

**HYBRID MICRO-SCALE PHOTOVOLTAICS FOR ENHANCED ENERGY
CONVERSION ACROSS ALL IRRADIATION CONDITIONS**

by

Gautam Agrawal

A thesis submitted to the Faculty of the University of Delaware in partial
fulfillment of the requirements for the degree of Master of Science in Electrical and
Computer Engineering

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TABLE OF CONTENTS

LIST OF TABLES	vi
LIST OF FIGURES	vii
ABSTRACT	ix

Chapter

1	INTRODUCTION	1
2	PERFORMANCE IMPROVEMENTS FROM EXPANDING FIELD OF VIEW OF MICRO-CONCENTRATOR PHOTOVOLTAICS	3
2.1	Effect of Atmospheric Variables on Solar Spectra	4
2.2	Effect of Acceptance Angles on Solar Spectra	6
2.3	Cell Efficiencies under Various Conditions	9
2.4	Annual Average Energy Produced	11
2.5	Conclusion	13
3	HYBRID CPV/PV ARCHITECTURE AND PERFORMANCE PROJECTIONS	15
3.1	Projected HPV System Performance	17
3.2	Conclusion	19
4	HYBRID CPV/PV COST PROJECTIONS	20
4.1	Projected HPV System Cost	20
4.2	Conclusion	24
5	OPTICAL MODULE INDOOR CHARACTERIZATION	25
5.1	Module Design and Simulation Results	25
5.2	Bulk Transmission Spectroscopy	27
5.3	Bulk Transmission under Solar Simulator	31
5.4	Focused Spot Transmission Measurements	33
5.5	Conclusion	35
6	OPTICAL MODULE OUTDOOR CHARACTERIZATION	36

6.1	Outdoor Bulk Transmission Measurement.....	36
6.2	Outdoor Focused Transmission Measurement	41
6.3	Simulation Comparison and Conclusion	43
7	CONCLUSION	46
	REFERENCES	47
Appendix		
A	CODE SAMPLES	50
A.1	MATLAB Code to filter and sort data from the data loggers for the reference dataset	50
A.2	MATLAB Code to filter and sort data from the data loggers for the measurement datasets	52

LIST OF TABLES

Table 1:	Atmospheric variables at CPV suitable locations [17].....	5
Table 2:	Integrated Incident Power per Unit Area under Various Conditions	7
Table 3:	Cell Efficiencies under Various Conditions	10
Table 4:	Annual Average Energy Produced under Various Conditions.....	12

LIST OF FIGURES

Figure 1:	Percentage change in solar radiation from the base case of ASTM-G173 AM1.5D to the typical spectra at various locations.	5
Figure 2:	Percentage increment in solar radiation from the base case of 2° acceptance angle to 5° and 9.5° vs. wavelength at AM2.0, PW value of 1.4164cm and elevation of 0m. The vertical lines denote the band gaps for the multi-junction cells considered in the next section.....	9
Figure 3:	Schematic depiction of the hybrid micro-scale CPV/PV architecture. ...	16
Figure 4:	Annual average solar radiation across the USA	17
Figure 5:	Energy production comparison of PV approaches	18
Figure 6:	c-Si cell break-even additional cost projections.....	22
Figure 7:	LCOE in present scenario: $CSiPV = 0.41\$/W_p$, $\eta SiPV = 15\%$	23
Figure 8:	LCOE in future scenario: $CSiPV = \$0.30/W_p$, $\eta SiPV = 18\%$	23
Figure 9:	a) MEPV micro-concentrator optical elements consisting of a sandwich of injection-molded polycarbonate (PC) lenses separated by PDMS filler material. b) Image of an optical module illuminated from front and back. c) Side view of an optical module.....	26
Figure 10:	Simulation's output plane results: a) Spot spatial profile. b) Spot X & Y cross-section. c) Encircled energy profile.	27
Figure 11:	Bulk spectroscopy measurements – polycarbonate slabs.....	28
Figure 12:	Module bulk spectroscopy measurement setups.	30
Figure 13:	Bulk spectroscopy measurements – prototype module.	30
Figure 14:	Bulk spectroscopy results – prototype module.....	31
Figure 15:	Corrected Bulk spectroscopy results – prototype module.....	32
Figure 16:	Focused spot transmission measurement setup.	33

Figure 17:	a) Example spot diagram. b) X & Y cross-sections.	34
Figure 18:	Average encircled energy results from spot diagrams.	34
Figure 19:	Bulk transmission measurement setup	37
Figure 20:	Bulk transmission vs. D/G ratio	40
Figure 21:	Focused transmission measurement setup.....	42
Figure 22:	Focused transmission vs. D/G ratio.....	43
Figure 23:	Bulk and focused transmission vs. D/G ratio: simulated and measured comparison	44

ABSTRACT

A novel hybrid photovoltaics (HPV) architecture is presented that integrates high-performance micro-optics-based concentrator photovoltaics (CPV) array technology with a 1-sun photovoltaic (PV) cell within a low-profile panel structure. The approach simultaneously captures the direct solar radiation components with arrayed high-efficiency CPV cells and the diffuse solar components with an underlying wide-area PV cell. Performance analyses predict that the hybrid approach will significantly enhance the average energy produced per unit area for the full range of diffuse/direct radiation patterns across the USA. Furthermore, cost analyses indicate that the hybrid concept may be financially attractive for a wide range of locations. Indoor and outdoor experimental evaluation of a micro-optical system designed for use in a hybrid architecture verified that a large proportion of the direct radiation component was concentrated onto emulated micro-cell regions while most of the diffuse radiation and the remaining direct radiation was collected in the 1-sun cell area.

Chapter 1

INTRODUCTION

Solar photovoltaic system prices have experienced significant declines with increasing economies of scale of the industry and technological advancements with average prices for utility-scale installations in USA settling at \$1.85/W in Q1 2014 [1] making it cost competitive with conventional energy technologies in several locations. The major driver of the reduction in costs has been the fall in crystalline silicon (c-Si) photovoltaic cell prices from \$76/W in 1977 to less than \$0.40/W in 2014 [2-4]. However, further reductions in solar system costs are still needed to make solar photovoltaics even more economically attractive across more locations.

Solar system costs are primarily divided into solar module costs, balance of system (BOS) costs and soft costs. The large reduction in solar cell and module costs has led to balance of system costs becoming a more significant component of solar system prices [5]. To achieve further cost reductions in solar system prices it is essential to reduce BOS costs [6]. Increasing efficiency of photovoltaic conversion is one of the primary ways to achieve reduction in BOS costs [5]. Of all the solar photovoltaic technologies, concentrator III-V multi-junction photovoltaics have demonstrated the highest efficiencies [7]. Hence, they are the prime candidates to achieve high efficiency photovoltaic systems. However, concentrator photovoltaic systems suffer from one major drawback in that they cannot collect and convert diffuse sunlight which can comprise ~20-40% of the annual solar insolation at different locations [8]. The idea presented here is to combine a commonly used, low

cost, flat plate solar photovoltaic technology like c-Si and combine it with high efficiency, concentrator III-V multi-junction photovoltaics to create a hybrid PV (HPV) system that can produce enhanced energy conversion across all irradiation conditions [9].

In particular for the concentrator part of the system, a micro-scale concentrator and micro-scale solar cell approach is pursued. This approach, also known as Microsystems Enabled Photovoltaics (MEPV), uses micro-scale pixilated $\sim 100\text{s } \mu\text{m}$ wide cell solar cells integrated with a thin sheet ($< 2\text{ cm}$ thick) of molded plastic optics [10]. Compared to other concentrator photovoltaic (CPV) technologies, MEPV has several advantages such as improved cell performance, better wafer utilization, better thermal management, thin and light-weight module form-factors, improved robustness to partial shading, wider acceptance angles and simple optical designs [11].

In the following chapters, the motivation and concept of HPV are explained in more detail, and HPV cost and performance projections are presented. Indoor and outdoor characterization results of optical module prototypes are presented that establish a proof-of-concept of hybrid micro-scale photovoltaic technology.

Chapter 2

PERFORMANCE IMPROVEMENTS FROM EXPANDING FIELD OF VIEW OF MICRO-CONCENTRATOR PHOTOVOLTAICS

As a first step to exploring the increased harvesting of diffuse sunlight in high efficiency systems, expanding the field of view of micro-concentrator photovoltaic systems is considered. The field of view is inversely related to the concentration ratio [12]. The theoretical limit for the two parameters is expressed as follows:

$$C_{MAX} = n^2/\sin^2\theta$$

Here, n is the index of refraction of the optics, θ is the half- angle of acceptance and C_{MAX} is the maximum concentration.

In an initial prototype of the micro-systems enabled photovoltaic technology a 3-stage imaging optical design was used due to its simplicity in terms of design and fabrication to achieve a concentration of 49X [10]. To achieve higher concentrations with high acceptance angles, non-imaging optics such as cones and paraboloids must be considered [12]. In this section, the performance improvements possible by increasing the acceptance angle of micro-systems enabled photovoltaics while maintaining the same concentration ratio are estimated [13]. This could conceivably be accomplished by using more sophisticated non-imaging optics based optical designs.

Quantitative estimates of the amount of solar radiation present within small fields of view (acceptance angles less than $\pm 10^\circ$) and the potential performance improvement that can be achieved by capturing the same for energy production in

CPV are developed. The SMARTS program, which models aerosol scattering and water vapor absorption of solar radiation [14], is employed to generate the solar spectra obtained within cones of various acceptance angles under various atmospheric conditions [15]. The resultant spectra are used to compute cell efficiencies for a 4-cell multi-junction cell of the kind that are expected to be used in MEPV [11]. The annual average energy produced by the different designs at various locations around the world is computed based on the results from the previous step. This analysis therefore quantitatively indicates the range of possible performance improvement. The results can be used to make decisions about design trade-offs between optical design complexity and cost vs. performance improvement.

2.1 Effect of Atmospheric Variables on Solar Spectra

The SMARTS program is used to generate the spectral data for our analysis, assuming cloudless conditions. CPV systems are typically considered suitable for locations with an annual average daily Direct Normal Irradiance (DNI) of about 6 kWh/m²-day or greater [16]. Aerosol Optical Depth (AOD), Precipitable Water (PW) and Elevation are the parameters that have the greatest influence on the spectra under cloudless conditions [17]. Some examples of atmospheric variables at various locations that are considered suitable for concentrator PV are given in Table 1.

It is observed from Table 1 that there is considerable variation in all three of the important parameters at the CPV suitable locations. To illustrate the effects of the different parameters on the solar spectrum, in Figure 1 we compare the spectra at a few example locations to the standard ASTM-G173 AM1.5D spectra [18]. All the spectra were calculated at AM1.5 with an acceptance angle of 2.9° using the annual average values of the atmospheric variables at the respective locations. The ASTM-

G173 AM1.5D standard spectrum is defined at an AOD value of 0.084, PW value of 1.4164 cm and an elevation of 0m.

Location	Elevation (m)	Annual Average		
		AOD	PW (cm)	Daily DNI (kWh/m ² -day)
Izana, Spain	2391	0.057	0.43	6.80
Seville, USA	1477	0.076	0.98	6.72
Maricopa, USA	360	0.091	1.49	7.11
Kaashidhoo, Maldives	0	0.192	4.29	5.79
Sede Boker, Israel	480	0.194	1.30	6.83
Bahrain	25	0.388	1.93	6.50
Kuwait	42	0.588	1.27	6.33

Table 1: Atmospheric variables at CPV suitable locations [17]

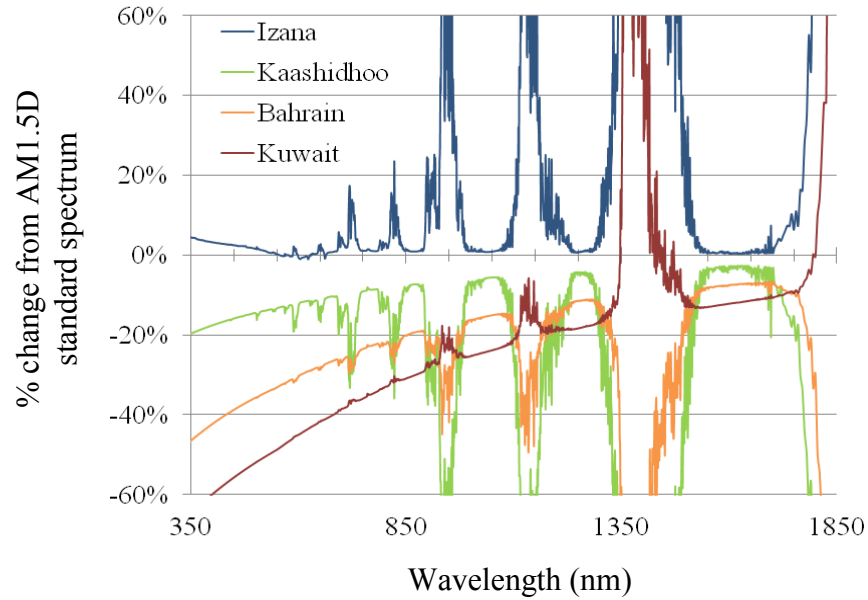


Figure 1: Percentage change in solar radiation from the base case of ASTM-G173 AM1.5D to the typical spectra at various locations.

We can clearly see the different manner in which AOD and PW affect the solar spectra. PW mainly affects the spectra in specific absorption windows while AOD affects the entire spectra, esp. the shorter wavelengths.

The two locations (Izana and Kuwait) that have lower PW than the standard value show peaks in the absorption windows indicating lower absorption due to lower levels of water vapor. The two locations (Kaashidhoo and Bahrain) that have higher PW than the standard value show valleys in the absorption windows indicating higher absorption due to higher levels of water vapor.

The location (Izana) that has lower AOD than the standard value shows a positive change at all wavelengths. The three locations (Kaashidhoo, Bahrain and Kuwait) that have higher AOD than the standard value show a negative change at all wavelengths (except in the regions where the effect of PW dominates) and the loss is more significant at shorter wavelengths. This indicates that shorter wavelengths are scattered more strongly by aerosols.

Higher elevations are expected to lead to an increase in the solar radiation [17], however, the effect is small and hence, difficult to observe in these example spectra.

2.2 Effect of Acceptance Angles on Solar Spectra

Changes in solar spectra within cones of various acceptance angles under various atmospheric conditions are now analyzed. The solar spectra are calculated within acceptance cone angles of 2° , 5° and 9.5° , centered on the solar disk. Various combinations of AOD, PW and elevation are considered. Two cases of AOD, 0.084 & 0.500, corresponding to a clear sky and hazy sky respectively are considered. PW values of 0.470, 1.416 and 4.250 corresponding to dry, average and humid conditions are considered. Two elevations of 0m and 1500m are considered. Various air mass

(AM) values are considered to study the effect of path length on the spectra. The integrated power per unit area in the solar spectra from 300nm to 1700nm under various conditions is given in Table 2.

