1000\,W/m^2$ solar irradiance for 33 different situations consisting of different combinations of Fresnel lenses (Table 2). Accordingly, $D1-D8$ represent the experiments where a single optical element is used, whereas $D9-D33$ represent the experiments where double optical elements are used. In $D9-D33$ experiments, the primary optical element was kept constant at its focal length, while the secondary optical element was moved vertically. The performance of CPV system configurations have been examined by determining $I-V$ and $P-V$ characteristics for different L_D values. $I-V$ and $P-V$ characteristic curves of photovoltaic cell were obtained by curve fitting to the discrete data read from the solar module analyzer with using the model proposed by Akbaba and Alattawi (1995). They proposed the following model based on the V_{OC} and I_{SC} read for the I-V characteristic of photovoltaic cell:

$$I = \frac{V_{oc} - V}{A + BV^2 - CV} \tag{1}$$

$$A = V_{oc}/I_{sc},\ B = (K_1 - K_2)/K_3,\ C = (K_1V_a - K_2V_b)/K_3 \tag{2a}$$

$$K_1 = V_aI_a(V_{oc} - V_b - AI_b) \tag{2b}$$

$$K_2 = V_bI_b(V_{oc} - V_a - AI_a) \tag{2c}$$

$$K_3 = V_aI_aV_bI_b(V_b - V_a) \tag{2d}$$

In the above equations, $0.94I_{sc}$ and $0.64I_{sc}$ values are suggested respectively for I_a and I_b and curve fitting process is completed by selecting the appropriate values for V_a and V_b. In addition, it is also worth noting that the effect of temperature on the performance of CPV system has been ignored since the measurements made to determine the $I-V$ and $P-V$ characteristics of the photovoltaic cell are carried out in a very short time (i.e. within 30 seconds).

Table 2. Experiment Configuration List

Test No	POE	SOE
$D1$	$F-150-140$ *	$-$
$D2$	$F-150-100$	$-$
$D3$	$F-150-70$	$-$
$D4$	$F-100-90$	$-$
$D5$	$F-100-70$	$-$
$D6$	$F-100-50$	$-$
$D7$	$F-52-35$	$-$
$D8$	$F-52-25$	$-$
$D9$	$F-150-140$	$F-150-100$
$D10$	$F-150-140$	$F-150-70$
$D11$	$F-150-140$	$F-100-90$
$D12$	$F-150-140$	$F-100-70$
$D13$	$F-150-140$	$F-100-50$
$D14$	$F-150-140$	$F-52-35$
$D15$	$F-150-140$	$F-52-25$
$D16$	$F-150-100$	$F-150-70$
$D17$	$F-150-100$	$F-100-90$
$D18$	$F-150-100$	$F-100-70$
$D19$	$F-150-100$	$F-100-50$
$D20$	$F-150-100$	$F-52-35$
$D21$	$F-150-100$	$F-52-25$
$D22$	$F-150-70$	$F-100-50$
$D23$	$F-150-70$	$F-52-35$
$D24$	$F-150-70$	$F-52-25$
$D25$	$F-100-90$	$F-100-70$
$D26$	$F-100-90$	$F-100-50$
$D27$	$F-100-90$	$F-52-35$
$D28$	$F-100-90$	$F-52-25$
$D29$	$F-100-70$	$F-100-50$
$D30$	$F-100-70$	$F-52-35$
$D31$	$F-100-70$	$F-52-25$
$D32$	$F-100-50$	$F-52-35$
$D33$	$F-100-50$	$F-52-25$

* F – 150 (diameter of the lens, mm) – 140 (focal length of the lens, mm)

Reliability Analysis of Experimental Measurement

In order to test the repeatability of the experimental measurements, each $I-V$ measurement was repeated three times and the reliability analyses were performed. One of the most commonly used indicators to reflect the consistency level of repeated experimental measurement is the Cronbach's alpha coefficient (Pallant, 2016). Essentially, the Cronbach's alpha coefficient is an internal consistency measure used to demonstrate the relationship level between different tests or measurements performed for the same situation. The Cronbach's alpha coefficient is defined as a function of the number of measurement data and the mean correlation between measurements:

$$\alpha_{\text{Cronbach}} = \frac{n}{n-1}\left(1-\frac{\sum V_i}{V_m}\right) \tag{3}$$

Here, n is the number of measurements, V_i is the average covariance between the measurement pairs and V_m is the mean variance. An ideal measurement result is expected to be Cronbach's alpha coefficient above 0.7 (Pallant, 2016). The outputs of reliability analysis are presented in Table 3 for some selected measurements. It is shown in Table 3 that the values of correlation among the repeated measurements and Cronbach's alpha coefficient are higher than 0.9. This indicates that the consistency level of the repeated experimental measurements is extremely high.

Table 3. The Outputs of Reliability Analysis for $I-V$ Measurements

$D9$	Correlation Matrix			Cronbach's Alpha Coefficient
	M1	M2	M3	
M1	1.000	0.960	0.995	0.992

M2	0.960	1.000	0.981	
M3	0.995	0.981	1.000	
$D10$	Correlation Matrix			Cronbach's Alpha Coefficient
	M1	M2	M3	
M1	1.000	0.985	0.922	
M2	0.985	1.000	0.892	0.970
M3	0.922	0.892	1.000	
$D16$	Correlation Matrix			Cronbach's Alpha Coefficient
	M1	M2	M3	
M1	1.000	0.870	0.820	
M2	0.870	1.000	0.991	0.901
M3	0.820	0.991	1.000	
$D25$	Correlation Matrix			Cronbach's Alpha Coefficient
	M1	M2	M3	
M1	1.000	0.959	0.973	
M2	0.959	1.000	0.901	0.974
M3	0.973	0.901	1.000	
$D26$	Correlation Matrix			Cronbach's Alpha Coefficient
	M1	M2	M3	
M1	1.000	0.906	0.922	
M2	0.906	1.000	0.994	0.970
M3	0.922	0.994	1.000	

RESULTS AND DISCUSSIONS

Effect of Distance between Lenses

For $D9 - D33$ configurations, using secondary optical elements, measurements at different L_D values were taken and the $I - V$, $P - V$ characteristic curves and performance parameters were compared with the CPV system with a single optical element, and the effect of L_D on the performance of CPV systems using double optical elements was examined in detail. In Figure 2, the results of $D12$ and $D14$ configurations are given, consisting of $F - 150 - 140\ x\ F - 100 - 70$ and $F - 150 - 140\ x\ F - 52 - 35$ optical element pairs, respectively. For both configurations, it is possible to observe that, the CPV system performance improves with increasing L_D until L_D reaches a critical value ($L_{D,crit}$), but it starts to worsen after L_D exceeds $L_{D,crit}$. For $D12$ ve $D14$ configurations, $L_{D,crit}$ values, where the highest performance was obtained, were determined as 100 mm and 120 mm, respectively. On the other hand, for the $D12$ ($D14$) configuration, the change in L_D does not affect the V_{OC} value of the photovoltaic cell, whereas the highest I_{SC} and P_{max} values were measured as 44 mA (47 mA) and 100.92 (110.17) respectively, $L_D = 100\ mm$ ($L_D = 120\ mm$). These values for $D12$ ($D14$) configuration correspond to an increase of approximately 260 % (285 %) and 257 % (289 %) for I_{SC} and P_{max}, respectively, when compared to $D1$ configuration where single optical element is used.

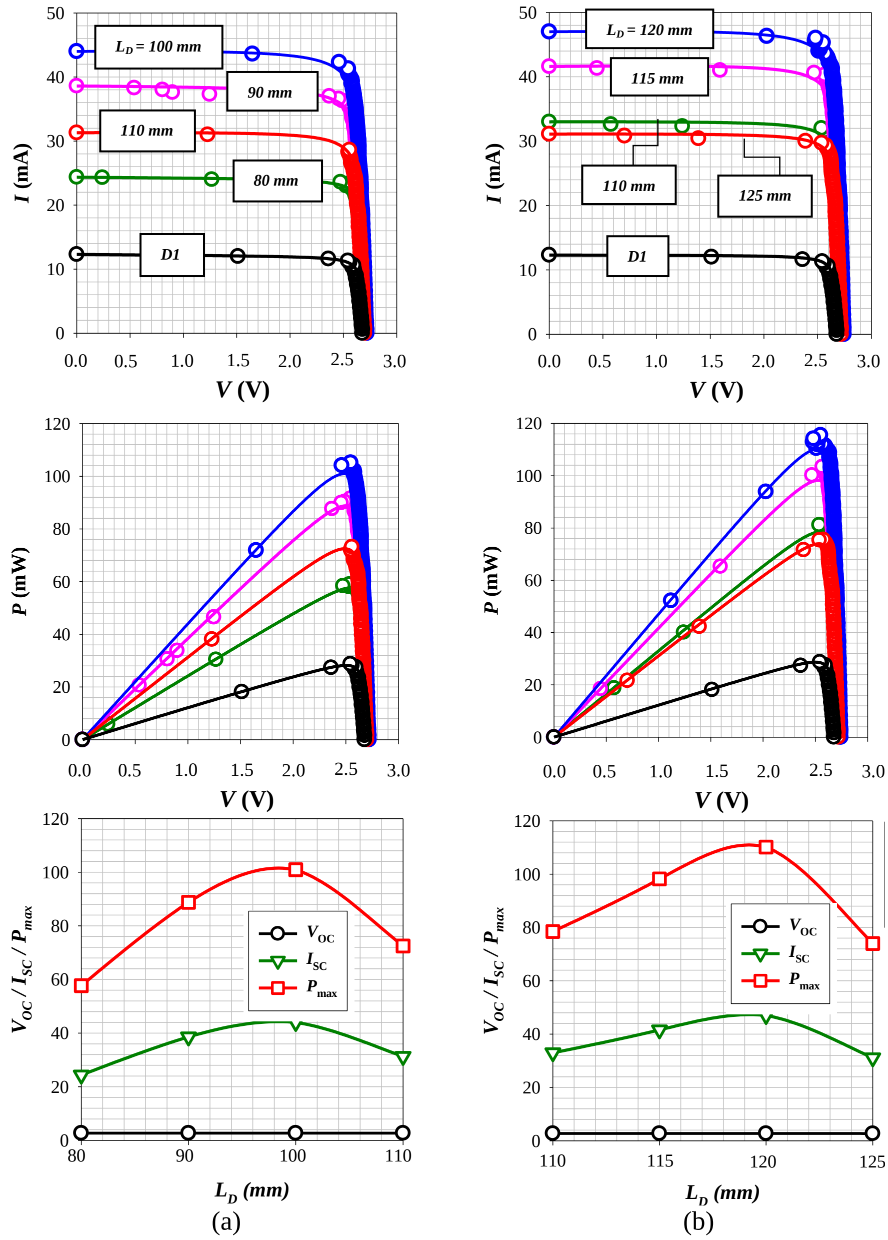


Figure 2. The Effect of L_D on Characteristic Curves and Performance Parameters of CPV System for a) $D12$ and b) $D14$ Configurations

