



## Analysis & modeling of metastable photovoltaic technologies: towards dynamic photovoltaic performance models

Marzella Amata Görig

Energie & Umwelt / Energy & Environment

Band / Volume 431

ISBN 978-3-95806-342-6

Forschungszentrum Jülich GmbH  
Institut für Energie- und Klimaforschung  
IEK-5 Photovoltaik

# **Analysis & modeling of metastable photovoltaic technologies: towards dynamic photovoltaic performance models**

Marzella Amata Görig

Schriften des Forschungszentrums Jülich  
Reihe Energie & Umwelt / Energy & Environment

Band / Volume 431

---

ISSN 1866-1793

ISBN 978-3-95806-342-6

# Contents

<b>Abstract</b>	<b>5</b>
<b>Zusammenfassung</b>	<b>7</b>
<b>1 Introduction</b>	<b>9</b>
<b>2 Fundamentals</b>	<b>15</b>
2.1 Basic physics of solar cells . . . . .	15
2.1.1 Electronic states . . . . .	16
2.1.2 Working principle of solar cells . . . . .	20
2.2 Photovoltaic performance models . . . . .	23
2.2.1 Device simulators for thin film photovoltaics . . . . .	24
2.2.2 Equivalent circuit models . . . . .	27
2.2.3 Empirical models . . . . .	34
2.2.4 General structure of PV performance models . . . . .	39
2.3 Modeling of degradation and metastable effects . . . . .	41
<b>3 Outdoor data and analysis method</b>	<b>43</b>
3.1 Outdoor data set . . . . .	43
3.2 Karmalkar-Haneefa model . . . . .	49
3.3 Loss Factor Model . . . . .	53
<b>4 Outdoor data analysis with the Karmalkar-Haneefa model</b>	<b>59</b>
4.1 Parameterization . . . . .	60
4.1.1 Results of the linear fits for CdTe . . . . .	61
4.1.2 Comparison of the KH and linear fits for CdTe . . . . .	64
4.1.3 Comparison of the KH and linear fits for all technologies . . . . .	71

## Contents

4.2	Maximum power point fitting . . . . .	74
4.2.1	Analysis of the entire <i>JV</i> curve fitting . . . . .	76
4.2.2	Comparison of the KH fit with the one-diode model . . . . .	81
4.2.3	Analysis of the fit at the MPP . . . . .	83
4.3	Parameter analysis . . . . .	85
4.3.1	Parameter analysis for the KH model . . . . .	86
4.3.2	Parameter analysis for the LFM . . . . .	93
4.3.3	Comparison of the KH model and LFM . . . . .	95
4.4	Yield prediction . . . . .	98
4.4.1	Methods . . . . .	99
4.4.2	Analysis and results . . . . .	101
4.5	Conclusion . . . . .	106
<b>5</b>	<b>Degradation Analysis and Modeling of CdTe Outdoor Data</b>	<b>109</b>
5.1	Introduction degradation and annealing effects . . . . .	109
5.2	Coefficient analysis . . . . .	111
5.2.1	Open circuit voltage . . . . .	115
5.2.2	Differential conductance at short circuit condition . . . . .	116
5.2.3	Differential resistance at open circuit condition . . . . .	118
5.2.4	Analysis of the fill factor . . . . .	119
5.2.5	Ideality factor . . . . .	121
5.3	Analysis and modeling of different modules . . . . .	124
5.3.1	Analysis of different CdTe modules in Tempe . . . . .	125
5.3.2	Analysis of CdTe in different climate zones . . . . .	127
5.3.3	Results for the maximum power density and fill factor . . . . .	131
5.3.4	An empirical dynamic performance model . . . . .	138
5.4	Conclusion . . . . .	139
<b>6</b>	<b>A new model for degradation and annealing of a-Si:H solar cells</b>	<b>143</b>
6.1	Annealing and degradation effects . . . . .	143
6.2	Light soaking experiment . . . . .	147
6.2.1	Execution of the experiment . . . . .	149
6.2.2	Experimental results . . . . .	151
6.3	Simulation model . . . . .	155

6.3.1	Opto-electronic device simulator . . . . .	157
6.3.2	Degradation model . . . . .	157
6.3.3	Simulation results . . . . .	161
6.3.4	Limitations of the simulation model . . . . .	164
6.4	Conclusion . . . . .	170
<b>7</b>	<b>Conclusion</b>	<b>173</b>
<b>References</b>		<b>178</b>
<b>Appendices</b>		<b>191</b>
<b>A Appendix for Chapter 3</b>		<b>193</b>
<b>B Appendix for Chapter 4</b>		<b>197</b>
<b>C Appendix for Chapter 5</b>		<b>205</b>
C.1	General results . . . . .	206
C.2	Parameter and coefficient changes for all 12 CdTe modules . . . . .	213
C.2.1	Open circuit voltage . . . . .	214
C.2.2	Differential conductance at short circuit condition . . . . .	217
C.2.3	Differential resistance at open circuit condition . . . . .	223
C.2.4	Fill Factor . . . . .	226
C.2.5	Maximum Power Density . . . . .	229
C.2.6	Tables with summarized analysis results . . . . .	230
<b>D List of Abbreviations and Symbols</b>		<b>235</b>
<b>E List of publications</b>		<b>241</b>
<b>F Curriculum Vitae</b>		<b>243</b>
<b>Acknowledgments</b>		<b>245</b>

Energie & Umwelt / Energy & Environment  
Band / Volume 431  
ISBN 978-3-95806-342-6

Mitglied der Helmholtz-Gemeinschaft