	AM	Acceptance Angle											
		2°	5°	9.5°	2°	5°	9.5°	2°	5°	9.5°	2°	5°	9.5°
		AOD 0.084			AOD 0.500			AOD 0.084			AOD 0.500		
		Elevation 0m			Elevation 0m			Elevation 1500m			Elevation 1500m		
PW 0.470		Int. (W/m ²)	% Increase from 2° case		Int. (W/m ²)	% Increase from 2° case		Int. (W/m ²)	% Increase from 2° case		Int. (W/m ²)	% Increase from 2° case	
	1.0	965.5	0.24	0.67	738.5	1.22	3.21	981.9	0.24	0.65	749.6	1.22	3.20
	1.3	914.0	0.31	0.85	650.5	1.52	3.98	932.8	0.30	0.82	661.8	1.52	3.98
	1.5	882.9	0.35	0.96	599.9	1.71	4.46	902.9	0.34	0.93	611.3	1.72	4.47
	2.0	813.4	0.44	1.21	495.1	2.15	5.56	835.8	0.44	1.19	505.8	2.16	5.58
	2.5	753.4	0.54	1.45	413.8	2.54	6.53	777.4	0.53	1.44	423.5	2.56	6.57
	3.0	701.2	0.62	1.68	349.4	2.89	7.40	725.9	0.62	1.67	358.2	2.92	7.45
	6.0	483.9	1.07	2.80	146.7	4.57	11.4	507.9	1.08	2.83	151.0	4.60	11.5
PW 1.416		AOD 0.084			AOD 0.500			AOD 0.084			AOD 0.500		
		Elevation 0m			Elevation 0m			Elevation 1500m			Elevation 1500m		
	1.0	930.7	0.25	0.69	708.4	1.24	3.27	947.4	0.24	0.67	719.7	1.24	3.26
	1.3	877.6	0.31	0.87	620.5	1.55	4.07	896.7	0.31	0.84	632.1	1.55	4.07
	1.5	845.4	0.35	0.98	569.9	1.75	4.57	865.7	0.35	0.96	581.5	1.75	4.57
	2.0	773.7	0.46	1.25	465.7	2.20	5.70	796.4	0.42	1.22	476.7	2.21	5.72
	2.5	712.3	0.55	1.49	385.6	2.60	6.70	736.4	0.55	1.48	395.6	2.62	6.74
	3.0	658.9	0.64	1.73	322.8	2.97	7.60	683.9	0.64	1.71	331.7	2.99	7.65
	6.0	441.6	1.10	2.89	130.0	4.65	11.6	465.4	1.12	2.92	134.3	4.69	11.7
PW 4.250		AOD 0.084			AOD 0.500			AOD 0.084			AOD 0.500		
		Elevation 0m			Elevation 0m			Elevation 1500m			Elevation 1500m		
	1.0	884.4	0.25	0.71	668.9	1.27	3.36	901.4	0.25	0.68	680.5	1.27	3.35
	1.3	829.4	0.32	0.89	581.4	1.59	4.19	848.9	0.32	0.87	593.3	1.60	4.18
	1.5	796.0	0.37	1.01	531.3	1.80	4.70	816.7	0.36	0.98	543.1	1.80	4.71
	2.0	722.6	0.47	1.29	429.0	2.26	5.88	745.5	0.47	1.26	440.1	2.27	5.90
	2.5	660.5	0.57	1.55	351.5	2.68	6.92	684.7	0.57	1.53	361.5	2.69	6.96
	3.0	607.0	0.66	1.79	291.4	3.05	7.84	631.8	0.66	1.77	300.3	3.08	7.90
	6.0	393.4	1.14	3.00	112.4	4.74	11.8	416.4	1.15	3.02	116.4	4.79	11.9

Table 2: Integrated Incident Power per Unit Area under Various Conditions

As expected, the impact of increasing the acceptance angle is more pronounced in the higher AOD cases as there is more diffuse light in those cases due to the increased scattering caused by the larger aerosol content. Also, the effect of increasing acceptance angle is more pronounced at higher AM values as the fraction of diffuse radiation in the total radiation is larger at higher AM values due to the increased scattering during the longer path.

Higher levels of PW also improve the impact of increasing the acceptance angle although the effect is much smaller than the effect of AOD. Higher elevations improve the impact of increasing the acceptance angle in the high scattering cases (i.e. high AOD and AM, or very high AM), while degrading the impact of increasing the acceptance angle in the low scattering cases (i.e. low AOD or AM). However, the magnitude of the effect of changes in elevation is even smaller than the effect due to change in PW.

A wavelength dependent analysis of the results is performed to examine how different wavelengths are affected by the increase in acceptance angle. The percentage increment in solar radiation from the base case of 2° acceptance angle to 5° and 9.5° vs. wavelength is plotted in Figure 2.

It is apparent from Figure 2 that the increase in solar radiation with the increase in acceptance angle is more significant at shorter wavelengths – indicating that there is a pronounced increase in scattering with decreasing wavelength within the narrow cone angles around the solar disk.

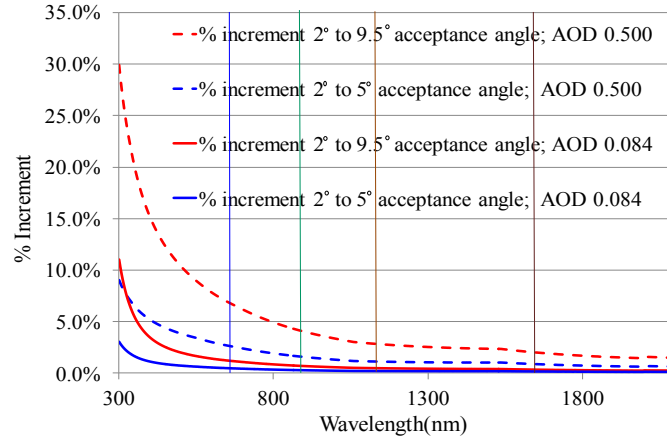


Figure 2: Percentage increment in solar radiation from the base case of 2° acceptance angle to 5° and 9.5° vs. wavelength at AM2.0, PW value of 1.4164cm and elevation of 0m. The vertical lines denote the band gaps for the multi-junction cells considered in the next section.

2.3 Cell Efficiencies under Various Conditions

Now, a 4-junction cell having the following layers with their respective band gaps at 25°C is considered: InGaP: 1.85 eV; GaAs: 1.40 eV; InGaAsP: 1.10 eV; InGaAs: 0.75 eV. The efficiency of this cell is calculated under the various spectra obtained earlier by using ideal-balance equations [19, 20]. The thickness of each of the sub-cell layers is assumed to be $3\text{ }\mu\text{m}$ to achieve near-complete absorption above the band gaps and hence, high efficiencies. A concentration of 100X and an operating temperature of 40°C are assumed. Light reflection and intercell losses are neglected.

The “total efficiency” is reported. This is the efficiency obtained by adding the power output of each of the four sub-cells and dividing by the total input power. The input and output powers are both defined as their respective integrated powers over the 300nm to 4000nm wavelength range. A “series/parallel module approach” is shown to closely follow this “total efficiency” under various conditions as opposed to a standard series connection like the kind in a monolithic multi-junction cell which can lead to

much lower performance [21]. The efficiencies under the various conditions are shown in Table 3.

It is observed from Table 3 that the efficiency increases marginally with the increase in acceptance angle. This marginal increase adds to the increase in received solar radiation with increase in acceptance angle and leads to better performance, or at the very least does not degrade performance due to increase in acceptance angle, provided the “series/parallel module approach” is followed.

Cell Efficiency (%)		Acceptance Angle											
		2°	5°	9.5°	2°	5°	9.5°	2°	5°	9.5°	2°	5°	9.5°
PW 0.470	AM	AOD 0.084			AOD 0.500			AOD 0.084			AOD 0.500		
		Elevation 0m			Elevation 0m			Elevation 1500m			Elevation 1500m		
	1.0	58.61	58.61	58.62	57.32	57.37	57.45	58.51	58.52	58.52	57.24	57.29	57.37
	1.3	58.70	58.71	58.72	56.95	57.03	57.14	58.60	58.61	58.62	56.87	56.95	57.06
	1.5	58.73	58.74	58.76	56.67	56.76	56.89	58.64	58.65	58.66	56.59	56.68	56.81
	2.0	58.76	58.78	58.80	55.86	55.98	56.17	58.67	58.69	58.71	55.79	55.92	56.11
	2.5	58.72	58.75	58.78	54.94	55.10	55.35	58.65	58.67	58.70	54.89	55.05	55.30
	3.0	58.64	58.67	58.71	53.96	54.15	54.46	58.58	58.61	58.65	53.91	54.11	54.41
	6.0	57.68	57.74	57.84	47.53	47.90	48.47	57.72	57.78	57.87	47.48	47.85	48.42
PW 1.416	AM	AOD 0.084			AOD 0.500			AOD 0.084			AOD 0.500		
		Elevation 0m			Elevation 0m			Elevation 1500m			Elevation 1500m		
	1.0	59.10	59.11	59.11	57.90	57.95	58.02	59.02	59.02	59.03	57.83	57.88	57.95
	1.3	59.20	59.20	59.21	57.55	57.62	57.73	59.11	59.11	59.12	57.48	57.55	57.65
	1.5	59.24	59.25	59.26	57.29	57.37	57.50	59.15	59.16	59.17	57.22	57.31	57.43
	2.0	59.30	59.31	59.33	56.53	56.65	56.83	59.21	59.22	59.24	56.47	56.59	56.77
	2.5	59.29	59.31	59.33	55.66	55.81	56.05	59.21	59.23	59.25	55.61	55.77	56.01
	3.0	59.23	59.26	59.29	54.70	54.90	55.19	59.16	59.19	59.22	54.67	54.86	55.16
	6.0	58.37	58.43	58.52	48.32	48.69	49.26	58.40	58.45	58.54	48.29	48.66	49.23
PW 4.250	AM	AOD 0.084			AOD 0.500			AOD 0.084			AOD 0.500		
		Elevation 0m			Elevation 0m			Elevation 1500m			Elevation 1500m		
	1.0	59.62	59.62	59.62	58.51	58.55	58.62	59.53	59.53	59.54	58.44	58.48	58.55
	1.3	59.73	59.74	59.75	58.21	58.27	58.37	59.64	59.64	59.65	58.14	58.20	58.29
	1.5	59.80	59.80	59.81	57.98	58.06	58.18	59.70	59.70	59.71	57.91	57.99	58.10
	2.0	59.89	59.90	59.92	57.30	57.41	57.58	59.79	59.80	59.81	57.24	57.35	57.52
	2.5	59.91	59.93	59.95	56.49	56.63	56.86	59.82	59.83	59.85	56.44	56.59	56.81
	3.0	59.88	59.90	59.93	55.59	55.77	56.06	59.80	59.82	59.85	55.56	55.74	56.02
	6.0	59.15	59.20	59.29	49.41	49.78	50.33	59.17	59.22	59.30	49.42	49.78	50.34

Table 3: Cell Efficiencies under Various Conditions

In general, the cell efficiencies are poorer in the higher AOD case as compared to the lower AOD case as the cell band gaps have been chosen keeping in mind the standard ASTM-G173 AM1.5D spectrum which has a low AOD value.

Cell efficiency is observed to improve with increasing water vapor content. This is presumably due to the fact that increase in water vapor reduces the energy more significantly in the part of the spectrum that is having energy lower than the smallest band gap as opposed to the energy in the part of the spectrum with energy greater than the smallest band gap. Hence, although the output and input power both reduce, the efficiency improves.

Higher elevations lead to lower efficiencies in almost all cases (except some of the AM6.0 cases). The magnitude of the change in efficiency due to elevation is quite small, <0.1% absolute. On the whole, other than extreme cases of high AOD and AM6.0, the total cell efficiencies are all in the range of ~54-60%, which shows the advantage of an approach that aims to closely follow “total efficiencies”.

2.4 Annual Average Energy Produced

The results obtained at various AM values are utilized to calculate the amount of annual average energy produced at different latitudes assuming the low and high values of AOD previously used. The AM number is calculated at intervals of 10 minutes during the sunshine hours of each day during the year. This calculated AM number is used to calculate the output power based on the solar radiation power and cell efficiency results from the previous sections via interpolation. This output power is subsequently multiplied by one-sixth of an hour and added to a running sum. This sum over the year gives the annual average energy produced. The results are given in Table 4.

		Acceptance Angle												
		2°	5°	9.5°	2°	5°	9.5°	2°	5°	9.5°	2°	5°	9.5°	
PW 0.470	Latitude	AOD 0.084			AOD 0.500			AOD 0.084			AOD 0.500			
		Elevation 0m			Elevation 0m			Elevation 1500m			Elevation 1500m			
		Annual Energy Prod. (kWh/m ²)	% Increase from 2° case		Annual Energy Prod. (kWh/m ²)	% Increase from 2° case		Annual Energy Prod. (kWh/m ²)	% Increase from 2° case		Annual Energy Prod. (kWh/m ²)	% Increase from 2° case		
		5° N/S	2056.6	0.39	1.06	1331.4	1.85	4.78	2103.8	0.39	1.05	1355.8	1.85	4.79
		10° N/S	2047.3	0.39	1.06	1323.9	1.85	4.80	2094.4	0.39	1.05	1348.2	1.86	4.81
		15° N/S	2039.2	0.40	1.07	1312.9	1.87	4.83	2086.5	0.40	1.06	1337.1	1.87	4.84
		25° N/S	1993.8	0.41	1.11	1266.4	1.92	4.96	2041.2	0.41	1.09	1290.2	1.93	4.98
		35° N/S	1922.6	0.43	1.17	1190.8	2.01	5.19	1970.3	0.43	1.15	1213.8	2.02	5.21
		50° N/S	1720.1	0.49	1.31	1008.7	2.19	5.66	1766.6	0.49	1.30	1029.3	2.21	5.68
PW 1.416		AOD 0.084			AOD 0.500			AOD 0.084			AOD 0.500			
		Elevation 0m			Elevation 0m			Elevation 1500m			Elevation 1500m			
		5° N/S	1966.1	0.40	1.08	1264.0	1.88	4.87	2013.9	0.40	1.07	1288.9	1.88	4.88
		10° N/S	1957.2	0.40	1.08	1256.8	1.88	4.89	2004.8	0.40	1.07	1281.6	1.89	4.90
		15° N/S	1948.8	0.40	1.10	1246.0	1.90	4.93	1996.7	0.40	1.08	1270.7	1.90	4.93
		25° N/S	1904.0	0.42	1.13	1200.6	1.95	5.06	1951.9	0.41	1.11	1224.9	1.96	5.07
		35° N/S	1833.3	0.44	1.19	1126.7	2.04	5.29	1881.6	0.44	1.18	1150.2	2.05	5.31
		50° N/S	1634.7	0.50	1.34	950.7	2.23	5.76	1681.8	0.49	1.32	971.7	2.24	5.78
PW 4.250		AOD 0.084			AOD 0.500			AOD 0.084			AOD 0.500			
		Elevation 0m			Elevation 0m			Elevation 1500m			Elevation 1500m			
		5° N/S	1848.2	0.41	1.11	1178.1	1.92	4.99	1896.4	0.40	1.09	1203.4	1.92	5.00
		10° N/S	1839.7	0.41	1.11	1171.2	1.92	5.01	1887.7	0.41	1.09	1196.4	1.93	5.01
		15° N/S	1831.3	0.41	1.12	1160.7	1.94	5.04	1879.5	0.41	1.11	1185.8	1.94	5.05
		25° N/S	1787.4	0.43	1.16	1117.0	1.99	5.18	1835.7	0.42	1.14	1141.6	2.00	5.19
		35° N/S	1718.0	0.45	1.22	1046.0	2.09	5.42	1766.4	0.45	1.21	1069.7	2.09	5.43
		50° N/S	1526.0	0.51	1.37	878.7	2.28	5.89	1573.0	0.50	1.35	899.7	2.29	5.91

Table 4: Annual Average Energy Produced under Various Conditions

A performance improvement of ~0.4-2.3% by increasing the acceptance angle from 2° to 5° is observed. The percentage increase in annual energy production at higher acceptance angles is higher for the high AOD cases as the proportion of diffuse radiation is larger in those cases. There is a very small increase in the percentage increase with increasing PW levels and there is hardly any effect of elevation changes on the percentage increase.