The findings for $D25$ $(F-100-90\ x\ F-100-70)$ and $D27$ $(F-100-90\ x\ F-52-35)$ configurations have been presented in Figure 3. Similar to $D12$ and $D14$ configurations (see Fig. 2), there is a non-monotonic relationship between L_D and CPV system performance parameters for the $D27$ configuration. In other words, up to a critical distance of L_D, CPV system performance enhances with increasing the distance between lenses, but it tends to deteriorate when this critical distance is exceeded. For the $D27$ configuration, it is seen that the values of maximum power and short-circuit current are obtained as $I_{SC} = 38.3\ mA$ and $P_{max} = 91.81\ mW$, respectively at $L_D = 70\ mm$ and the CPV system performance parameters tend to decrease for $L_D > 70\ mm$. In other respects, it is observed that the system performance increases with increasing L_D for the $D25$ configuration. In Fig. 3, at low L_D distances, it is also remarkable that the CPV system performance stays under the performance of $D4$ configuration that consists of the single optical element, which has the same optical properties as POE of $D25$ configuration. The findings in Figures 2 and 3 indicate that the performance of CPV systems with double optical elements will be lower than CPV systems with single optical elements if the distance between the lenses is not properly set up.

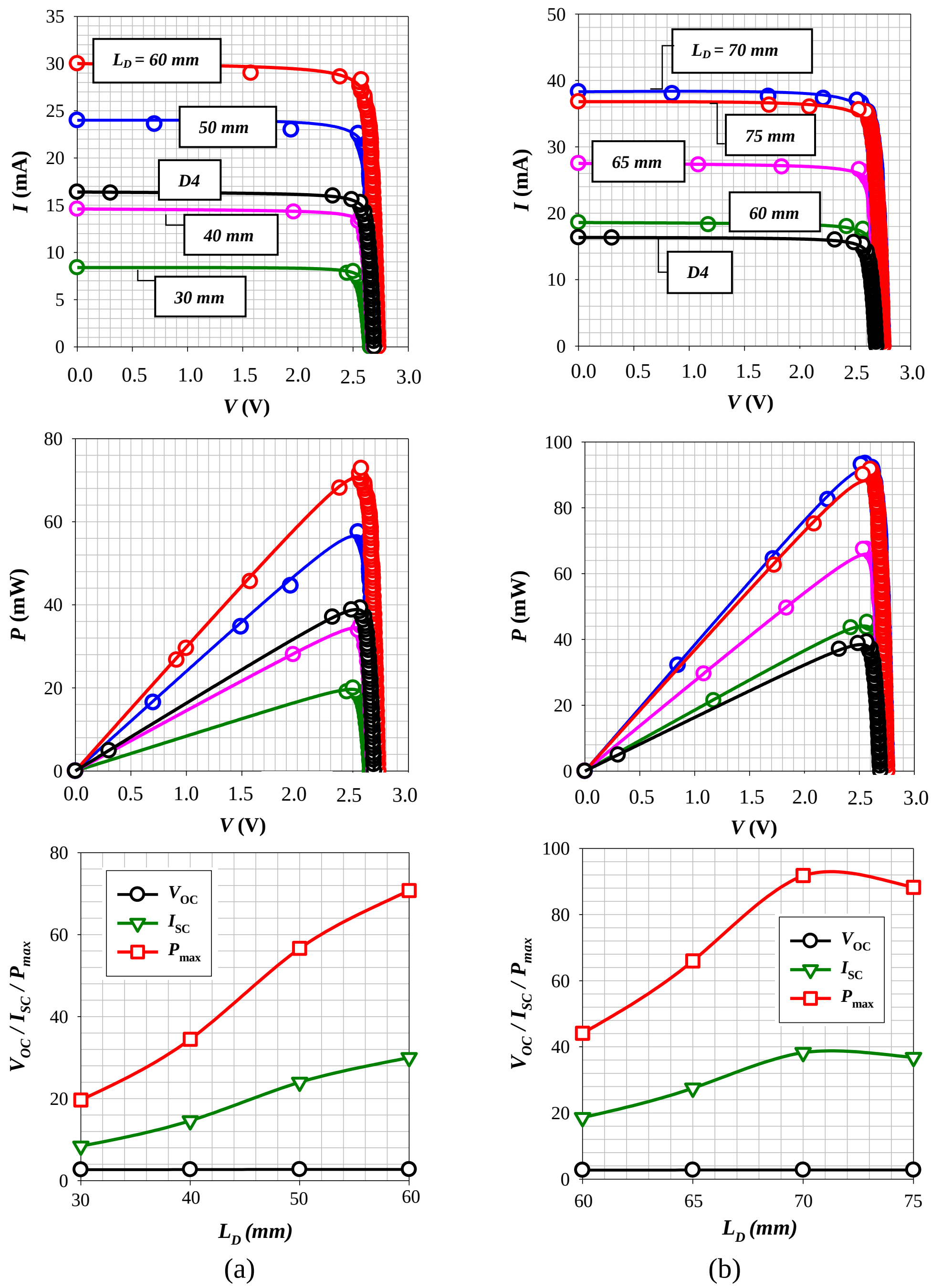


Figure 3. The Effect of L_D on Characteristic Curves and Performance Parameters of CPV System for a) $D25$ and b) $D27$ Configurations

Table 4. The Optical Properties of the Fresnel Lens Pairs and the Values of $L_{D,crit}$ and P_{max}

Experiment No	$Ø_1$ (mm)	F_{L1} (mm)	$Ø_2$ (mm)	F_{L2} (mm)	C_1	C_2	f_1	f_2	$L_{D,crit}$ (mm)	Pmax (mW) Double Lens	Pmax (mW) Single Lens
D9	150	140	150	100	176.71	176.71	0.9	0.7	80	71.31	28.30
D10	150	140	150	70	176.71	176.71	0.9	0.5	100	98.85	28.30
D11	150	140	100	90	176.71	78.54	0.9	0.9	90	89.47	28.30
D12	150	140	100	70	176.71	78.54	0.9	0.7	100	100.92	28.30
D13	150	140	100	50	176.71	78.54	0.9	0.5	110	113.45	28.30
D14	150	140	52	35	176.71	21.24	0.9	0.7	120	110.17	28.30
D15	150	140	52	25	176.71	21.24	0.9	0.5	120	114.52	28.30
D16	150	100	150	70	176.71	176.71	0.7	0.5	70	77.84	46.89
D17	150	100	100	90	176.71	78.54	0.7	0.9	70	93.63	46.89
D18	150	100	100	70	176.71	78.54	0.7	0.7	70	98.44	46.89
D19	150	100	100	50	176.71	78.54	0.7	0.5	80	102.58	46.89
D20	150	100	52	35	176.71	21.24	0.7	0.7	85	118.22	46.89
D21	150	100	52	25	176.71	21.24	0.7	0.5	85	117.47	46.89
D22	150	70	100	50	176.71	78.54	0.5	0.5	50	80.98	79.53
D23	150	70	52	35	176.71	21.24	0.5	0.7	55	94.62	79.53
D24	150	70	52	25	176.71	21.24	0.5	0.5	55	84.76	79.53
D25	100	90	100	70	78.54	78.54	0.9	0.7	60	70.74	38.44
D26	100	90	100	50	78.54	78.54	0.9	0.5	60	74.03	38.44
D27	100	90	52	35	78.54	21.24	0.9	0.7	70	91.81	38.44
D28	100	90	52	25	78.54	21.24	0.9	0.5	75	100.37	38.44
D29	100	70	100	50	78.54	78.54	0.7	0.5	40	51.06	54.19
D30	100	70	52	35	78.54	21.24	0.7	0.7	55	90.18	54.19
D31	100	70	52	25	78.54	21.24	0.7	0.5	55	80.78	54.19
D32	100	50	52	35	78.54	21.24	0.5	0.7	35	60.88	60.65
D33	100	50	52	25	78.54	21.24	0.5	0.5	35	48.90	60.65

In Table 4, the optical properties of the Fresnel lens pairs, the critical distances between the lenses (where the highest performance occurs) and the maximum power outputs have been given by comparing to the CPV systems with single optical element. It is possible to observe that the $L_{D,crit}$ value, where the maximum CPV system performance occurs, varies depending on the optical properties of the Fresnel lens pairs. In addition to this, the optical properties of the secondary optical element such as the concentration ratio (C_2) and the f- number (f_2), significantly affect the value of $L_{D,crit}$. This can be detected more clearly from Figure 4 where the variation of $L_{D,crit}$ with C_2 and f_2 are given for the CPV system configuration in which the lens, which has $C_1 = 176.6$ and $f_1 = 0.9$ optical properties, is used as POE. Figure 4 indicates that when f_2 (C_2) is kept constant and C_2 (f_2) is increased, the values of $L_{D,crit}$ (where the maximum power output arises) reduce in CPV systems with double optical elements.

