CONTENTS

Acknowledgements i
Summary ii
Contents v

1. INTRODUCTION 1

1.1 RATIONALE BEHIND THIS STUDY 2
1.2 OBJECTIVES OF THIS STUDY 2
1.3 METHODOLOGY 3
1.4 REFERENCES 5

2. THE PHYSICS GOVERNING THE OPERATION OF PHOTOVOLTAIC MODULES 6

2.1 INTRODUCTION 6
2.2 THEORETICAL OVERVIEW OF PV CELLS 7
2.3 EQUIVALENT CIRCUIT OF A p-n JUNCTION SOLAR CELL 12
2.4 FACTORS INFLUENCING PERFORMANCE OF p-n JUNCTION SOLAR CELL 13
  2.4.1 Effect of Irradiance on the I-V curve 13
  2.4.2 Effect of temperature 15
  2.4.3 Effect of mismatched conditions 18
    2.4.3.1 Non identical solar cells in PV modules 18
  2.4.4 Effect of spectrum on the I-V curves 20
2.5 SPECTRAL INFLUENCE ON PV MODULE 22
  2.5.1 Introduction 22
  2.5.2 Variation of Solar spectrum within the earth’s atmosphere 22
  2.5.3 Effect of Spectral Distribution on Photovoltaic devices 24
  2.5.4 Global solar radiation components 25
    2.5.4.1 Atmospheric Scattering 26
    2.5.4.2 Water Vapor absorption 27
    2.5.4.3 Mixed gas and Ozone absorption 27
2.6 AIR MASS SPECTRAL CONDITIONS AND PV PERFORMANCE 28
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.6.1</td>
<td>Introduction</td>
<td>28</td>
</tr>
<tr>
<td>2.6.2</td>
<td>Influence of Solar Spectral variation on module’s $I_{sc}$</td>
<td>28</td>
</tr>
<tr>
<td>2.6.3</td>
<td>Site – Specific module determination</td>
<td>29</td>
</tr>
<tr>
<td>2.7</td>
<td>SUMMARY</td>
<td>33</td>
</tr>
<tr>
<td>2.8</td>
<td>REFERENCE</td>
<td>34</td>
</tr>
<tr>
<td>3.</td>
<td>METHODOLOGIES FOR OUTDOOR SPECTRUM EVALUATION</td>
<td>37</td>
</tr>
<tr>
<td>3.1</td>
<td>INTRODUCTION</td>
<td>37</td>
</tr>
<tr>
<td>3.2</td>
<td>THE CONCEPT OF AVERAGE PHOTON ENERGY</td>
<td>39</td>
</tr>
<tr>
<td>3.3</td>
<td>THE AIR MASS CONCEPT</td>
<td>39</td>
</tr>
<tr>
<td>3.4</td>
<td>THE SPECTRAL FACTOR CONCEPT</td>
<td>39</td>
</tr>
<tr>
<td>3.5</td>
<td>THE USEFUL FRACTION CONCEPT</td>
<td>40</td>
</tr>
<tr>
<td>3.6</td>
<td>CONCLUSION</td>
<td>41</td>
</tr>
<tr>
<td>3.7</td>
<td>REFERENCE</td>
<td>48</td>
</tr>
<tr>
<td>4.</td>
<td>PV MODULE CHARACTERIZATION SYSTEM</td>
<td>49</td>
</tr>
<tr>
<td>4.1</td>
<td>INTRODUCTION</td>
<td>49</td>
</tr>
<tr>
<td>4.2</td>
<td>SYSTEM DESCRIPTION</td>
<td>49</td>
</tr>
<tr>
<td>4.3</td>
<td>SYSTEM COMPONENTS AND OPERATION</td>
<td>51</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Data Acquisition System</td>
<td>51</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Programmable Power Supply Unit</td>
<td>52</td>
</tr>
<tr>
<td>4.3.3</td>
<td>Current Measurement and Calibration</td>
<td>53</td>
</tr>
<tr>
<td>4.3.4</td>
<td>Voltage Calibration</td>
<td>55</td>
</tr>
<tr>
<td>4.3.5</td>
<td>Operational Principle of the I-V tester</td>
<td>57</td>
</tr>
<tr>
<td>4.3.6</td>
<td>I-V tester data validation using solar cell theoretical model</td>
<td>60</td>
</tr>
<tr>
<td>4.4</td>
<td>METEOROLOGICAL PARAMETERS</td>
<td>62</td>
</tr>
<tr>
<td>4.4.1</td>
<td>Plain-of-array Irradiance Measurements</td>
<td>62</td>
</tr>
<tr>
<td>4.4.2</td>
<td>Temperature Measurements</td>
<td>63</td>
</tr>
<tr>
<td>4.4.3</td>
<td>Outdoor Spectral Measurements</td>
<td>64</td>
</tr>
<tr>
<td>4.4.3.1</td>
<td>Infrared thermography measurements</td>
<td>64</td>
</tr>
<tr>
<td>4.5</td>
<td>SUMMARY</td>
<td>66</td>
</tr>
<tr>
<td>4.6</td>
<td>REFERENCES</td>
<td>67</td>
</tr>
<tr>
<td>5.</td>
<td>OUTDOOR SPECTRAL EVALUATION OF CRYSTALLINE – Si MODULES</td>
<td>68</td>
</tr>
<tr>
<td>5.1</td>
<td>INTRODUCTION</td>
<td>68</td>
</tr>
<tr>
<td>5.2</td>
<td>EXPERIMENTAL PROCEDURE</td>
<td>68</td>
</tr>
</tbody>
</table>
5.3 RESULTS AND DISCUSSION

5.3.1 Spectral influence on mc-Si module’s performance

5.3.2 Performance of mono-Si

5.3.3 Performance of poly-Si

5.4 SUMMARY AND CONCLUSION

5.5 REFERENCE

6. OUTDOOR SPECTRAL ANALYSIS OF AMORPHOUS - SILICON AND HETERO-JUNCTION WITH INTRINSIC THIN LAYER MODULES

6.1 INTRODUCTION

6.2 OVERVIEW: STRUCTURE AND MANUFACTURING STAGES

6.3 METHODOLOGY

6.4 RESULTS AND DISCUSSION

6.4.1 Spectral Analysis

6.4.2 Initial Performance Analysis

6.4.3 Effect of Outdoor Spectrum

6.4.4 Degradation effect on Spectral Response of PV modules

6.4.5 Seasonal effect on Spectral Response of PV modules

6.5 SUMMARY AND CONCLUSION

6.6 REFERENCE

7. OUTDOOR SPECTRAL EVALUATION OF COPPER INDIUM DISELENIDE TECHNOLOGY

7.1 INTRODUCTION

7.2 METHODOLOGY

7.3 RESULTS AND DISCUSSION

7.4 REFERENCES

8. CAUSES OF HOT-SPOTS IN CRYSTALLINE-SILICON SOLAR CELLS

8.1 INTRODUCTION

8.2 HOT-SPOT HEATING PHENOMENON

8.3 EXPERIMENTAL PROCEDURE