At a given location in a system with a fixed acceptance angle, an increase in AOD from 0.084 to 0.500 causes a ~33-43% reduction in annual energy production. Tripling of the water vapor content causes a ~4.5-7.5% reduction in energy produced over the year. Increase in elevation from 0 to 1500m causes an increase of ~2.5% in annual energy production. A change in latitude from 5° to 35° causes a decrease of ~6-11% in energy produced over the year.

As previously shown in Table I, there are locations with various combinations of AOD, PW and elevation that have high DNI. This is due to the fact that these effects are superimposed with the effect of latitude in deciding the duration and path length of sunlight and the effect of local weather and climatic conditions on cloud cover. Hence, there is a wide variety of locations with high DNI and there is a small but significant performance improvement in improving the acceptance angle at all locations.

2.5 Conclusion

A performance improvement of ~0.4-2.3% in annual average energy produced can be achieved by increasing the acceptance angle from 2° to 5°. The effect of cloudiness on the performance is not considered here. It is expected that it would further increase the diffuse component of the radiation and hence would widen the gap between performance of the wider acceptance angle system and narrower acceptance angle system further.

Advanced design and fabrication of cost-effective optical concentrators are required to achieve sufficiently high acceptance angles without reducing the concentration ratio. But if it can be done the potential for improvement in performance possible is shown here. Increased acceptance angles can also lead to reductions in

system cost by reducing the requirements on tracker accuracy, thereby increasing the cost effectiveness of the system.

Thus, it is found that small performance improvements are possible by increasing acceptance angle. However, the complications introduced in the optical module fabrication due to the non-imaging optics layer need to be carefully evaluated. For the current MEPV prototype as described in section 5 a two-stage imaging optics design is used to avoid the complexities associated with fabrication of non-imaging structures such as cones or paraboloids.

In the next section, the hybrid micro-scale photovoltaics concept is described which allows capture of much larger fraction of diffuse radiation than could be accomplished by merely expanding the acceptance angle through advanced optical designs.

Chapter 3

HYBRID CPV/PV ARCHITECTURE AND PERFORMANCE PROJECTIONS

The sunlight (global radiation) incident on a PV module is composed of direct and diffuse components. The diffuse radiation (i.e., light scattered by atmospheric aerosols and clouds) constitutes a considerable portion of the total incident power and should be accounted for in the overall performance of concentrating photovoltaic (CPV) systems. However, limited by the second law of thermodynamics, traditional CPV systems are unable to capture most of the diffuse radiation. There is a fundamental trade-off between the concentration ratio and acceptance angle [12] achievable by CPV systems as shown in the previous chapter. Consequently, for less sunny locales conventional CPV approaches will not be economically feasible [16]. On the other hand, the relatively low efficiency of crystalline silicon (c-Si) based 1-sun flat panel PV limits its application space in areas where installation space is limited.

A novel hybrid PV (HPV) solar cell architecture is described here, aiming to enhance solar energy collection and conversion under all radiation conditions and reduce overall costs. The key notion is to combine high-performance integrated micro-optics-based concentrator cells with low-cost flat panel PV that collects non-concentrated light (such as diffuse and scattered light) and light missing the solar cell due to optical system imperfections and misalignment. The concept is schematically depicted in Figure 3.

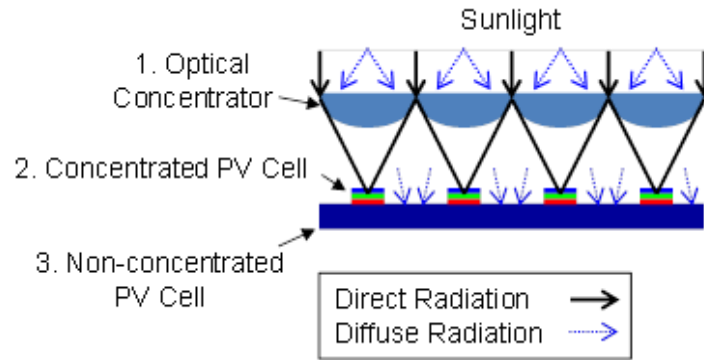


Figure 3: Schematic depiction of the hybrid micro-scale CPV/PV architecture.

The addition of a Si solar cell to a micro-optical CPV system to capture the diffuse components of the solar spectrum has been previously proposed [22] and advanced [9]. Recent analysis [23] highlighted the general potential performance advantages afforded by such an approach. A detailed analysis of a version of the hybrid PV (HPV) concept that is currently under development as part of the Microsystems-Enabled PV (MEPV) program using micro-scale solar cells [11] is presented here. By dramatically scaling down the dimensions of the concentrated PV cells (e.g., ~100's microns in diameter) and accordingly the concentrating optics (e.g., ~ a few millimeters in diameter), micro-concentrating PV integrates arrays of these components more closely within a single module that has a small form factor similar to conventional flat panel PV. Arrays of concentrators can be fabricated in large optical sheets via low-cost plastic molding. In the hybrid system, a large area 1X Si cell is used as the substrate for the high-performance concentrated solar cells and the micro-optical concentrating components.

An analysis of the geographic distribution of the average daily direct and diffuse solar radiation components across the USA is presented in the next section.

This is used to project performance of the HPV approach across a wide range of USA locations.

3.1 Projected HPV System Performance

Standard solar radiation data [8] for various locations across USA provide a starting point for comparing the performance of HPV with flat-panel and CPV systems under a range of solar insolutions. Interestingly, as shown in Figure 4, the contribution from diffuse radiation is approximately 2-2.5 kWh/m²-day for all locations, but this component represents ~20-40% of the global radiation, depending on location.

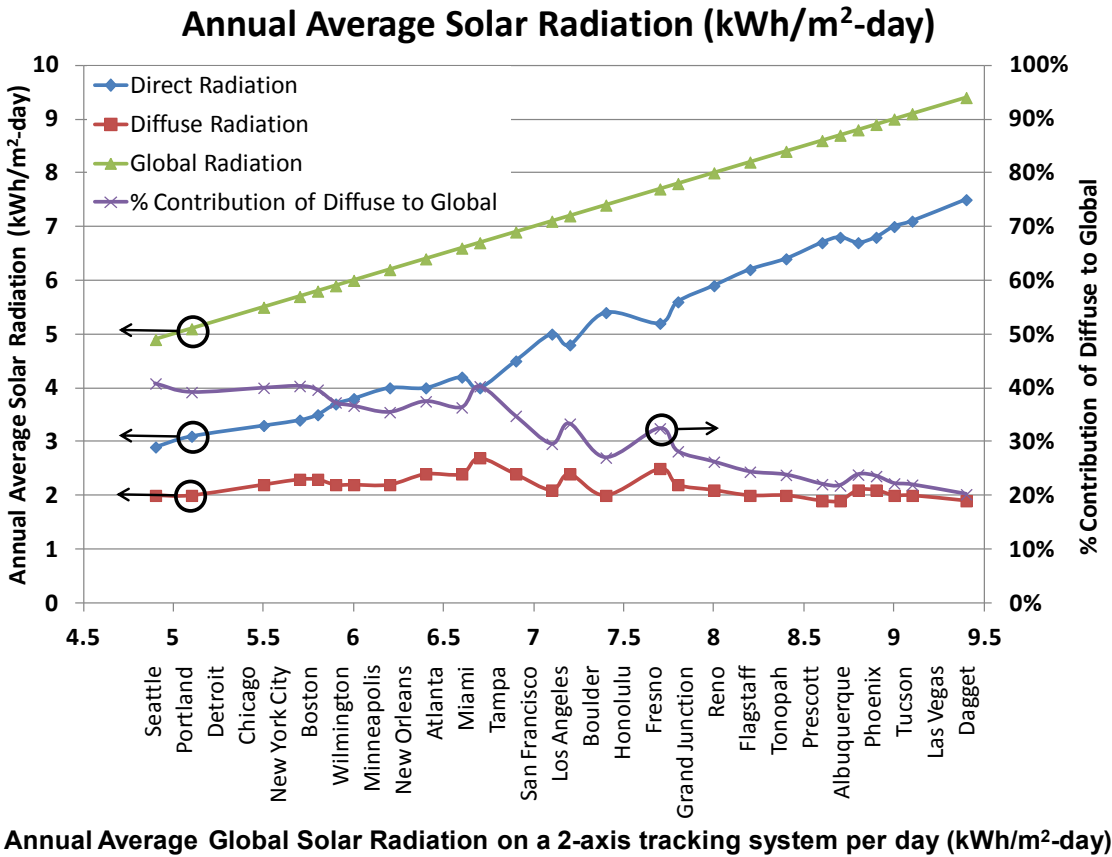


Figure 4: Annual average solar radiation across the USA

Assuming a conversion efficiency of 15% and 30% for a silicon-based flat panel PV system (η_{SiPV}) and a high-efficiency CPV system (η_{CPV}), respectively, the average energy produced per unit area per day for the HPV approach is compared in Figure 5 to conventional CPV and flat panel PV. Two-axis trackers are assumed to be used in all scenarios to maximize energy yield.

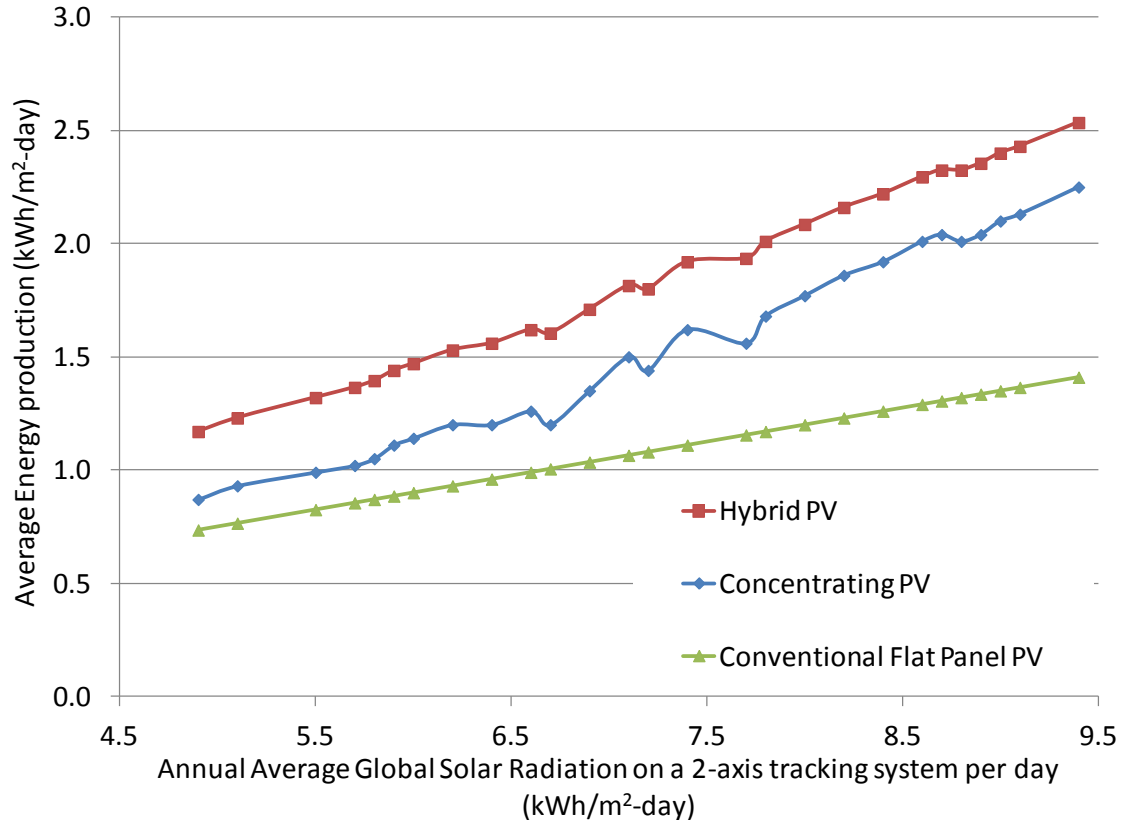


Figure 5: Energy production comparison of PV approaches

Figure 5 shows that the HPV approach significantly outperforms conventional flat panel PV and CPV in all of the locations considered. Depending on location, HPV provides 67-84% and 13-34% more energy production per unit area than conventional flat panel PV and CPV respectively – indicating that HPV may be useful in space-

constrained applications. Due to the flat profile of MEPV, HPV based on integrating MEPV onto flat panel Si PV would also be comparable to flat panel Si PV in terms of weight per unit area. This may also make HPV especially attractive for mobile applications in remote locations where minimal form-factor and transportation weight are a priority.