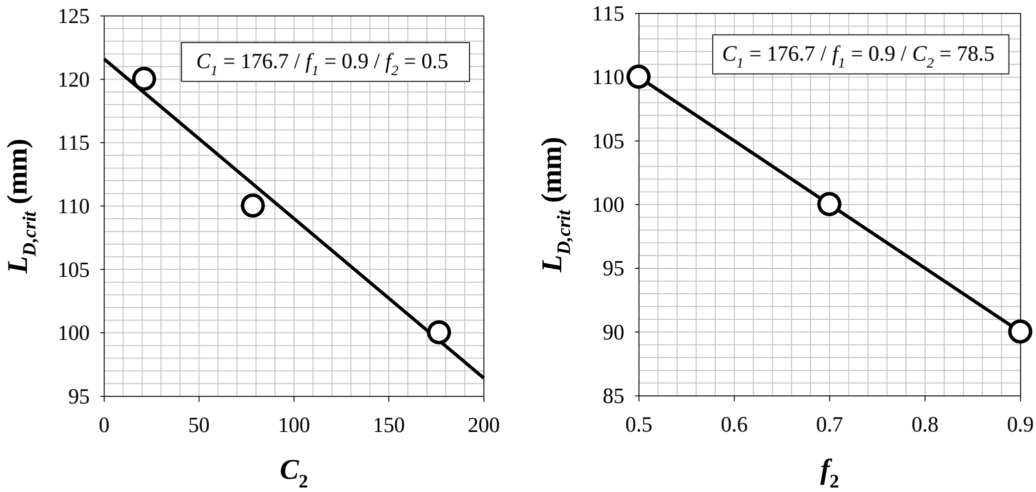


Figure 4. The Variation of $L_{D,crit}$ with Optical Properties of Secondary Fresnel Lens (i.e. C_2 and f_2)

In Figure 5, the values of maximum power output obtained from different CPV system configurations using double optical elements are compared with the cases with a single optical element. It is possible to conclude from Fig. 5 that using double lenses has positively affected the CPV system performance in general. It was observed that the highest power output was obtained from the D20 configuration consisting of the $F-150-100\ x\ F-52-35$ Fresnel lens pair with 118.22 mW. This corresponds to a power increase of approximately 152 % compared to the $D2$ configuration using single Fresnel lens ($F-150-100$). Compared to the case with single optical element, the highest performance increase with approximately 305 % has been achieved for the $D15$ configuration ($F-150-140\ \times F-52-35$). On the other hand, it has been observed that using secondary optical elements does not have a significant effect on the CPV system performance in D22 ($F-150-70\ x\ F-\ 100-50$) and D32 ($F-100-50\ x\ F-52-35$), whereas it adversely influences the CPV system performance in the D29 ($F-100-70\ x\ F-100-50$) and $D33$ ($F-100-50\ x\ F-52-25$).

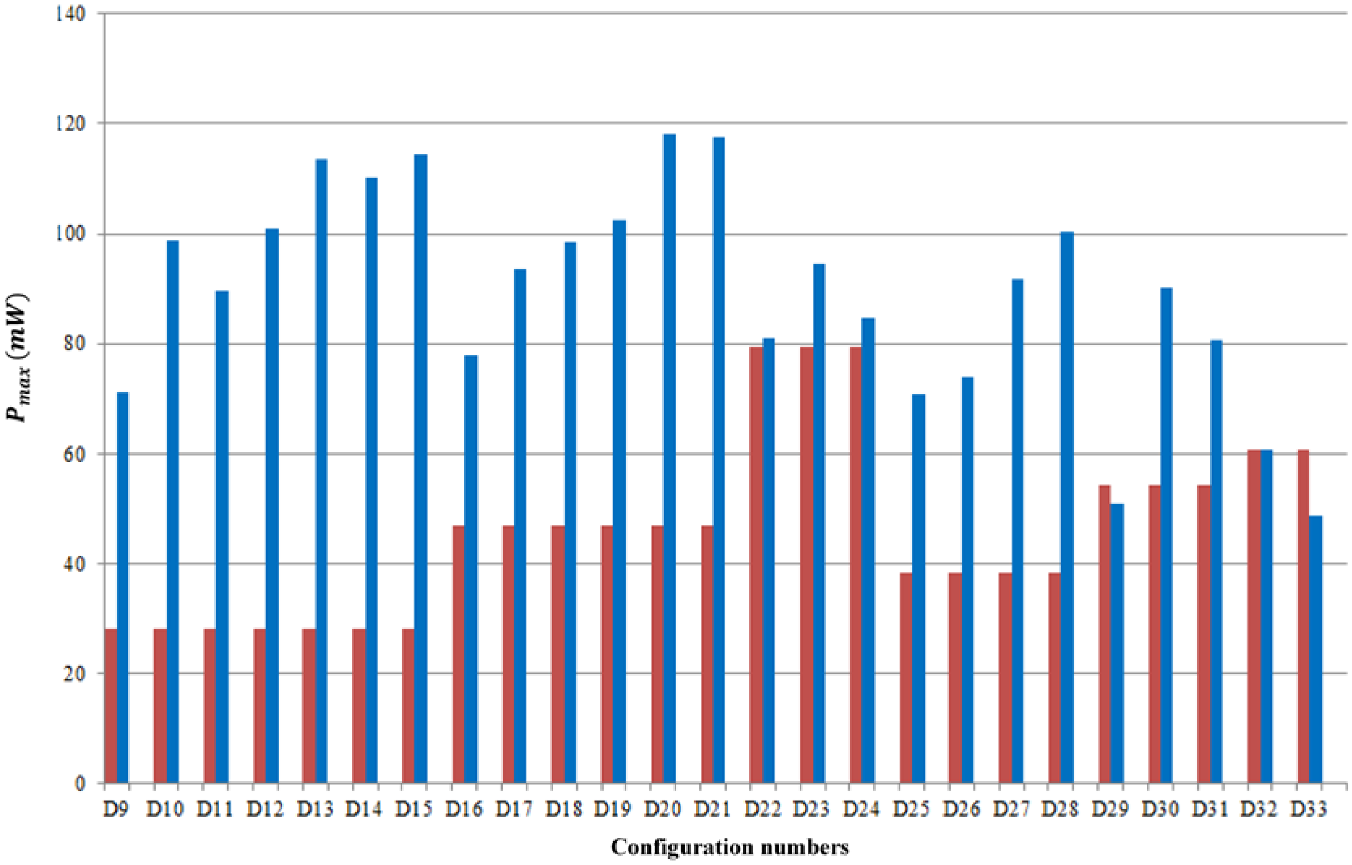


Figure 5. P_{max} Values Obtained from CPV System Configurations with Single (Red) and Double (Blue) Fresnel Lenses

Besides, it is also possible to observe from Fig. 5 that the CPV system configurations, which have high POE concentration ratio, produce higher power output than the other configurations with double lenses. In addition to this, it is worth noting that double optical element CPV systems with high f_1 value generally exhibit higher performance compared to CPV systems with single optical elements. However, the maximum power output for the CPV systems with double optical elements, which have low f_1 values, occurs rather close (or lower) levels to the systems, which have single optical element. This can be observed more explicitly from Fig. 6, where maximum power outputs of CPV system configurations with double and single optical elements are compared according to the f-number of POE (i.e. f_1). Figure 6 indicates that the performances of CPV system configurations with single Fresnel lens improve by supporting a secondary Fresnel lens when f_1 is higher than 0.5. In other words, it is possible to state that using a secondary optical element does not have a positive influence on the power output if $f_1 \leq 0.5$ for a CPV system with single Fresnel lens.

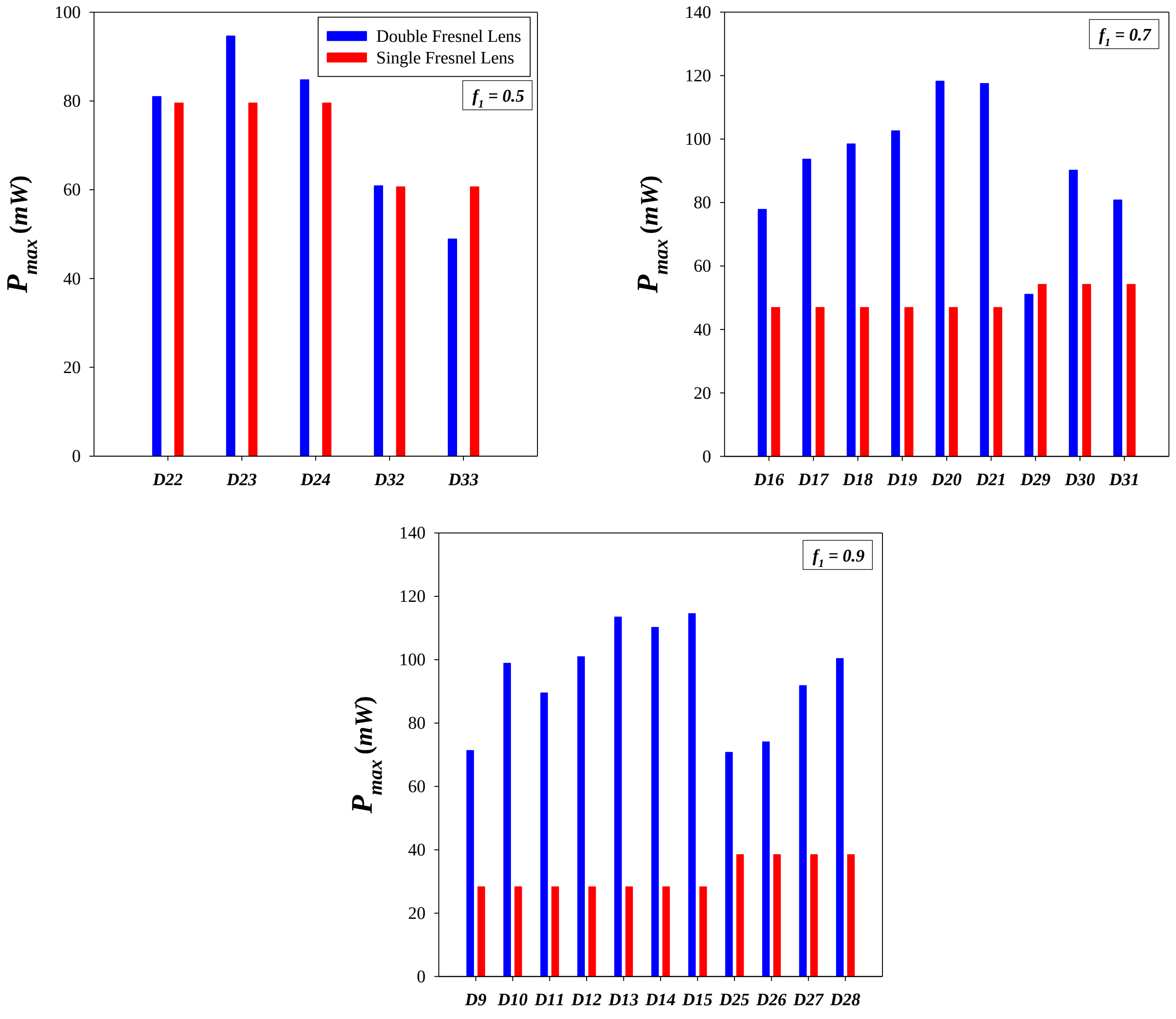
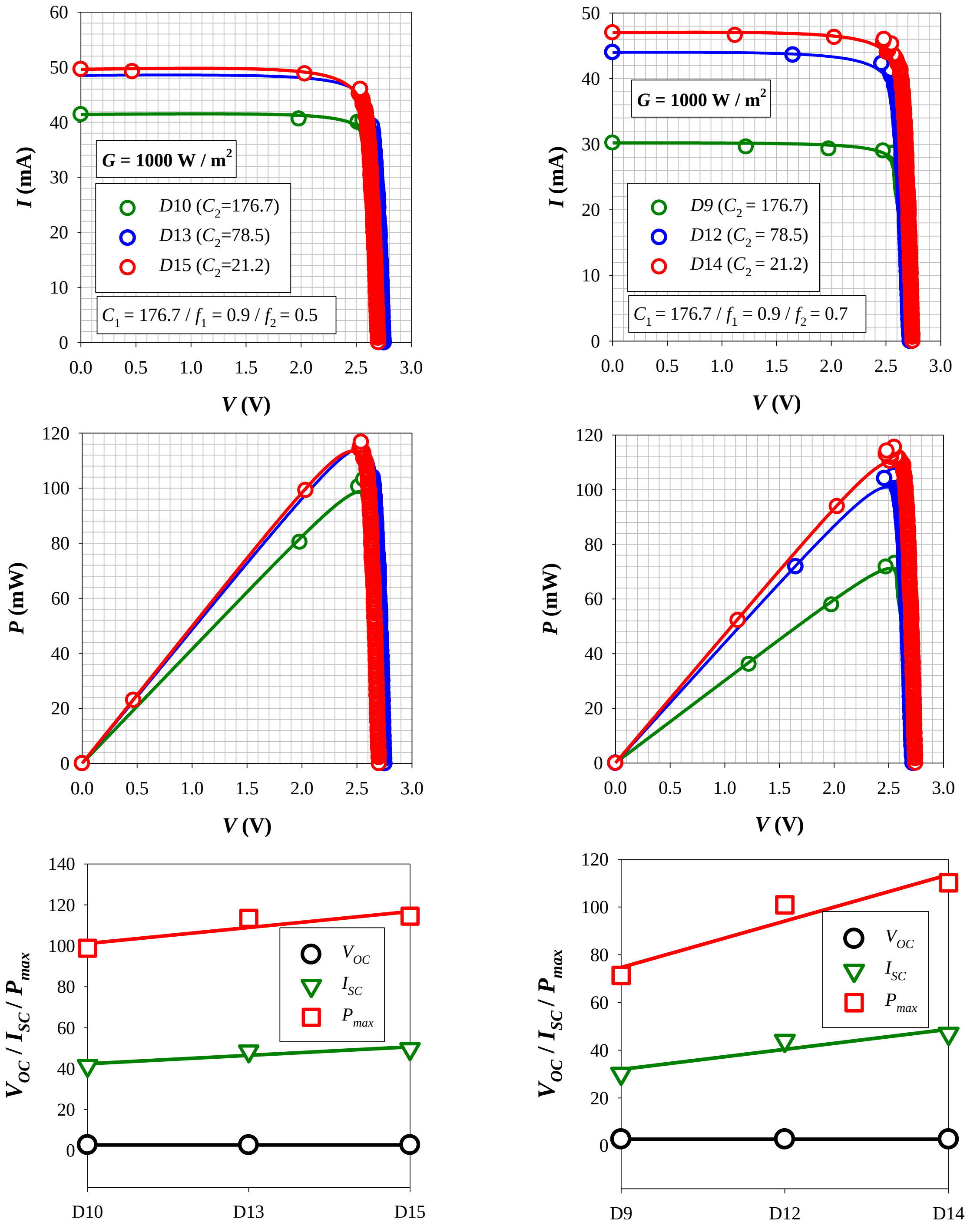


Figure 6. Comparison P_{max} Values of CPV System Configurations with Double and Single Fresnel Lens for Different f_1 Values

Effect of Concentration Ratio of Secondary Optical Element

In order to reveal the effect of concentration ratio of secondary optical element (SOE) on CPV system performance, $I-V$ and $P-V$ characteristic curves and performance parameters of CPV system configurations consisting of the SOE, which have different concentration ratios, have been compared in Figures 7 and 8. Accordingly, the findings for $D10$, $D13$ and $D15$ ($D9$, $D12$ and $D14$) configurations consisting of the same primary optical element (POE) but different SOE which have $f_2 \cong 0.5$ ($f_2 \cong 0.7$) were presented in Fig. 7a (Fig. 7b). From Figures 7a and 7b, it is possible to observe that CPV system performance improves with decreasing C_2. Moreover, it is also attractive that this behaviour occurs more significantly especially for the cases, which have high f_2 value (Fig. 7b). For example, among the configurations where f-number of SOE (i.e f_2) equals to 0.7 (0.5), P_{max} was obtained as 71.31 mW (98.85 mW) for $D9$ ($D10$) configuration where $C_2 = 176.7$, whereas it was measured as 110.17 mW (114.52 mW) with nearly 55 % (16 %) increasing for $D14$ ($D15$) configuration where $C_2 = 21.2$. Besides, the results for $D16$, $D19$ and $D21$ configurations, consisting of the POE which has lower f_1 ($\cong 0.7$) value and the SOE which have $F - 150 - 70$, $F - 100 - 50$ and $F - 52 - 25$ optical properties respectively, were given in Fig 8. Similarly, the CPV system performance significantly increases when C_2 decreases. Finally, it is also worth noting that when Fig. 7a and Fig. 8 are compared, the performance improvement is higher in the CPV systems with double Fresnel lenses, which have low f_1 value.



(a) (b)

Figure 7. The Effects of C_2 on the Performance of CPV System Configurations at which $f_1 = 0.9$: (a) $f_2 = 0.5$ and (b) $f_2 = 0.7$