3.2 Conclusion

The HPV concept combines the high-performance enabled by MEPV's micro-concentration approach – to capture the direct components of the solar irradiance, with an integrated 1-sun approach – which captures the diffuse components of the solar irradiance. The combination thus optimally harvests solar energy under all atmospheric conditions. The potential payoff of the HPV concept stems from its tight integration of micro-optics-based CPV and flat-panel technology that enables enhanced energy capture per unit area in a flat panel profile. The projected cost of energy produced from a HPV system that uses an active c-Si cell as the substrate for the arrayed micro-concentrating elements is presented in the following chapter.

Chapter 4

HYBRID CPV/PV COST PROJECTIONS

4.1 Projected HPV System Cost

To provide an economic comparison of Si flat panel PV, MEPV, and HPV based on MEPV, a break-even cost analysis [24] provides the range of additional c-Si costs that would make HPV more cost effective than MEPV. The simplified levelized cost of energy (LCOE) for MEPV and HPV systems are:

$$LCOE_{MEPV} = \frac{C_{MEPV}}{\sum_{n=1}^N \frac{(I_D A_{MEPV} \eta_{MEPV})(PR)(365)(1-d)^n}{(1+r)^n}}$$
$$LCOE_{HPV} = \frac{C_{MEPV} \left\{ \frac{A_{HPV}}{A_{MEPV}} x + (1-x) \right\} + C_{SiPV} \frac{A_{HPV}}{A_{SiPV}}}{\sum_{n=1}^N \frac{(I_D A_{HPV} \eta_{MEPV} + I_{diff} A_{HPV} \eta_{SiPV})(PR)(365)(1-d)^n}{(1+r)^n}}$$

where C_{MEPV} = MEPV system cost (\$/Wp)

C_{SiPV} = SiPV cell cost (\$/Wp)

A = Area per watt-peak (m^2/Wp)

η_{MEPV} = MEPV system efficiency, 30%

η_{SiPV} = Si flat panel system efficiency,

PR = Performance ratio, 0.80

x = MEPV area scaling factor; x denotes what fraction of MEPV system cost scales linearly with area; $(1-x)$ denotes what fraction of MEPV system cost doesn't depend on area, this fraction depends only on rated system power;

I_D = Annual Average daily direct radiation (kWh/m²-day)

I_{diff} = Annual Average daily diffuse radiation (kWh/m²-day)

d = Annual system degradation rate, 1%

r = Discount rate, 7%

N = System lifetime, 25 years

SiPV is rated at STC conditions (1000 W/m², AM1.5G spectrum), MEPV rated at CSTC conditions (1000 W/m², AM1.5D spectrum) and HPV is rated at 900W/m² of direct radiation and 100W/m² of diffuse radiation. MEPV area scaling factor is assumed to be 0.60 based on typical data for tracking systems [5]. Si flat panel efficiency is assumed to be 15% and 18% for the present and future scenarios respectively.

An expression for C_{SiPV}/C_{MEPV} is obtained by equating $LCOE_{MEPV}$ and $LCOE_{HPV}$. Two example locations, Wilmington DE and Albuquerque NM are chosen to represent moderate and high solar insolation locations. The results are shown in Figure 6. For comparison, current and projected Si cell costs [25] of \$0.41/Wp and \$0.30/Wp respectively are also shown in Figure 6. Thus, for MEPV system costs greater than ~\$1.50/Wp and ~\$1.00/Wp, HPV is better than break-even, i.e., a better choice than MEPV, across various insolation conditions in the present and future scenarios respectively.

Assuming various scenarios of c-Si cell costs and MEPV system costs, LCOE for MEPV and HPV is computed under various insolation conditions. The results are shown in Figure 7 and Figure 8. HPV has lower LCOE than MEPV in almost all the scenarios. Thus, HPV is viable and a better choice from a cost standpoint for grid-

competitive applications like commercial or utility scale power plants, provided MEPV is viable.

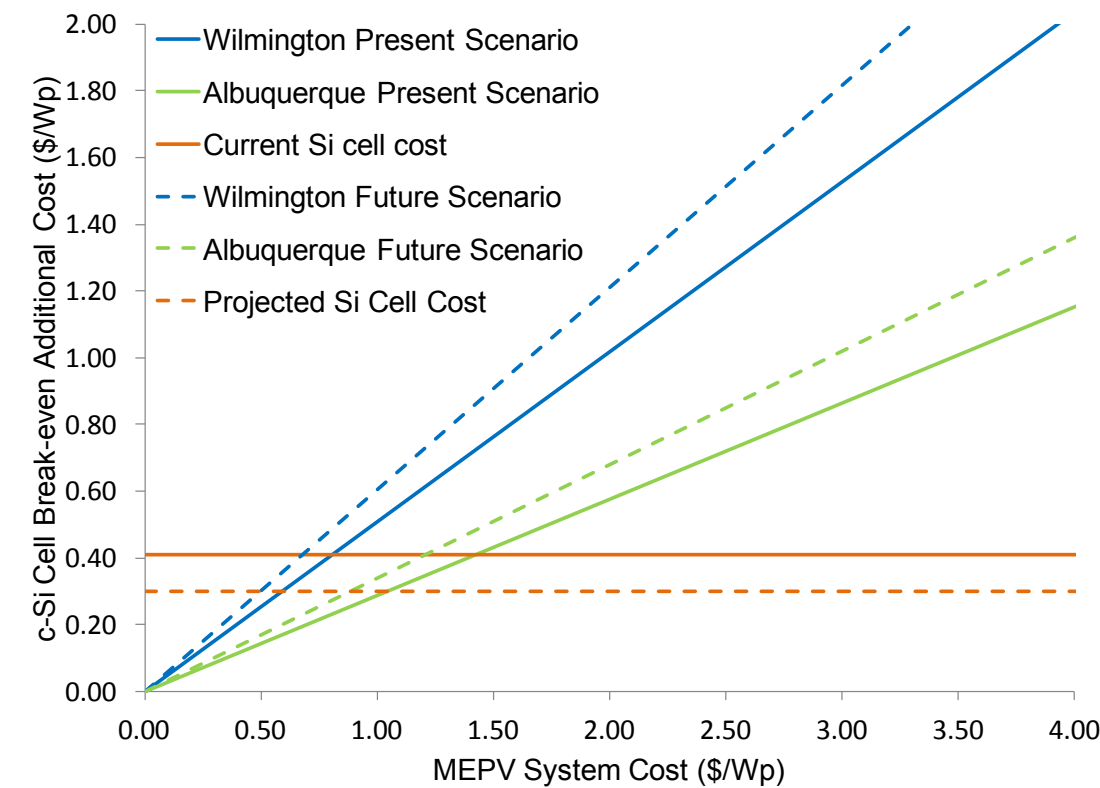


Figure 6: c-Si cell break-even additional cost projections.

Furthermore, HPV is significantly cheaper than MEPV in locations with lower direct insolation ($< 4.5 \text{ kWh/m}^2\text{-day}$). Hence, HPV allows MEPV technology to be more widely applicable across various locations, unlike typical CPV technology which is usually only viable in high direct insolation locations ($> 6 \text{ kWh/m}^2\text{-day}$).

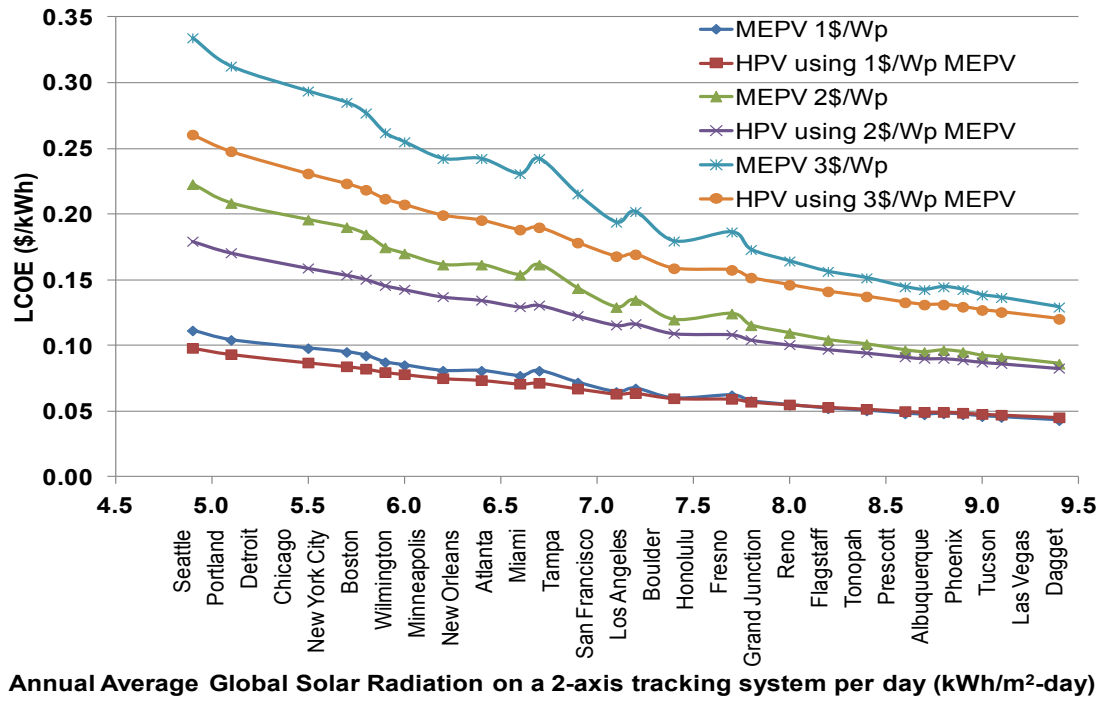


Figure 7: LCOE in present scenario: $C_{SiPV} = 0.41\$/Wp$, $\eta_{SiPV} = 15\%$.

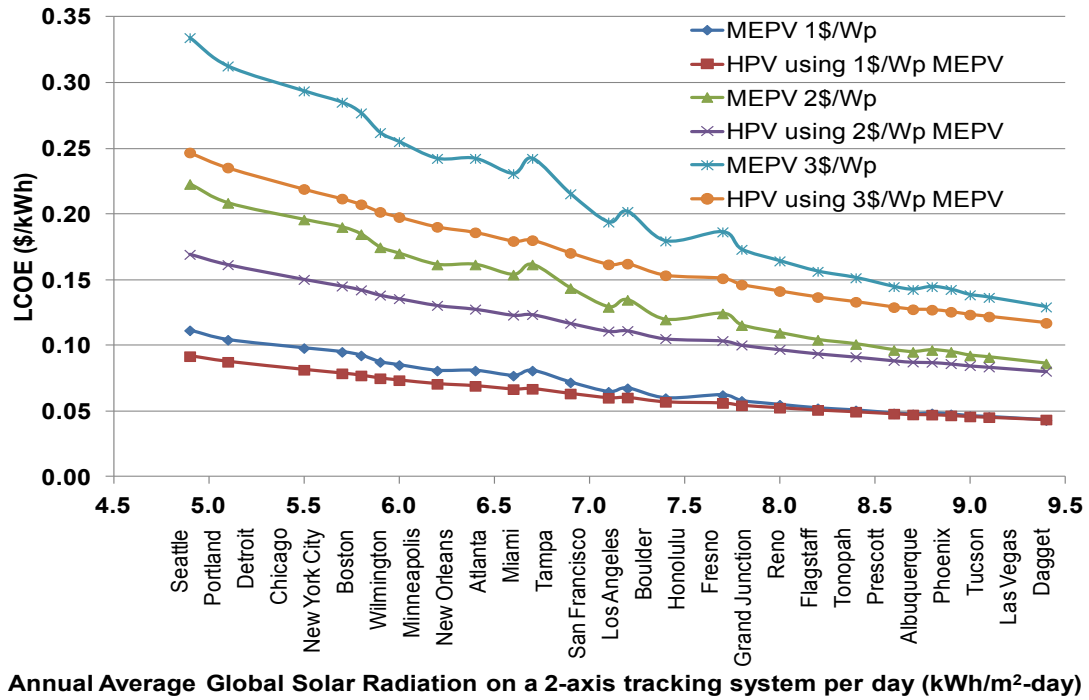


Figure 8: LCOE in future scenario: $C_{SiPV} = \$0.30/Wp$, $\eta_{SiPV} = 18\%$.

4.2 Conclusion

If low-cost, high efficiency MEPV is achieved, the HPV approach can provide a cost-effective solution for space- and mass-constrained applications – and thereby extend the cost-effective geographic and market domain for future deployment of solar PV systems. In the following sections, the results from the optical characterization of the latest generation of MEPV optical module prototypes that will be integrated in an HPV system are presented.

Chapter 5

OPTICAL MODULE INDOOR CHARACTERIZATION

Recent research has led to the development of a second-generation MEPV prototype with improved performance [26] that is compatible with the HPV architecture [27]. Results from the indoor experimental testing of the current prototype of MEPV optical concentrator modules under simulated light sources are presented in this section. Tests are performed to determine the bulk transmission vs. wavelength of the micro-concentrator array and total focused transmission on the designated micro-solar cell region. The results are compared with the simulated performance as per the design specifications.

5.1 Module Design and Simulation Results

The 2-stage optical concentrating system consists of two molded polycarbonate optical plates with the gap between the two lens layers filled with PDMS. The optical module is designed to have a 100X geometric concentration with a hexagonal primary lens aperture and a circular cell aperture 250 μ m in diameter. The unit cells are arranged in a 15x16 hexagonal closed packed array with 2.381mm and 2.058mm pitch spacing respectively. The thickness of the lens “sandwich” is approximately 5.30mm. The optical modules for testing do not have glass cover sheets with anti-reflection coatings which will be applied to the final fully-assembled module. Figure 9 shows the resulting design for the two plano-convex lens, 8th order aspheric design.

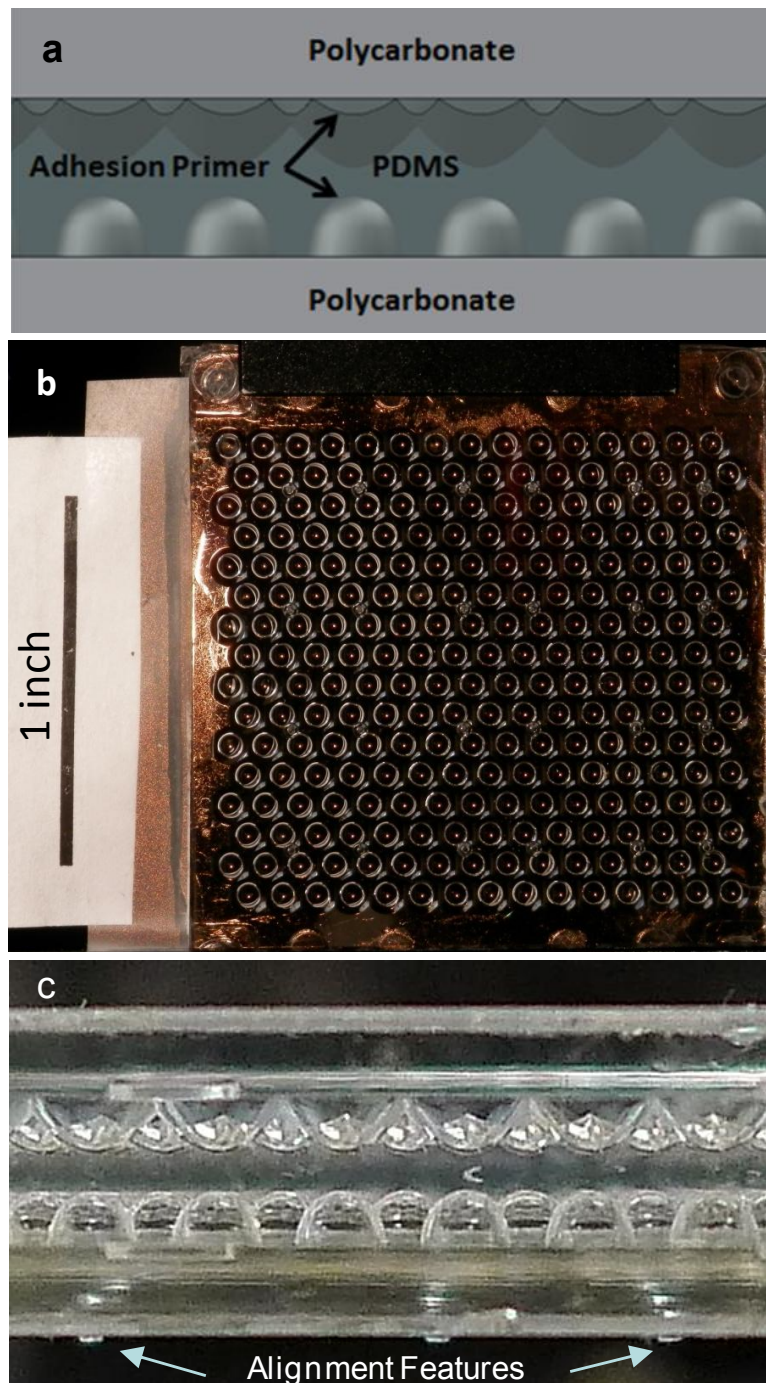


Figure 9: a) MEPV micro-concentrator optical elements consisting of a sandwich of injection-molded polycarbonate (PC) lenses separated by PDMS filler material. b) Image of an optical module illuminated from front and back. c) Side view of an optical module.

The optical performance of the designed micro-concentrator is simulated using the ray-tracing software, *LightTools*. A $\pm 0.25^\circ$ divergent light source with AM1.5D spectrum is used to simulate direct sunlight. Results from the simulation at the output plane are shown in Figure 10.

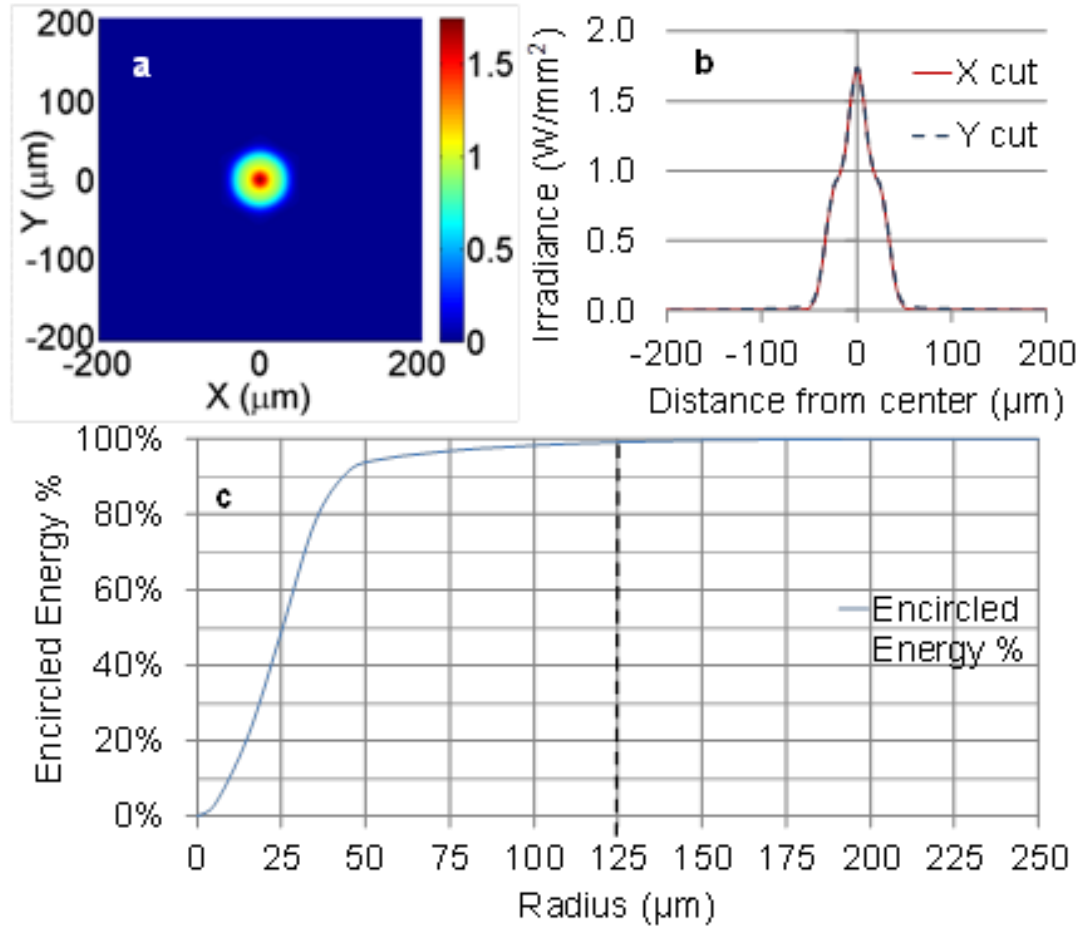


Figure 10: Simulation's output plane results: a) Spot spatial profile. b) Spot X & Y cross-section. c) Encircled energy profile.

5.2 Bulk Transmission Spectroscopy

The Perkin Elmer Lambda 650 UV-Vis-IR spectroscopy tool is used to determine the bulk transmission of the module vs. wavelength. This tool has a variable

wavelength source which emits a light beam $\sim 4 \times 13 \text{ mm}$ in size which is incident within the 24mm diameter input aperture of an integrating sphere. The photo-detector is housed in the integrating sphere. The instrument provides the percentage of light collected at the detector in the measurement setup as compared to a reference setup.

First, the bulk transmission of a 5mm thick slab of polycarbonate (PC) which is used to make the lenses in the optical module is measured. This measurement is made to have a reference for comparison for the optical module. Next, the bulk transmission of a 5mm thick slab of polycarbonate material with a 1mm thick gorilla glass sheet (no AR coating) on top is measured. This is to simulate the surface expected in the final module in which the optical module will be assembled onto a front glass plate. The final module would have AR coatings on the gorilla glass to further improve transmission. The results for the optical transmission of the PC slab without and with the uncoated gorilla glass are shown in Figure 11.

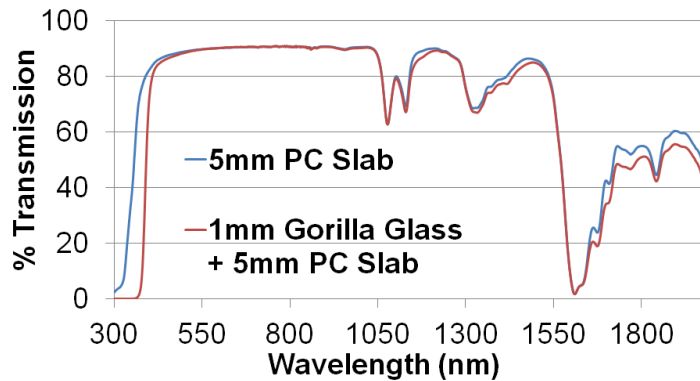


Figure 11: Bulk spectroscopy measurements – polycarbonate slabs.

The results lead to AM1.5G weighted bulk transmissions of 89.0% and 88.5% over 400-1127 nm for the PC slab without and with the uncoated gorilla glass respectively. Also, the transmission spectrum is fairly constant across the spectrum

band most relevant for our solar PV application i.e. 400-1127 nm. These results validate the choice of polycarbonate as the lens material for solar applications from the point of view of bulk optical transmission.

The bulk transmission spectrum of the optical concentrator module without the front glass plate is now measured using the same spectrophotometer. Due to the focusing nature of the tested optical module, the light transmitted through the module is focused differently than the light transmitted in the reference case with nothing at the input. This disturbance to the measurement system yields inaccurate transmission results compared to flat samples. Therefore, modifications were required to the usual measurement approach. The 3 setups shown in Figure 12 were used to obtain the module's bulk transmission.

The percentage transmission for each of the 3 setups shown in Figure 12 is as follows:

$$\begin{aligned} \%_{3a} &= \frac{P_{in} \eta_{r-diff}}{P_{in}} \\ \%_{3b} &= \frac{P_{in} T_{lens} (n_{lens-r-diff} \eta_{r-diff} + 1 - n_{lens-r-diff})}{P_{in} n_{r-diff}} \\ \%_{3c} &= \frac{P_{in} T_{lens} (1 - n_{lens-r-diff})}{P_{in} n_{r-diff}} \end{aligned}$$

where P_{in} is the power incident from the source,

η_{r-diff} is the fraction of light reflected from the rear diffuser that is collected by the detector,

$n_{lens-r-diff}$ is the fraction of transmitted light from the micro-lens array incident on the rear diffuser and,

T_{lens} is the bulk transmission of the micro-lens array.

This system of equations is solved at each wavelength to obtain T_{lens} . Figures 13 and 14 show the measurements and results for the prototype module, respectively.

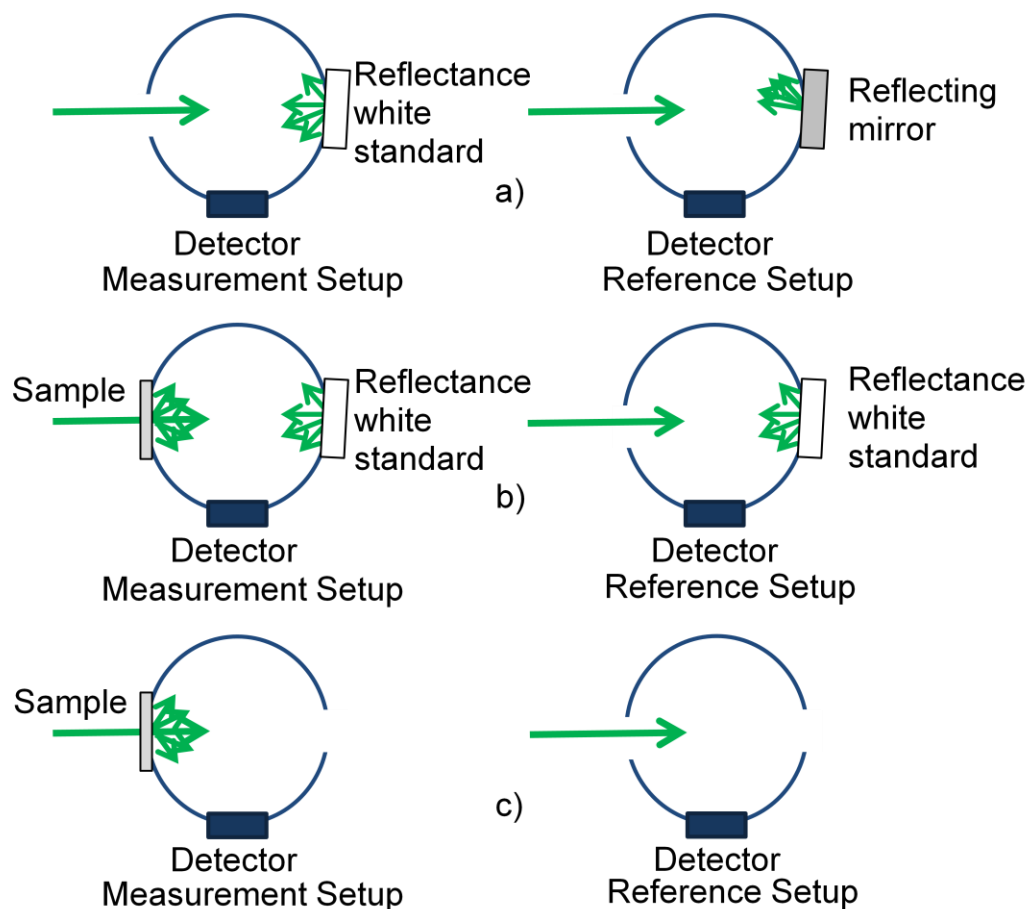


Figure 12: Module bulk spectroscopy measurement setups.

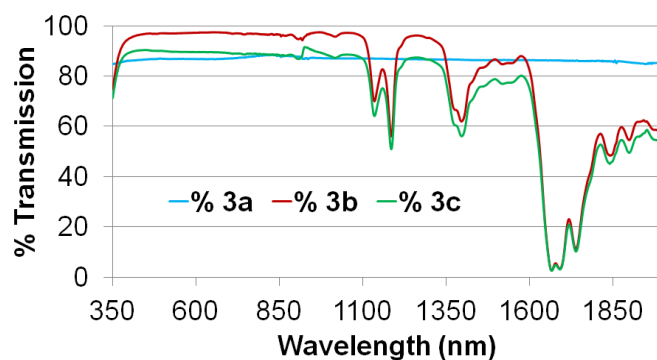


Figure 13: Bulk spectroscopy measurements – prototype module.

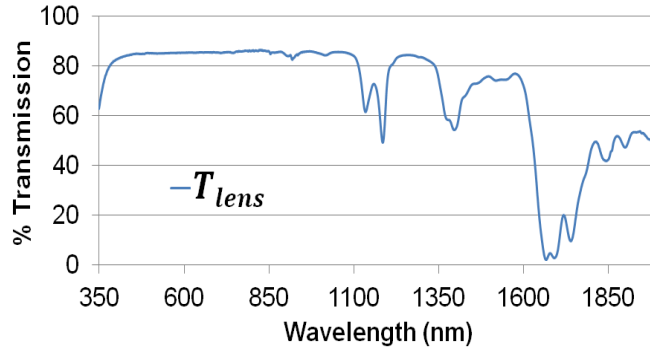


Figure 14: Bulk spectroscopy results – prototype module.