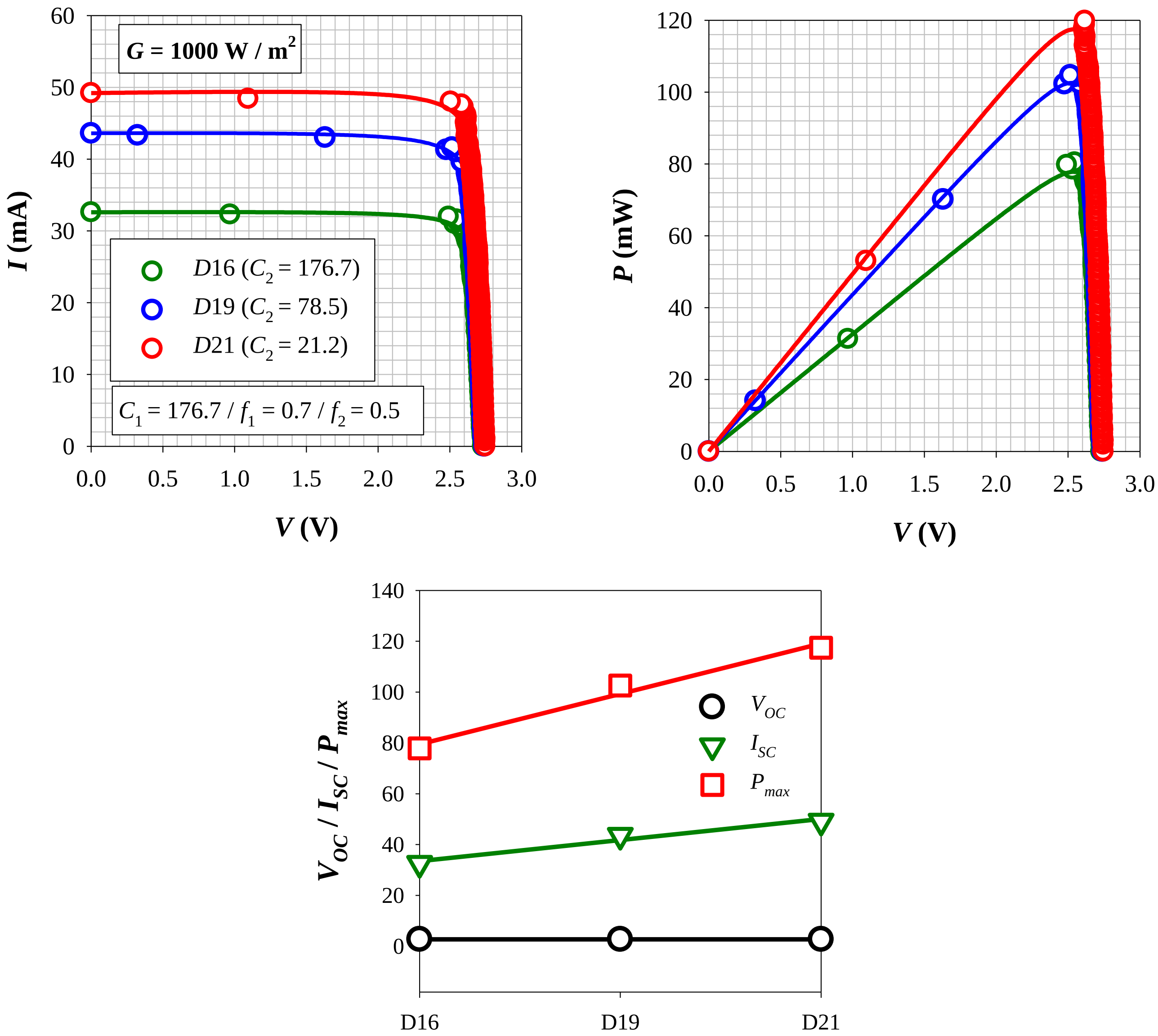


Figure 8. The Effects of C_2 on the Performance of CPV System Configurations at which $f_1 = 0.7$ and $f_2 = 0.5$.

Effect of f-Number of Secondary Optical Element

In order to observe the effects of the f- number of SOE on the double Fresnel lens CPV system performance, it will be useful to examine Figure 9 where the performances of CPV system configurations consisting of the SOE with different f_2 values, are compared. The findings have been given in Fig.9a (Fig. 9b) for the $D11$, $D12$ and $D13$ ($D17$, $D18$ and $D19$) configurations, which consist of $F-150-140$ ($F-150-100$) optical featured POE and $F-100-90$, $F-100-70$ and $F-100-50$ optical featured SOE respectively. It can be noticed from Figures 9a and 9b that the performance of the double Fresnel lens CPV system improves when the f_2 value decreases. Accordingly, in the CPV system configurations using Fresnel lens in which $f_1 = 0.9$ as the POE, $P_{max} = 89.47\ mW$ for the $D11$ configuration in which $f_2 = 0.9$; for the $D13$ configuration where $f_2 = 0.5$, the maximum power output was determined as $P_{max} = 113.45\ mW$ with an increase of approximately 27 %. On the other hand, among the CPV system configurations using the POE with lower f_1 (= 0.7) value, $P_{max} = 93.63\ mW$ ($I_{SC} = 39.20\ mA$) for the $D17$ configuration where $f_2 = 0.9$ whereas P_{max} (I_{SC}) was obtained as 102.58 mW (43.6 mA) with an increase of approximately 9.5 % (11.2 %) for the $D13$ configuration in which $f_2 = 0.5$ (Fig. 9b). This explicitly reflects that the performance improvement with decreasing f_1 value of the secondary Fresnel lens is much more apparent in double Fresnel lens CPV system configurations which have a high f_1 value POE.

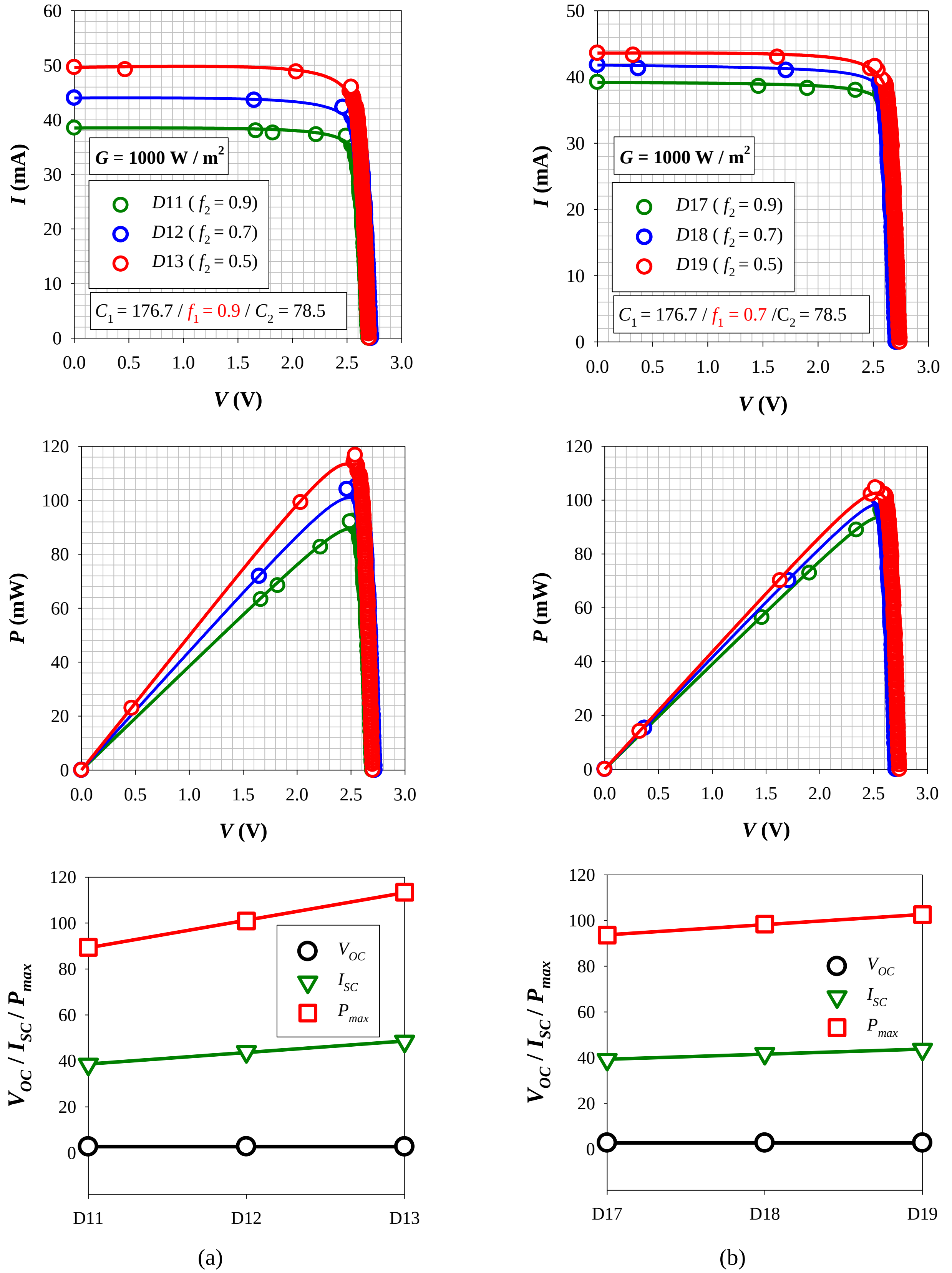


Figure 9. The Effects of f_2 on the Performance of CPV System Configurations: (a) $f_1 = 0.9$ and (b) $f_1 = 0.7$

ANOVA Analysis

In this section, the statistical studies have been carried out to reveal the weight factors of optical properties such as concentration ratio and $f-$ number of primary and secondary Fresnel lenses on the performance of CPV systems. One of the most common statistical approaches used to reveal weight factors of independent variables on the dependent variable is Analysis of Variance (i.e. ANOVA). Essentially, the ANOVA method is applied in order to predict the importance order of the factors by revealing the proportional effect of each factor which are effective on the target function (Canbolat et. al, 2019). In the ANOVA method, degrees of freedom (DOF), sum of squares (SS), mean of squares (MS), F value and contribution ratios of the each factors in data set are calculated by using the following equations:

$$F_{factor} = \frac{V_{factor}}{V_{error}} \tag{4a}$$

$$V_{factor} = \frac{SS_{factor}}{DOF_{factor}} \tag{4b}$$

$$DOF_{factor} = k - 1 \tag{4c}$$

$$SS_{factor} = \frac{\sum \beta_{factor,i}{}^{2}}{N} - \frac{(\sum \beta_i)^2}{n} \tag{4d}$$

Here, F_{factor} represents the effect rate of the relevant parameter on the target function, and the larger the value of F_{factor} means the greater the effect rate for the relevant parameter. V_{factor} and V_{error} represent the variance value of the factor and error, respectively. DOF_{factor} is the degrees of freedom of the factor, SS_{factor} is the sum of squares depending on the factor, $\beta_{factor,i}$ is $S\ /\ N$ (signal / noise) ratio of the factor at the ith level, N is the number of repetitions of the factor at each level and n is the total number of tests or analyses. MS is also calculated as the ratio of SS value to degrees of freedom for each parameter. The values of the target function are converted to the S/N ratio, taking into account the "Biggest-Best" performance characteristic with the help of the following equation:

$$S/_{N} = -10log\left(\frac{1}{n}\sum_{i=1}^{n} y_i{}^{-2}\right) \tag{5}$$

Where n is the number of tests or experiments, y_i represents the result value obtained for the ith performance characteristic. For this study, y_i shows maximum power output (P_{max}) obtained for each experiment, double and single optical element CPV system maximum output power ratios ($P_{max}\ /\ P_{max,single}$) or critical distance between lenses ($L_{D,crit}$) value for each experiment. The selected parameters and levels for ANOVA analysis are summarized in Table 5 in order to reveal the weight factors of optical properties of primary and secondary optical elements on P_{max}, $P_{max}\ /\ P_{max,single}$ and $L_{D,crit}$. Accordingly, one parameter with two levels (i.e. C_1) and three parameters with three levels (i.e. f_1, f_2 and C_2) have been taken into account for ANOVA analysis.