5.3 Bulk Transmission under Solar Simulator

To validate and correct the magnitude of the data obtained from the bulk spectroscopy, the optical transmission of the concentrator module is subsequently measured under a Class AAA solar simulator with a silicon (Si) photo-detector positioned at the output plane of the concentrator module. The photo-detector's photo-current is measured with and without the optical module above it under illumination in the solar simulator. The detector's quantum efficiency (QE) over 350-1200 nm is also measured separately. The photo-currents of the Si photo-detector under the solar simulator are expressed as:

$$I_{NoModule} = q A \sum_{\lambda} \frac{P_{\lambda} QE_{\lambda}}{E_{\lambda}}$$

$$I_{WithModule} = q A \sum_{\lambda} \frac{P_{\lambda} N T_{\lambda} QE_{\lambda}}{E_{\lambda}}$$

where q is the electron charge,

A is the photo-detector area,

P_{λ} is the energy at wavelength λ as per AM1.5G,

QE_{λ} is the photo-detector's QE at wavelength λ ,

E_{λ} is the energy of a photon of wavelength λ ,

N is the correction factor and,

T_λ is the transmission of the module obtained from the bulk spectroscopy experiment at wavelength λ .

Upon simplification,

$$N = \frac{I_{WithModule}}{I_{NoModule}} \frac{\sum_\lambda \frac{P_\lambda Q E_\lambda}{E_\lambda}}{\sum_\lambda \frac{P_\lambda T_\lambda Q E_\lambda}{E_\lambda}}$$

Using the transmission spectrum from the spectroscopy tool, QE data of the photo-detector and the measured photocurrents we obtain the correction factor, N , as 1.02, which is used to correct the magnitude of the transmission spectrum measured from spectroscopy. The small correction error of $\sim 2\%$ validates the methodology used to measure the bulk spectroscopy. The corrected bulk transmission spectrum weighted with the AM1.5G spectrum is shown in Figure 15.

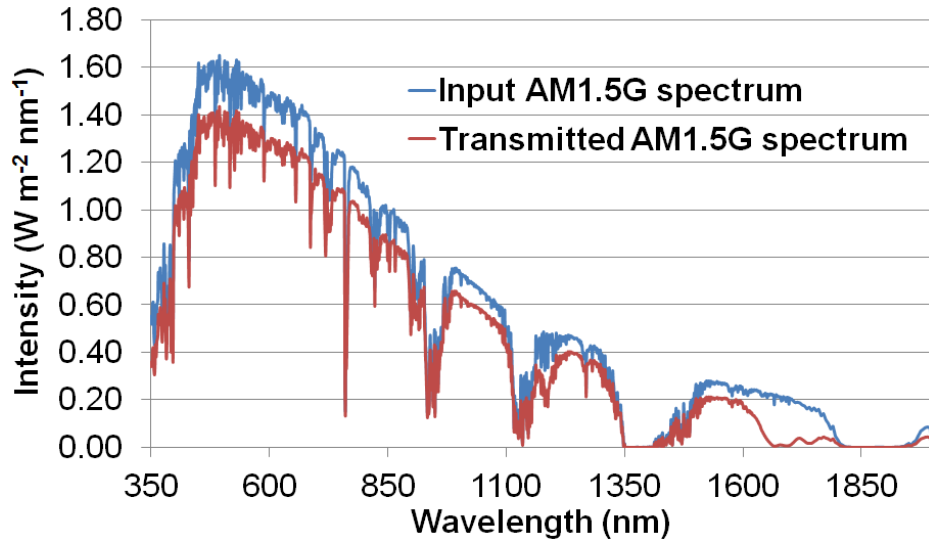


Figure 15: Corrected Bulk spectroscopy results – prototype module.

An AM1.5G weighted bulk transmission of 87.04% is obtained over 400-1127 nm, which is ~2% less than the 89% bulk transmission of the 5mm thick flat slab of polycarbonate. This shows that there are minimal losses within the optical module.

5.4 Focused Spot Transmission Measurements

In order to determine the transmission of the input light onto the designated cell (i.e., focused transmission), an experiment was performed using the setup shown in Figure 16. A halogen lamp white light source having a fiber bundle output with a radius of 1/8 inches is placed 30 inches from the sample to approximately simulate the $\pm 0.25^\circ$ divergence of the solar disk's angular extent. The spot array at the output plane generated by the optical module is captured by a camera and the spatial profile of the spots is analyzed. Pixel resolution of $13.5\mu\text{m}$ is achieved using this setup. An example spot profile is shown in Figure 17.

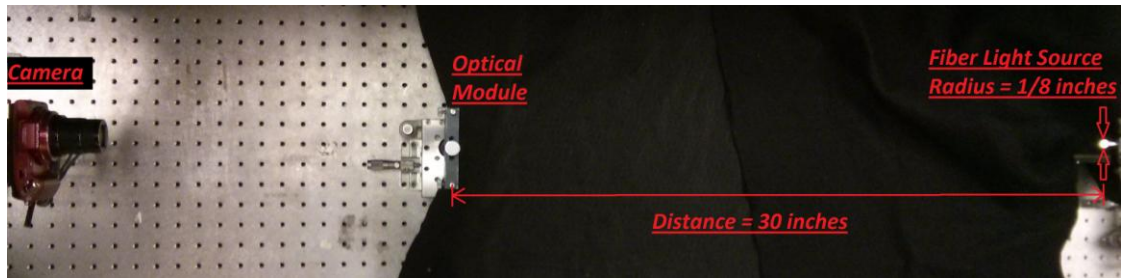


Figure 16: Focused spot transmission measurement setup.

The images were processed in MATLAB and the percentage of encircled energy within circles of various radii up to $1250.4\mu\text{m}$, which corresponds to the area of the input aperture, was computed and is shown in Figure 18. On average, 87.45% of the transmitted energy is confined within a circle of radius $125\mu\text{m}$ around the center of the spot, which is the designated photovoltaic cell region of the optical module.

Therefore, when multiplied by the previously measured bulk transmission, a net focused transmission of 76.1% is obtained.

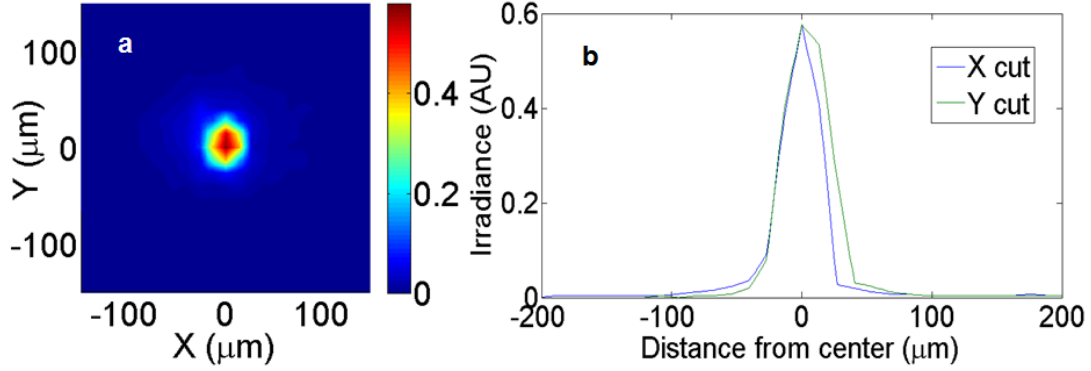


Figure 17: a) Example spot diagram. b) X & Y cross-sections.

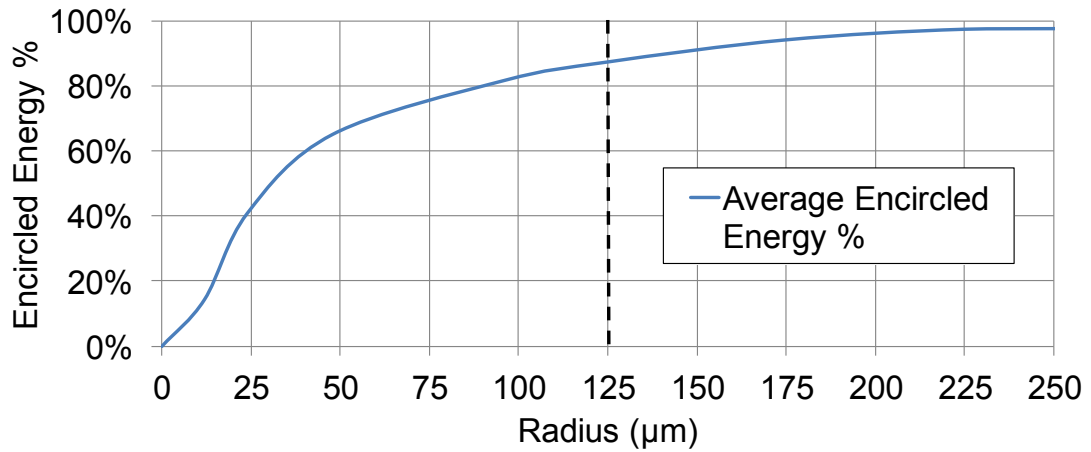


Figure 18: Average encircled energy results from spot diagrams.

Simulations for an ideal module predict 99.1% of the transmitted energy is within the 125 μm radius focus region. Factors that contribute to the reduced encircled energy may include light scattering from surface defects (such as flow lines and scratches) which reduce the focused transmission, warpage of the polycarbonate

optical plates which varies the separation between the two lens arrays leading to defocusing the focused spots, and the loss in focused light due to non-focusing flat edges around the perimeter of each hexagonal front lens because of the resolution limit of the tool used in mold fabrication. These potential causes are being investigated in on-going outdoor characterization under natural sunlight and improved upon by future iterations of fabricated optic arrays. A surface finish of 24nm R_a and a form error of $\pm 11\mu\text{m}$ were measured for the molded optic array [26].

Simulations of the experiment predict that $\sim 5\%$ of the incident light is lost at each of the front & rear optics-air interface. Since the fully assembled module will have index matching layers to immerse the photovoltaic cells in the optics and AR coatings on the front surface of the optics, the concentrated transmission to the photovoltaic cell would be expected to increase to over 84%. Additionally, $\sim 12\%$ of the direct sunlight would be captured by the non-concentrated cell in a hybrid photovoltaic design [27].

5.5 Conclusion

Indoor characterization of the second generation MEPV micro-concentrator prototype showed a $\sim 76\%$ focused transmission and $\sim 87\%$ total transmission (air-optics-air) under simulated light sources using our current prototype module [28]. Initial results demonstrate the potential of small form-factor, high concentration MEPV optics. Outdoor characterization of the optical module under natural sunlight is presented in the next chapter to further investigate the optical performance of the micro-concentrators. It is expected that high performance MEPV modules will be achieved by integrating these optical modules with high-efficiency, multi-junction micro-photovoltaic cells.

Chapter 6

OPTICAL MODULE OUTDOOR CHARACTERIZATION

Experiments are performed outdoors under natural sunlight using a 2-axis tracker system to measure the bulk and focused transmission of the optical module prototypes under different radiation conditions. The aim is to obtain the bulk and focused transmission vs. direct radiation/global radiation (D/G) ratio to provide a proof-of-concept for the HPV architecture. It is expected that the non-concentrated cell region would receive most of the diffuse sunlight in all conditions and most of the direct sunlight would be focused on the concentrated cell region. Thus, it is expected that focused transmission is strongly dependent on the D/G ratio whereas the bulk transmission (which includes the focused transmission) is only weakly dependent on the D/G ratio.

6.1 Outdoor Bulk Transmission Measurement

The optical module and measurement setup are mounted on a high precision 2-axis solar tracker, EKO STR-22. A First Class pyranometer, MS-402, is used to measure the global radiation in the plane of array (POA). A First Class pyrliometer, MS-54, is used to measure the direct radiation in the POA. Two similar c-Si photo-detectors are used in a calibrated setup to perform the transmission measurements. The rotational stages are adjusted to align the system to be exactly perpendicular to the sun and then locked for the rest of this section's measurements. The top view of the setup is shown in Figure 19.

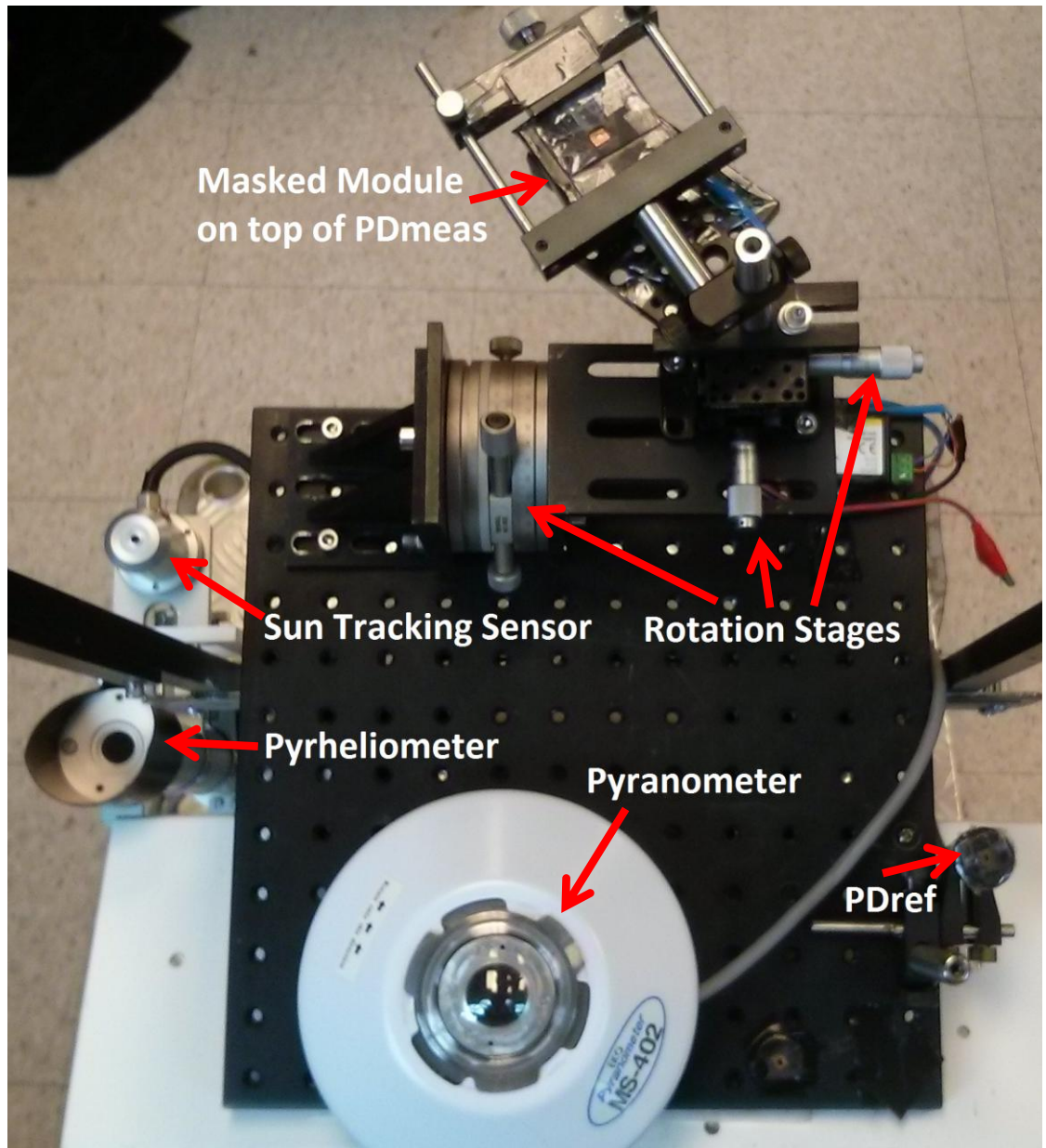


Figure 19: Bulk transmission measurement setup

As a first step to performing the transmission measurements, the two c-Si photo-detectors are calibrated with respect to each other under different irradiation conditions. The two photo-detectors are hereafter referred to as the measurement

photo-detector, PDmeas, and the reference photo-detector, PDref. A copper mask with a hexagonal aperture with the same size as a unit cell (2.75mm x 2.54mm) in the prototype module is affixed on to both c-Si photo-detectors. This is done so as to standardize the amount of input radiation on to a unit cell of the optical module under various conditions. These reference measurements are then used as inputs to calculate the bulk and focused transmission values.

To perform these measurements, the following four data streams are collected at a 4Hz sample rate using MadaTech current and voltage data loggers:

1. Global Radiation in POA
2. Direct Radiation in POA
3. PDmeas short circuit current
4. PDref short circuit current

This data is collected over several days under varying radiation conditions to capture data under a variety of D/G ratios. Once sufficient data is collected, the data is processed using MATLAB. The procedure for processing in MATLAB is outlined below:

1. The first step is to filter the data to remove unreliable data. Some data can be unreliable due to the fast changing nature of sunlight in semi-cloudy conditions. In such conditions, when sunlight is fluctuating rapidly the response of the four sensors can be out of sync (due to small differences in response time) leading to unreliable data. So, we filter out data at times when direct radiation has fluctuations greater than 5 W/m² in the 1 second preceding and following the data point under consideration. In other words, only data points for which the value for

direct radiation for the 4 preceding and following data points (i.e. ± 1 second) are within $\pm 5 \text{ W/m}^2$ of the value of direct radiation for the data point under consideration are allowed.

2. The next step is to sort the filtered data into bins of global radiation and D/G ratios. The global radiation bins are 0-10, 10-20, 20-30, ... , 1390-1400 W/m^2 . The Direct/Global ratio bins are 0-1%, 1-2%, 2-3%, ... , 99%-100%. Thus, a 2-D matrix of data bins is obtained.
3. Now, the PDmeas and PDref values within each bin are added up.
4. If there are more than three PDmeas (or PDref) values in a bin, divide the total PDmeas by total PDref for the bin to obtain the PDmeas/PDref value for the bin.
5. For bins that have three or less PDmeas (or PDref) values, set the PDmeas/PDref value for that bin to be equal to the average PDmeas/PDref value for the corresponding D/G ratio.

Thus, a dataset, hereafter referred to as the input reference measurement dataset is obtained. Now to measure the bulk transmission, the hexagonal mask is applied on the front of a prototype optical module and the module is placed on top of PDmeas. The PDref photo-detector is left undisturbed. All the four data streams are again collected over several days under varying radiation conditions to capture data under a variety of D/G ratios. Once sufficient data is collected, the data is processed using MATLAB following steps 1-4 as outlined above. Step 5 is not performed on this data set. This dataset is hereafter referred to as the bulk measurement dataset.

Thus, the two datasets required to calculate bulk transmission vs. D/G ratio are obtained. Now, for each bin in the bulk measurement data set that has a known

PDmeas/PDref value, the bulk transmission is calculated by dividing the same by the PDmeas/PDref value for the same bin in the reference measurement data set. Now, the bulk transmission values for each D/G ratio are averaged over the global radiation values. Thus, the bulk transmission vs. D/G ratio data points are obtained. These are shown in Figure 20.

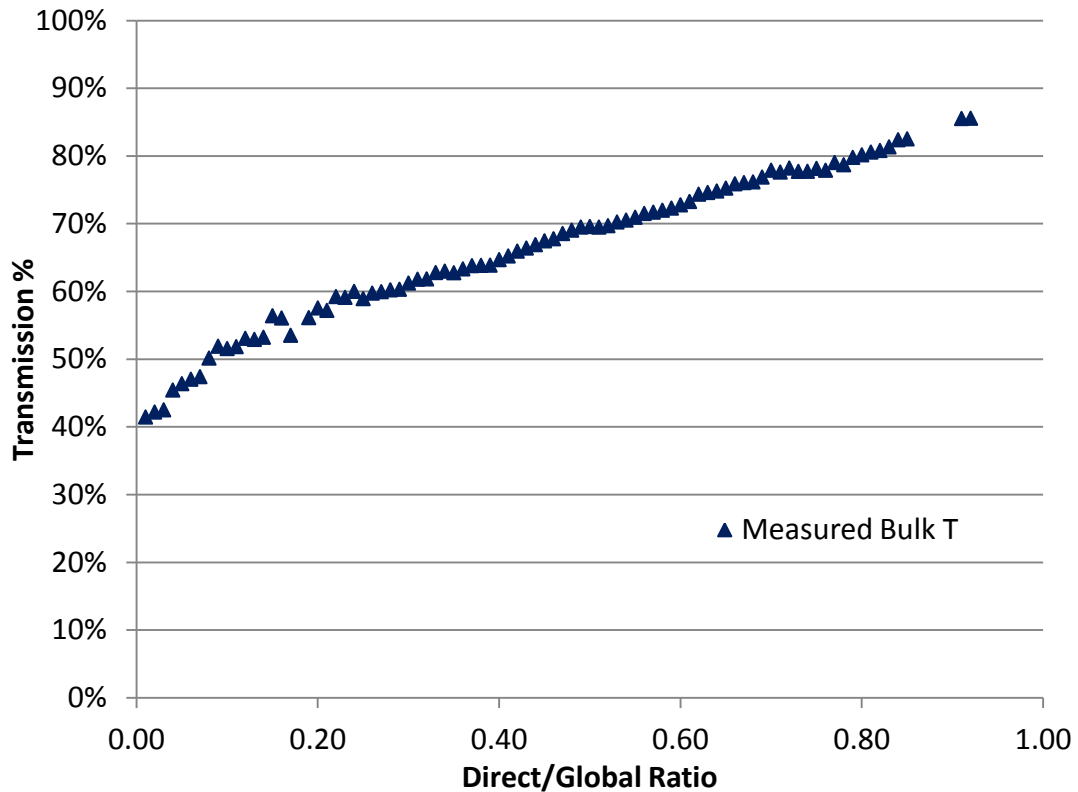


Figure 20: Bulk transmission vs. D/G ratio

It can be seen that there is some decrease in the bulk transmission with reducing D/G ratio. This can be attributed to increasing total internal reflection (TIR) at the rear optics-air interface with increase in diffuse radiation which comes in at higher angles of incidence. This effect is particularly exaggerated in this measurement

setup as there is an additional optics-air interface before the PV cell. In the final fabricated module, the cells would be adhered to the rear optics using an index matching adhesive significantly reducing the TIR losses and thereby, improving the bulk transmission.

6.2 Outdoor Focused Transmission Measurement

To perform the focused transmission measurements, a blocking copper mask with 250 μ m diameter windows simulating the high-efficiency III-V multi-junction concentrator PV cells is assembled onto the optical module's rear surface to measure the concentrated optical power that falls onto the cell region only. The rear mask is aligned using alignment features on the rear surface and bonded to the optical module via PDMS. The optical module has no front mask in this setup. It is assumed that no light from adjacent unit cells is incident on the concentrated cell region of the unit cell under consideration. The rear-masked optical module is placed on top of PDmeas. The rotational stages are adjusted to align the system to be exactly perpendicular to the sun and then locked for rest of this section's measurements. The top view of the setup is shown in Figure 21.

All the four data streams are again collected over several days under varying radiation conditions to capture data under a variety of D/G ratios. Once sufficient data is collected, the data is processed using MATLAB following steps 1-4 as outlined in the previous section. Step 5 is also not performed on this data set. This dataset is hereafter referred to as the focused measurement dataset.

Thus, the two datasets required to calculate focused transmission vs. D/G ratio are obtained. Now, for each bin in the focused measurement data set that has a known PDmeas/PDref value, the focused transmission is calculated by dividing the same by

the PD_{meas}/PD_{ref} value for the same bin in the reference measurement data set obtained in the previous section. Now, the focused transmission values for each D/G ratio are averaged over the global radiation values. Thus, the focused transmission vs. D/G ratio data points are obtained. These are shown in Figure 22.

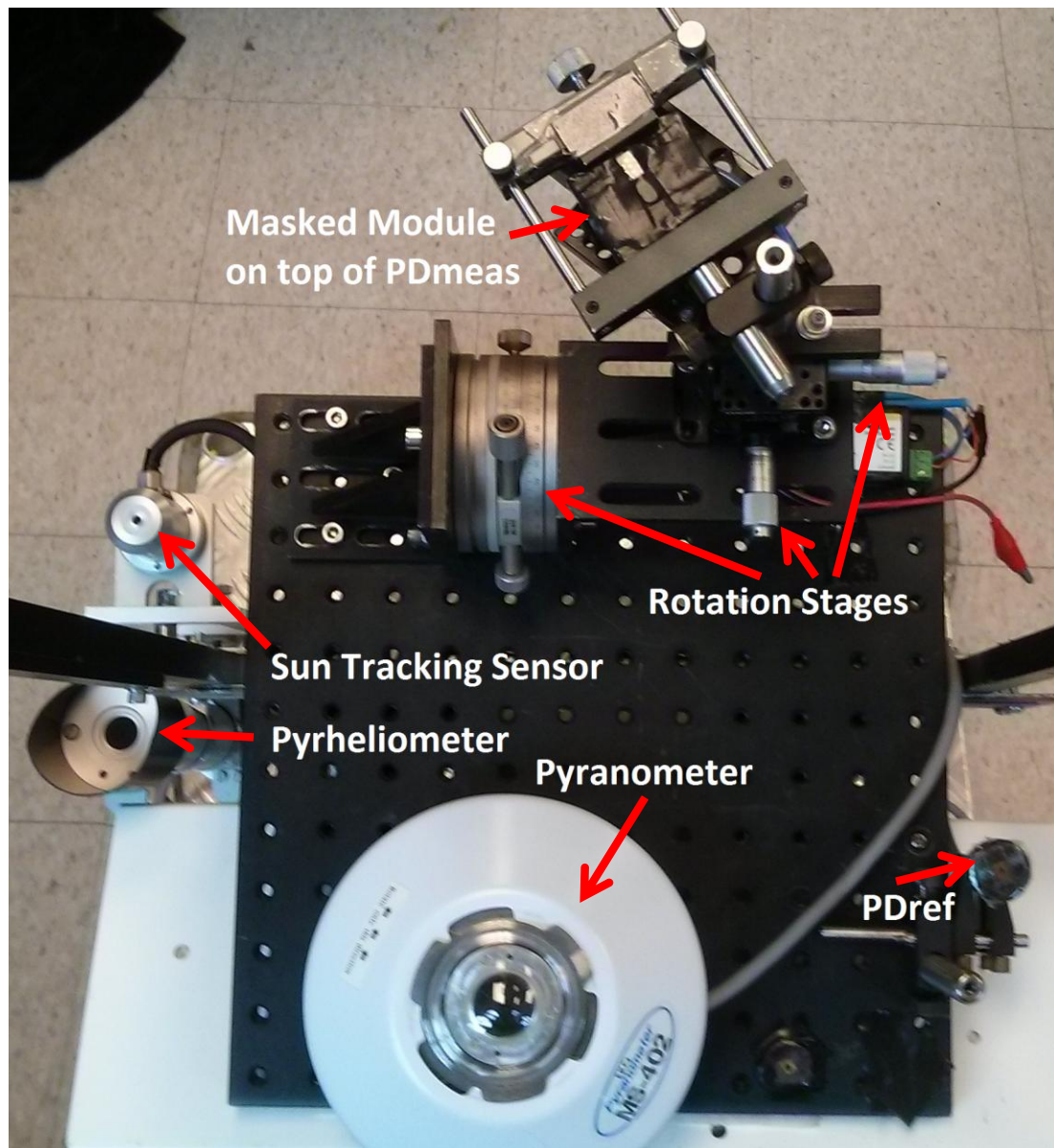


Figure 21: Focused transmission measurement setup

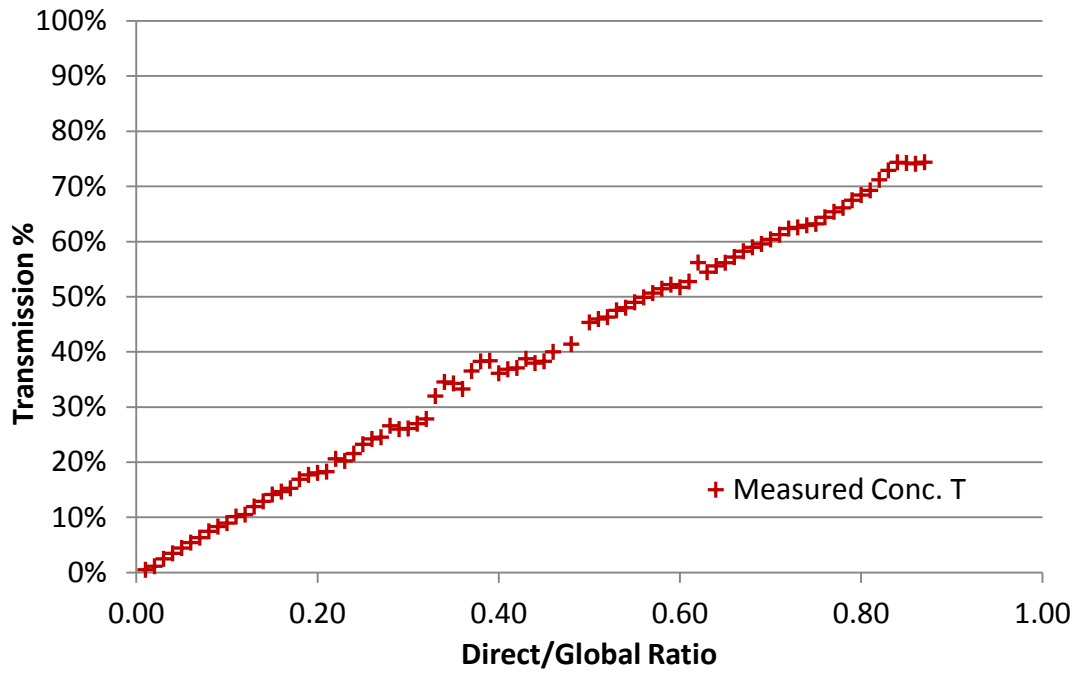


Figure 22: Focused transmission vs. D/G ratio

It can be seen that there is a significant decrease in the focused transmission with reducing D/G ratio. This can be explained by the fact that the concentrator optics are unable to focus diffuse light into the small concentrator region and hence, as diffuse radiation increases in percentage, focused transmission declines.