Table 5. The Selected Parameters and Levels for ANOVA Analysis

Parameters	Levels		
$\boldsymbol{C_1}$	78.5	176.7	-
$\boldsymbol{f_1}$	0.5	0.7	0.9
$\boldsymbol{C_2}$	21.2	78.5	176.7
$\boldsymbol{f_2}$	0.5	0.7	0.9

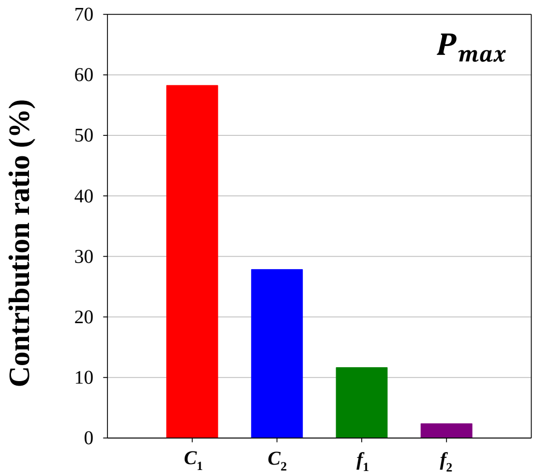
Table 6. The Data Set Used in ANOVA Analysis

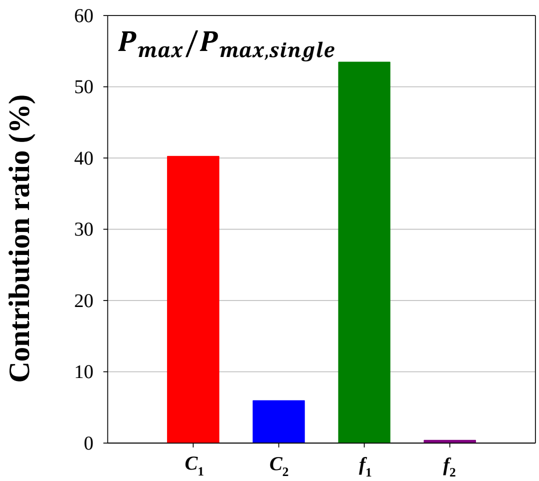
Exp. No	Parameters				P_{max} (mW)	S/N	P_R	S/N	$L_D, crit$ (mm)	S/N
	C_1	C_2	f_1	f_2						
$D9$	176.7	176.7	0.9	0.7	71.31	37.06	2.52	8.03	80	38.06
$D10$	176.7	176.7	0.9	0.5	98.85	39.90	3.49	10.86	100	40.00
$D11$	176.7	78.5	0.9	0.9	89.47	39.03	3.16	10.00	90	39.08
$D12$	176.7	78.5	0.9	0.7	100.92	40.08	3.57	11.04	100	40.00
$D13$	176.7	78.5	0.9	0.5	113.45	41.10	4.01	12.06	110	40.83
$D14$	176.7	21.2	0.9	0.7	110.17	40.84	3.89	11.81	120	41.58
$D15$	176.7	21.2	0.9	0.5	114.52	41.18	4.05	12.14	120	41.58
$D16$	176.7	176.7	0.7	0.5	77.84	37.82	1.66	4.40	70	36.90
$D17$	176.7	78.5	0.7	0.9	93.63	39.43	2.00	6.01	70	36.90
$D18$	176.7	78.5	0.7	0.7	98.44	39.86	2.10	6.44	70	36.90
$D19$	176.7	78.5	0.7	0.5	102.58	40.22	2.19	6.80	80	38.06
$D20$	176.7	21.2	0.7	0.7	118.22	41.45	2.52	8.03	85	38.59
$D21$	176.7	21.2	0.7	0.5	117.47	41.40	2.51	7.98	85	38.59
$D23$	176.7	21.2	0.5	0.7	94.62	39.52	1.19	1.51	55	34.81
$D24$	176.7	21.2	0.5	0.5	84.76	38.56	1.07	0.55	55	34.81
$D25$	78.5	78.5	0.9	0.7	70.74	36.99	1.84	5.30	60	35.56
$D26$	78.5	78.5	0.9	0.5	74.03	37.39	1.93	5.69	70	36.90
$D27$	78.5	21.2	0.9	0.7	91.81	39.26	2.39	7.56	70	36.90
$D28$	78.5	21.2	0.9	0.5	100.37	40.03	2.61	8.34	75	37.50
$D30$	78.5	21.2	0.7	0.7	90.18	39.10	1.66	4.42	55	34.81
$D31$	78.5	21.2	0.7	0.5	80.78	38.15	1.49	3.47	55	34.81

Table 7. The Results of ANOVA Analysis for P_{max}, $P_{max}/P_{max,single}$ and $L_{D,crit}$

P_{max}					
Parameters	SD	SS	MS	F	**Contribution ratio (%)**
C_1	1	21.03	21.03	34.89	58.23
C_2	2	20.10	10.05	16.67	27.82
f_1	2	8.39	4.20	6.96	11.62
f_2	2	1.68	0.84	1.40	2.34
Error	13	7.84	0.60		
Σ	20	38.59			
$P_R = P_{max}/P_{max,single}$					
Parameters	SD	SS	MS	F	**Contribution ratio (%)**
C_1	1	71.80	71.80	107.31	26.60
C_2	2	21.23	10.61	15.86	3.51
f_1	2	190.78	95.39	142.57	69.71
f_2	2	1.36	0.68	1.01	0.18
Error	13	8.70	0.67		
Σ	20	222.71			
$L_{D,crit}$					
Parameters	SD	SS	MS	F	**Contribution ratio (%)**
C_1	1	53.48	53.48	282.84	57.15
C_2	2	10.35	5.18	27.37	5.53
f_1	2	66.45	33.22	175.71	35.50
f_2	2	3.39	1.70	8.97	1.81
Error	13	2.46	0.19		
Σ	20	95.44			

The weight factors of double optical element CPV systems on P_{max} were analysed by ANOVA method depending on the considered levels of optical properties. The data set and analysis results are presented in Tables 6 and 7 respectively. In addition, the contribution ratio of the optical properties on P_{max} are compared in percentage in Fig. 10. Accordingly, the most effective optical parameter on P_{max} was found to be C_1 with 58.23 %. On the other hand, it was seen that the lowest contribution ratio on P_{max} is f_2 with 2.34 %. In addition to this, the other optical properties which have a significant effect on P_{max} after C_1 were found to be C_2 (27.82 %) and f_1 (11.62 %) respectively. Essentially, it needs to be stated that the outputs of the ANOVA analysis presented in Table 7 and Fig. 10a regarding the contribution ratio of optical properties on P_{max} are the expected results. Because higher power output is always expected from a CPV system with a high concentration ratio. Therefore, it will be useful to consider the maximum output power ratio of the double and single optical element CPV system ($P_R = P_{max} / P_{max,single}$) in order to better observe the contribution ratio of optical properties on the performance increase (Tables 6, 7 and Fig. 10b). Figure 10b reflects that the performance improvement in CPV systems, which reinforced with a secondary Fresnel lens significantly depends on the optical properties of the primary Fresnel lens and also f- number of secondary optical element (i.e f_2) has no effect. According to ANOVA analysis results, it was determined that the most effective optical parameter on $P_{max} / P_{max,single}$ ratio was f_1 with 69.71 %. It should also be emphasized that the results in Figure 10b are consistent with the previous findings in Fig. 6. These findings also indicate that using a secondary optical element does not have a positive effect on performance for $f_1 \leq 0.5$. Finally, the effects of optical properties of primary and secondary Fresnel lenses on $L_{D,crit}$ were analysed using the data set in Table 6 with ANOVA method and the results are presented in Table 7 and Figure 10c. Accordingly, although optical properties of both Fresnel lens are effective on the $L_{D,crit}$, it is possible to observe that C_1 and f_1 are much more effective on the $L_{D,crit}$. It was determined that the most effective optical parameter on the $L_{D,crit}$ was C_1 with 57.15 %, followed by f_1, C_2 and f_2 with 35.5 %, 5.53 % and 1.81 % respectively. In summary, ANOVA analysis results indicate that primary optical element properties C_1 and f_1 are predominantly effective on double Fresnel lens CPV system performance, while secondary optical element f- number (i.e. f_2) is the optical parameter with the least contribution ratio.





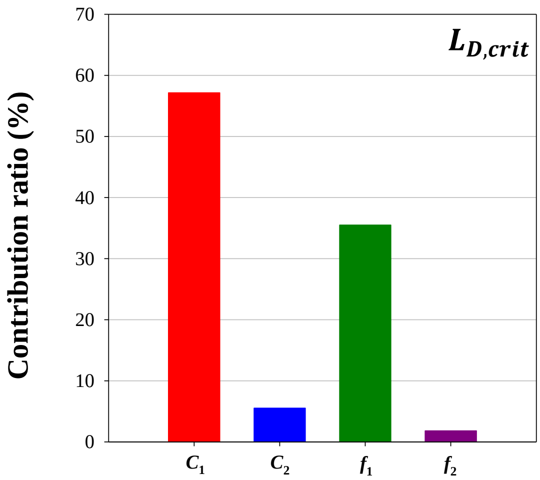


Figure 10. The Contribution Ratios of Optical Properties of Primary and Secondary Fresnel Lenses on P_{max}, $P_{max}/P_{max,single}$ and $L_{D,crit}$

OPTIMIZATION OF THE CPV SYSTEM

In this section, artificial neural network (ANN) and genetic algorithm (GA) based optimization studies are carried out in order to get the best performance of the designed CPV system. In Figure 11, the scenario of the optimization study is summarized. First, mathematical models were created in ANN for $1/P_{max}$ and $L_{D,crit}$ using input parameters ($i.e. C_1\ C_2, f_1, f_2$). Then, the optimum input parameters were estimated by optimizing the mathematical model created for $1/P_{max}$ using GA. Finally, the optimum $L_{D,crit}$ distance was estimated by using these optimal input parameters in the mathematical model created for $L_{D,crit}$.

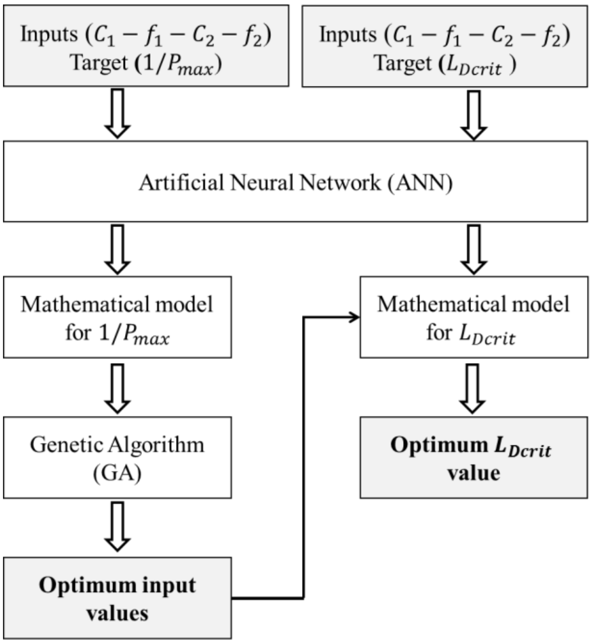


Figure 11. Flowchart of optimization methodology.

Artificial Neural Network

Artificial Neural Networks (ANNs) are computer algorithms that can learn events using examples related to a particular situation and produce solutions against changes from the environment. Similar to the functional abilities of the human brain, ANNs create their own experiences with the information getting from the examples after then make similar decisions on similar issues. Today, ANNs are effectively used in many areas such as classification, modeling, and prediction applications (Rodriguez et al., 2018; Li et al., 2022). In this study, ANNs are used to predict $1/P_{max}$ and $L_{D,crit}$ for different optical properties of POE and SOE in order to optimize CPV system. Two separate multi-layer feedforwards ANNs with sigmoid hidden neurons and linear output neurons were designed to find out mathematical model between inputs and outputs. The input layer of each ANN structures consists of 4 parameters which are C_1, C_2, f_1, and f_2. In the output layers, $1/P_{max}$ and $L_{D,crit}$ were defined as separate targets for ANNs. In addition, each ANN structure has a hidden layer, which consists of 10 neurons (Figs. 12 and 13). 70% of the experimental results given in Table 4 were used for training, 15% for validation, and 15% for testing. The ANNs were trained with Levenberg-Marquardt backpropagation algorithm. The mean square error (MSE) was used to indicate difference between real and predicted data and regression values (R) were measured the correlation:

$$MSE = \frac{1}{N}\sum_{i=1}^{N}(Y_i - Y_i')^2 \tag{6}$$

$$R = \frac{N\sum Y_i Y_i' - \sum Y_i \sum Y_i'}{\sqrt{N\sum {Y_i}^2 - (\sum Y_i)^2}\sqrt{N\sum {Y_i'}^2 - (\sum Y_i')^2}} \tag{7}$$

where Y_i and Y_i' represent the actual measured values and the predicted points respectively while N is the number of predictions. Figures 12 and 13, in which training performances of the ANNs are shown, indicate a strong correlation between the predictions of the ANNs and the experimental results. This reflects that the mathematical models created with ANNs can be safely used for CPV system optimization.

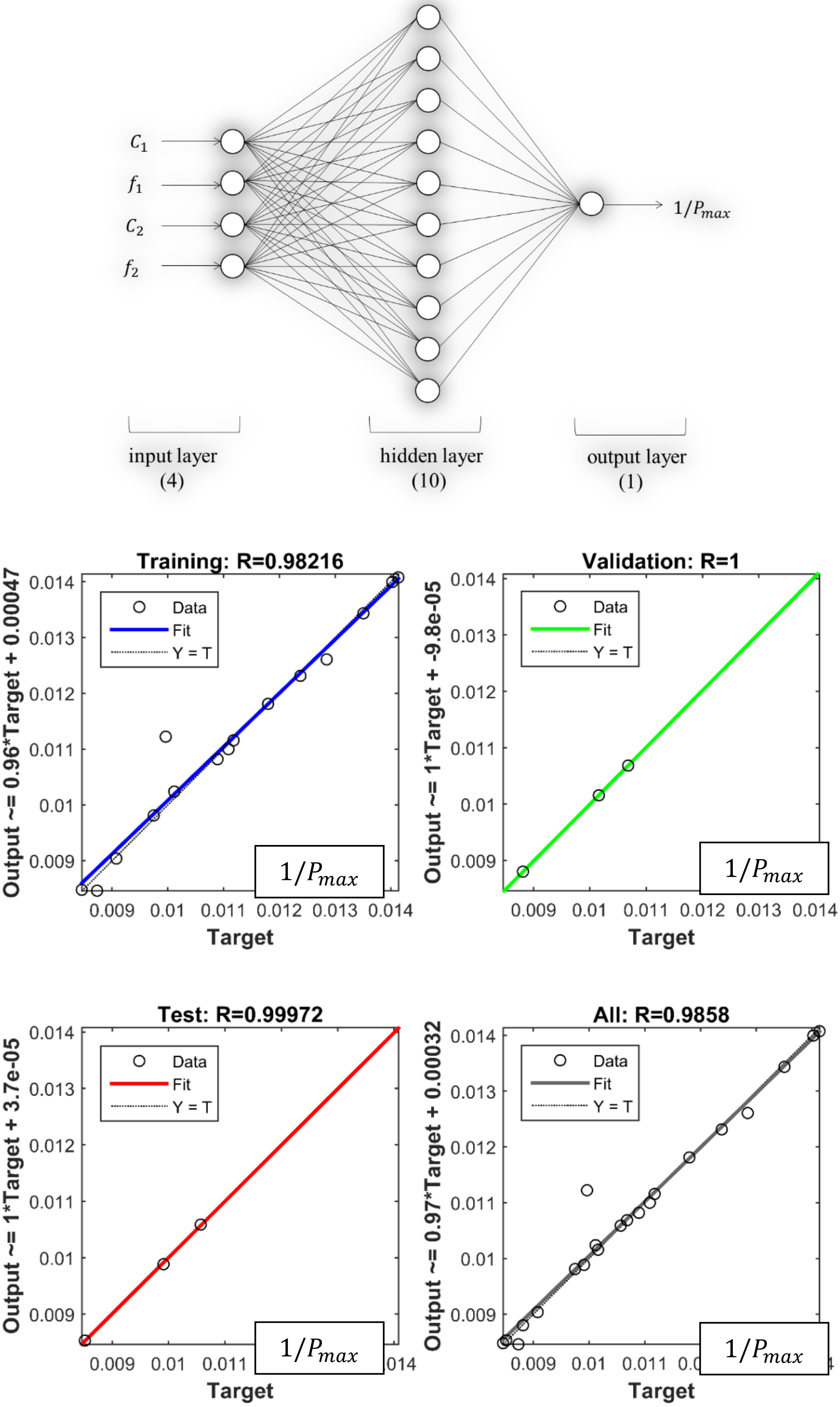


Figure 12. The Structure and Training Results of ANN Model for $1/P_{max}$ Values