6.3 Simulation Comparison and Conclusion

The bulk and focused transmission measurements performed in the previous two sections are modeled in the ray tracing software, LightTools and the simulated results for the bulk and focused transmission vs. D/G ratio are obtained. The comparison of the simulated and measured results is shown in Figure 23.

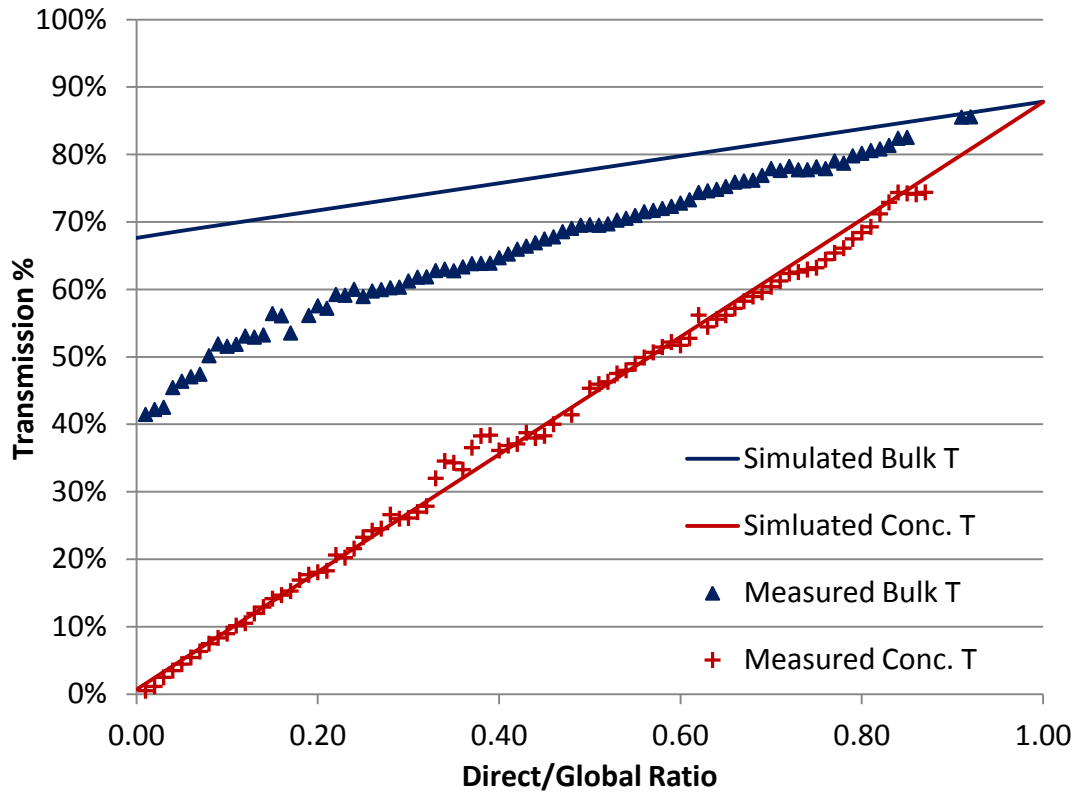


Figure 23: Bulk and focused transmission vs. D/G ratio: simulated and measured comparison

It can be seen that the focused transmission results agree very well with the simulations however, the bulk transmission measured values are clearly lower than the simulation results. Also, it can be seen that the discrepancy increases with reducing D/G ratio. This can be explained due to a limitation of the experimental setup, namely, the small size of PDmeas. Due to the finite size of PDmeas, some of the high-angle diffuse radiation goes beyond the photo-detector's area and misses it. Thus, it is not measured even though it is transmitted. Thus, the bulk transmission measurements are lower than expected. This also explains why the discrepancy is magnified at lower D/G ratios as the error only affects high-angle diffuse radiation which increases at

lower D/G ratios. It should also be noted that the peak bulk transmission would be expected to increase by 8-10% in the final fabricated module due to reduction in reflection losses at the front and rear surfaces due to the addition of a glass sheet with anti-reflection coatings and adhesion of the PV cells to the rear optics surface using index matching layers respectively. This would also lead to a corresponding increase in focused transmission.

In conclusion, these experiments establish that the focused transmission is strongly dependent on the D/G ratio whereas the bulk transmission is only weakly dependent on the D/G ratio. This proves that the micro-scale HPV architecture can be used to harvest direct sunlight using small area, high-efficiency, multi-junction cells while using low cost, large area cells to harvest diffuse sunlight.

Chapter 7

CONCLUSION

A novel HPV solar cell architecture is described here, aiming to enhance solar energy collection and conversion under all radiation conditions and reduce overall costs. It is shown that while increases in acceptance angle can help increase CPV energy production slightly, a completely new architecture is required to harvest a large fraction of the diffuse sunlight which can comprise ~20-40% of the global solar radiation at different locations. It is shown that the HPV approach achieves significantly higher production per unit area as compared to either conventional flat panel PV or concentrator PV. It is also shown that HPV can be more financially attractive as compared to micro-scale concentrator PV across all geographical locations, assuming current and projected future c-Si cell costs and efficiencies. Finally, indoor and outdoor characterization results of the optical module prototypes are presented that establish a proof-of-concept of the HPV architecture.

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Appendix A

CODE SAMPLES

A.1 MATLAB Code to filter and sort data from the data loggers for the reference dataset

```
Global = [Global1; Global2; Global3; Global4; Global5; Global6;
Global7; Global8; Global9; Global10; Global11; Global12; Global13;
Global14];
Direct = [Direct1; Direct2; Direct3; Direct4; Direct5; Direct6;
Direct7; Direct8; Direct9; Direct10; Direct11; Direct12; Direct13;
Direct14];
PD = [PD1; PD2; PD3; PD4; PD5; PD6; PD7; PD8; PD9; PD10; PD11; PD12;
PD13; PD14];
PDref = [PDref1; PDref2; PDref3; PDref4; PDref5; PDref6; PDref7;
PDref8; PDref9; PDref10; PDref11; PDref12; PDref13; PDref14];
DirectRatio=100*Direct./Global;

c=5;
j=0;
num=3;

for i=5:length(Global)-4
    if DirectRatio(i)>=0
        if DirectRatio(i)<100
            if abs(Direct(i)-Direct(i-1))<c
                if abs(Direct(i+1)-Direct(i))<c
                    if abs(Direct(i)-Direct(i-2))<c
                        if abs(Direct(i+2)-Direct(i))<c
                            if abs(Direct(i)-Direct(i-3))<c
                                if abs(Direct(i+3)-Direct(i))<c
                                    if abs(Direct(i)-Direct(i-4))<c
                                        if abs(Direct(i+4)-Direct(i))<c
                                            j=j+1;
                                            fDirect(j)=Direct(i);
                                            fGlobal(j)=Global(i);
                                            fPD(j)=PD(i);
                                            fPDref(j)=PDref(i);
                                            fDirectRatio(j)=DirectRatio(i);
                                        end
                                    end
                                end
                            end
                        end
                    end
                end
            end
        end
    end
end
```

```

end
end
end
end
end
end
end

clear P*;
clear D*;
clear G*;

PDref=fPDref;
PD=fPD;
Global=fGlobal;
Direct=fDirect;
DirectRatio=fDirectRatio;
clear f*;

Global_index=[10:10:1400];
Direct_index=[1:100];

Global_index=sort(Global_index);

datagridPD=zeros(length(Global_index),length(Direct_index));
datagridPDref=zeros(length(Global_index),length(Direct_index));
datagridRatio=zeros(length(Global_index),length(Direct_index));
datagridcount=zeros(length(Global_index),length(Direct_index));
datagridRatiofiltered=zeros(length(Global_index),length(Direct_index));

for i=1:length(Global)

datagridPD(ceil(Global(i)/10),ceil(DirectRatio(i)+0.00001))=datagridPD(ceil(Global(i)/10),ceil(DirectRatio(i)+0.00001))+PD(i);

datagridPDref(ceil(Global(i)/10),ceil(DirectRatio(i)+0.00001))=datagridPDref(ceil(Global(i)/10),ceil(DirectRatio(i)+0.00001))+PDref(i);

datagridcount(ceil(Global(i)/10),ceil(DirectRatio(i)+0.00001))=datagridcount(ceil(Global(i)/10),ceil(DirectRatio(i)+0.00001))+1;
end

for j=1:length(Global_index)
    for k=1:length(Direct_index)
        if datagridcount(j,k)~=0
            datagridPD(j,k)=datagridPD(j,k)./datagridcount(j,k);

datagridPDref(j,k)=datagridPDref(j,k)./datagridcount(j,k);
datagridRatio(j,k)=datagridPD(j,k)/datagridPDref(j,k);

```

```

        if datagridcount(j,k)>num
            datagridRatiofiltered(j,k)=datagridRatio(j,k);
        end
    end
end
end

datagridsum=zeros(1,100);
datagridsumcount=zeros(1,100);
for k=1:length(Direct_index)
    for j=1:length(Global_index)
        if datagridRatiofiltered(j,k)>0
            datagridsum(k)=datagridsum(k)+datagridRatiofiltered(j,k);
            datagridsumcount(k)=datagridsumcount(k)+1;
        end
    end
    if datagridsumcount(k)>0
        datagridsum(k)=datagridsum(k)/datagridsumcount(k);
    end
end

for k=1:length(Direct_index)
    for j=1:length(Global_index)
        if datagridRatiofiltered(j,k)==0
            datagridRatiofiltered(j,k)=datagridsum(k);
        end
    end
end

Global_index=transpose(Global_index);
surf(Direct_index,Global_index,datagridRatiofiltered,'EdgeColor',
'none');
view(2); axis image; caxis([0.9 1.1]);

```

A.2 MATLAB Code to filter and sort data from the data loggers for the measurement datasets

```

Global = [Global1; Global2; Global3; Global4; Global5; Global6;
Global7; Global8; Global9; Global10];
Direct = [Direct1; Direct2; Direct3; Direct4; Direct5; Direct6;
Direct7; Direct8; Direct9; Direct10];
PD = [PD1; PD2; PD3; PD4; PD5; PD6; PD7; PD8; PD9; PD10];
PDref = [PDref1; PDref2; PDref3; PDref4; PDref5; PDref6; PDref7;
PDref8; PDref9; PDref10];
DirectRatio=100*Direct./Global;

c=5;
j=0;
num=3;

```

```

for i=5:length(Global)-4
    if DirectRatio(i)>=0
        if DirectRatio(i)<100
            if abs(Direct(i)-Direct(i-1))<c
                if abs(Direct(i+1)-Direct(i))<c
                    if abs(Direct(i)-Direct(i-2))<c
                        if abs(Direct(i+2)-Direct(i))<c
                            if abs(Direct(i)-Direct(i-3))<c
                                if abs(Direct(i+3)-Direct(i))<c
                                    if abs(Direct(i)-Direct(i-4))<c
                                        if abs(Direct(i+4)-Direct(i))<c
                                            j=j+1;
                                            fDirect(j)=Direct(i);
                                            fGlobal(j)=Global(i);
                                            fPD(j)=PD(i);
                                            fPDref(j)=PDref(i);
                                            fDirectRatio(j)=DirectRatio(i);
                                        end
                                    end
                                end
                            end
                        end
                    end
                end
            end
        end
    end
end

clear P*;
clear D*;
clear G*;

PDref=fPDref;
PD=fPD;
Global=fGlobal;
Direct=fDirect;
DirectRatio=fDirectRatio;
clear f*;

Global_index=[10:10:1400];
Direct_index=[1:100];

Global_index=sort(Global_index);

datagridPD=zeros(length(Global_index),length(Direct_index));
datagridPDref=zeros(length(Global_index),length(Direct_index));
datagridRatio=zeros(length(Global_index),length(Direct_index));
datagridcount=zeros(length(Global_index),length(Direct_index));
datagridRatiofiltered=zeros(length(Global_index),length(Direct_index)
);

```

```

for i=1:length(Global)
    if DirectRatio(i)>=0
        if DirectRatio(i)<=100

            datagridPD(ceil(Global(i)/10),ceil(DirectRatio(i)+0.00001))=datagridPD(ceil(Global(i)/10),ceil(DirectRatio(i)+0.00001))+PD(i);

            datagridPDref(ceil(Global(i)/10),ceil(DirectRatio(i)+0.00001))=datagridPDref(ceil(Global(i)/10),ceil(DirectRatio(i)+0.00001))+PDref(i);

            datagridcount(ceil(Global(i)/10),ceil(DirectRatio(i)+0.00001))=datagridcount(ceil(Global(i)/10),ceil(DirectRatio(i)+0.00001))+1;
        end
    end
end

for j=1:length(Global_index)
    for k=1:length(Direct_index)
        if datagridcount(j,k)~=0
            datagridPD(j,k)=datagridPD(j,k)./datagridcount(j,k);

            datagridPDref(j,k)=datagridPDref(j,k)./datagridcount(j,k);
            datagridRatio(j,k)=datagridPD(j,k)/datagridPDref(j,k);
            if datagridcount(j,k)>num
                datagridRatiofiltered(j,k)=datagridRatio(j,k);
            end
        end
    end
end

Global_index=transpose(Global_index);

surf(Direct_index,Global_index,datagridRatiofiltered,'EdgeColor','none');
view(2); axis image; caxis([0 1]);

```