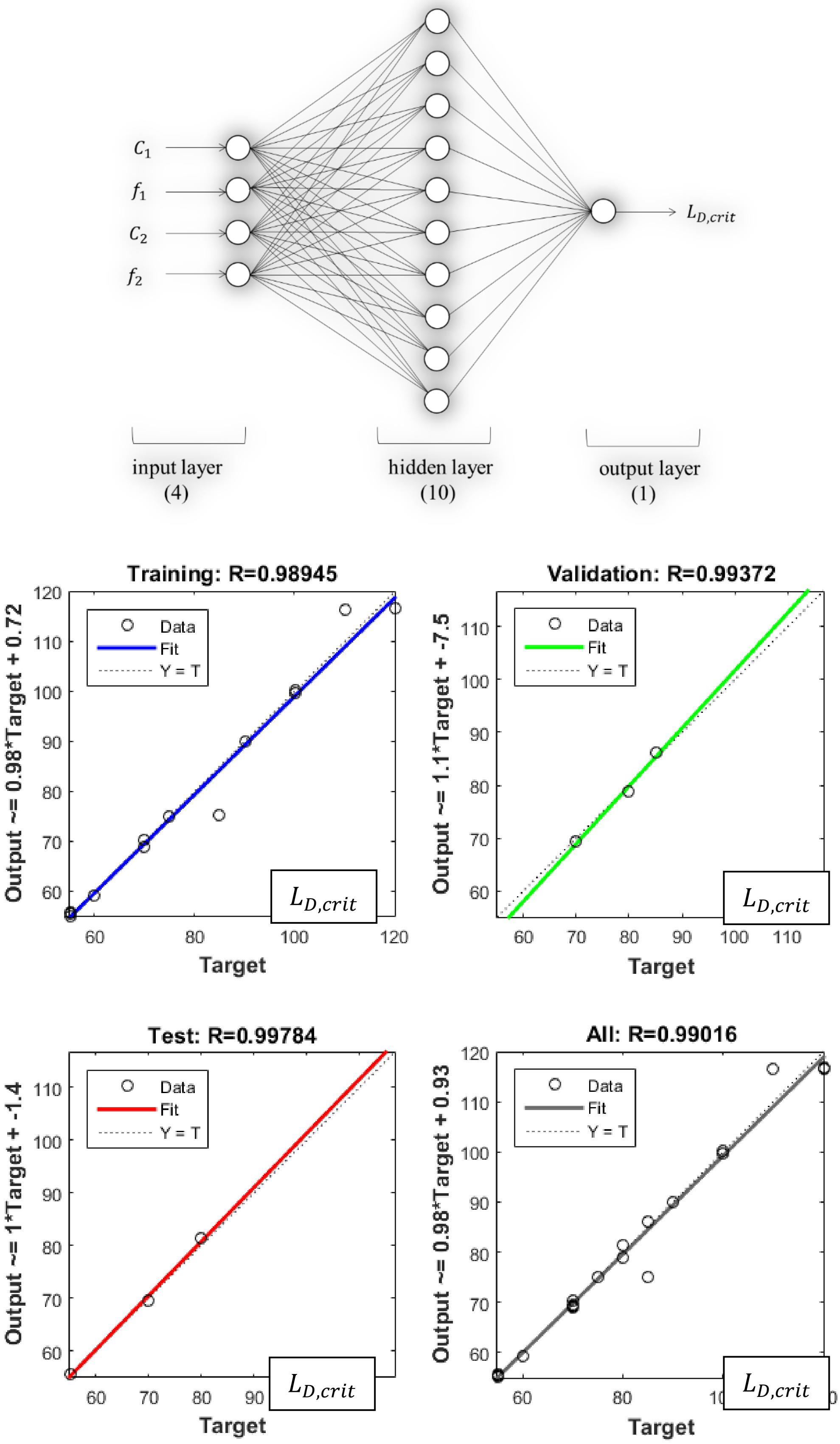


Figure 13. The Structure and Training Results of ANN Model for $L_{D,crit}$ Values

Genetic Algorithm

In this section, there are Genetic Algorithm (GA) based studies for estimating the optimum optical properties of the CPV system that will minimize the $1/P_{max}$ (i.e. maximize P_{max}) by using the mathematical model (i.e. fitness function) developed with ANN in the previous section. GA is a stochastic optimization method based on natural selection principles and working according to probability rules. It has successful applications in many areas such as function optimization, machine learning, classification and mechanism design (Cai et al., 2020; Cai et al., 2021). In this study, MATLAB *optimization toolbox* was used for GA optimization. The optimization parameters considered in this study and lower-upper bounds of variables have been given in Tables 8.

Table 8. Optimization Parameters and Lower-Upper Bounds of Variables

Parameters	Values
Population size	100
Crossover rate	0.8
Mutation rate	0.05
Number of generations	50
Lower bound of C_1, C_2	21.24
Upper bound of C_1, C_2	176.71
Lower bound of f_1, f_2	0.5
Upper bound of f_1, f_2	0.9

The algorithm has regenerated 50 times to observe the stability of the GA results. The variation of fitness (i.e. $1/P_{max}$) and optimum variables ($C_{1,opt}$, $C_{2,opt}$, $f_{1,opt}$ and $f_{2,opt}$) values at each generation are shown in Fig. 15. It can be seen from Fig. 15 that the GA algorithms give quite stable results for the values of fitness function and optimum variables. This explicitly indicates the reliability of the optimization results obtained with GA. According to this, the minimum (maximum) $1/P_{max}$ (P_{max}) value was obtained as $0.0077\ 1/mW$ ($129.87\ mW$) for $C_{1,opt} = 164.68$, $C_{2,opt} = 21.24$, $f_{1,opt} = 0.7$ and $f_{2,opt} = 0.61$ see Table 9. Finally, these optimum values were used as inputs in the ANN developed for critical distance between lenses and $L_{D,crit}$ was predicted as 91 mm. It is also worth noting that an additional 10% improvement in the performance of the CPV system was achieved with the optimization study.

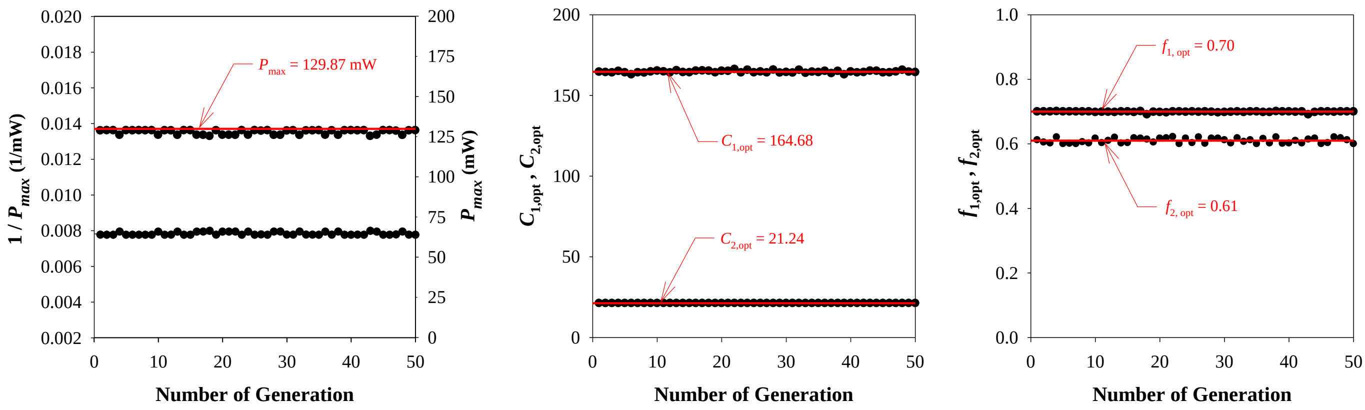


Fig. 14. The Variation of Fitness Value (i.e.$1/P_{max}$) and Optimum Optical Properties of CPV System at Each Generation

Table 9. Optimized Values of Optical Properties and Maximum Power Output

$C_{1,opt}$	$C_{2,opt}$	$f_{1,opt}$	$f_{2,opt}$	$L_{D,crit}$ (mm)	P_{max} (mW)
164.68	21.24	0.70	0.61	91.00	129.87

CONCLUSIONS

In this study, the effects of primary and secondary optical element concentration ratios, f -numbers and distance between lenses on CPV system performance have been investigated in detail, considering different CPV system configurations with single and double optical elements consisting of point-focus Fresnel lenses. It has been observed that the performance of CPV systems using double Fresnel lenses fluctuates significantly depending on the optical properties of the secondary Fresnel lens (i.e. C_2 and f_2) and the distance between the lenses. Thus, if the relevant parameters are not determined properly, the use of secondary optical elements does not positively affect CPV system performance. It has been detected that the $L_{D,crit}$ value, at which maximum CPV system performance occurs, varies depending on the optical properties of the Fresnel lens pairs and when C_2 (f_2) is increased by being kept constant f_2 (C_2), the $L_{D,crit}$ must be reduced in order to get maximum power output. In addition, CPV systems with double Fresnel lenses with a high f_1 value have been found to perform better than single Fresnel lens applications, and it has been observed that the performance of the CPV system can be improved by using a secondary Fresnel lens when $f_1 > 0.5$. Besides these, the ANOVA analyses were carried out by using the data obtained from experimental studies in order to compare the contribution ratio of the optical properties of Fresnel lens pairs on CPV system performance. ANOVA analysis results indicate that primary optical element properties C_1 and f_1 are predominantly effective on double Fresnel lens CPV system performance, while f- number of SOE (i.e. f_2) is the optical parameter with the least contribution ratio. It is also concluded that the importance order of the optical properties of the Fresnel lens pairs on CPV system performance is $C_1 > f_1 > C_2 > f_2$. Finally, ANN and GA based optimization studies were carried out in order to get the best performance of the designed CPV system. With the help of optimization studies, an additional 10% improvement in the performance of the CPV system was achieved.

NOMENCLATURE

C	[-]	Concentration ratio
CPV	[-]	Concentrated photovoltaic
DOF	[-]	Degrees of freedom
G	W/m^2	Solar radiation intensity
Ge	[-]	Germanium
$InGaAs$	[-]	Indium gallium arsenide
$InGaP$	[-]	Indium gallium phosphide
I	[mA]	Current
I_{sc}	[mA]	Short circuit current
L_D	[mm]	Distance between lenses
$L_{D,crit}$	[mm]	Critical distance between lenses where P_{max} is obtained
P	[mW]	Power output of CPV system
P_{max}	[mW]	Maximum power output of CPV system
P_R	[-]	Double and single optical element CPV system maximum output power ratios (P_{max} / $P_{max,single}$)
POE	[-]	Primary optical element
SOE	[-]	Secondary optical element
SS	[-]	Sum of squares
S/N	[-]	Signal to noise
V	[V]	Voltage
V_{oc}	[V]	Open circuit voltage
$\alpha_{Cronbach}$	[-]	Cronbach's alpha coefficient
Ø	[mm]	Diameter

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