

ACKNOWLEDGMENTS.....	15
-----------------------------	-----------

PART I. INTRODUCTION

1. PREFACE.....	20
2. DERIVING THE ISSUE OF PHOTOVOLTAIC POWER GENERATION.....	21
2.1 <i>Energy Sources and Uses</i>	21
2.2 <i>Solar Energy and Photovoltaic Power Generation</i>	23
3. OUTLINE OF THE DOCTORAL THESIS	26

PART II. RESEARCH TARGET, HYPOTHESES, AND ASSESSMENT TOOLS

4. TARGET OF RESEARCH	30
5. HYPOTHESES	30
6. ASSESSMENT TOOLS.....	32
6.1 <i>Modeling Complex and Dynamic Real-World Systems</i>	32
6.2 <i>STELLA Dynamic Modeling Software</i>	33

PART III. ELECTRIC RESTRUCTURING OVERVIEW

7. ELECTRIC RESTRUCTURING IN THE USA	36
7.1 <i>The Rise of Vertically Integrated Electricity Monopolies</i>	36
7.2 <i>Milestones in Electric Restructuring</i>	38
7.3 <i>Toward Liberal Power Markets</i>	40
7.4 <i>California Pioneering the Deregulation Process</i>	42
8. ELECTRIC RESTRUCTURING IN GERMANY	42
8.1 <i>The Origins and Development of the German Electric Power Industry</i>	42
8.2 <i>European Legislation for Electric Restructuring</i>	45
8.3 <i>Political Reform Attempts</i>	45
8.4 <i>New Energy Legislation</i>	46

PART IV. PHOTOVOLTAIC TECHNOLOGIES OVERVIEW

9. PHOTOVOLTAIC POWER GENERATION COMPONENTS	50
9.1 <i>Systematic Overview</i>	50
9.2 <i>PV Cell Types</i>	50
9.3 <i>PV Module Types</i>	52
9.4 <i>PV System Types</i>	53
9.4.1 <i>Standalone versus Grid-Connected PV Systems</i>	53

9.4.2 Central PV Generation versus Distributed Photovoltaics	54
9.4.2.1 Central PV Power Stations	54
9.4.2.2 Grid-Support PV Substations.....	55
9.4.2.3 Residential Grid-Connected PV Systems	55
9.4.3 Special System Types: Concentrators, Trackers, and Fixed Module Systems	57
10. PV SYSTEM COST COMPARISON AND FORECAST	58

PART V. THE ECONOMICS OF PV POWER GENERATION IN A REGULATED AND VERTICALLY INTEGRATED ELECTRICITY MARKET

11. COSTS OF PHOTOVOLTAIC POWER TECHNOLOGIES.....	62
11.1 <i>Historic Cost Decline of PV Systems</i>	62
11.2 <i>Break-Even System Price for Selected States</i>	63
11.3 <i>Projected Costs of State-of-the-Art PV Technologies</i>	65
11.4 <i>Utility PV Cost Calculation</i>	67
12. COSTS OF FOSSIL FUEL POWER TECHNOLOGIES	68
12.1 <i>Costs for Electricity</i>	68
12.2 <i>Stranded Costs</i>	69
13. ENERGY TAXATION AND SUBSIDIES	70
13.1 <i>Subsidies for Fossil Fuels</i>	70
13.1.1 Research and Development Subsidies	70
13.1.2 Fuel Subsidies.....	71
13.1.3 Social Costs and Taxation of Fossil Fuel Power Generation.....	72
13.2 <i>Subsidies for Renewable Energies</i>	73
13.2.1 German Government 1000-Roofs-Program (1990-1994).....	73
13.2.2 Investment Subsidies by German State Governments	73
13.2.3 Subsidies by State-Owned Financial Institutes	74
13.2.4 Feed Law (Stromeinspeisegesetz; since 1991)	75
13.2.5 Full Cost Rates (Kostendeckende Vergütung; since 1994)	76
13.2.6 Utility Green Pricing Programs.....	77

PART VI. THE ECONOMICS OF PV POWER GENERATION IN A RESTRUCTURED AND LIBERALIZED MARKET ENVIRONMENT

14. THE THREAT OF ELECTRIC COMPETITION.....	80
14.1 <i>Consumer Choice</i>	80
14.2 <i>A New Market Structure</i>	80
14.2.1 The California Power Exchange (PX).....	81
14.2.2 The California Independent System Operator (ISO)	81
<i>New Power Producers</i>	82

15. KEY ISSUES FOR UTILITY INVESTMENT DECISION MAKING.....	84
15.1 Mergers and Acquisitions	84
15.2 High-Quality versus Low-Price Strategy	84
15.3 Customer Loyalty.....	85
15.4 Risk Assessment	86
16. STRATEGIES FOR PHOTOVOLTAIC POWER GENERATION	88
16.1 Customer Support for Renewable Energies.....	88
16.2 Marketing and Branding: Selling Clean Energy.....	89
16.3 Utility-Customer-Manufacturer-Cooperation.....	90
16.3.1 System Cost Reductions.....	90
16.3.2 Long-Term Customer Contracts.....	90
16.4 An Empiric Example of a Utility Photovoltaic Market Strategy.....	90
16.4.1 A Municipal Utility's Case Study: From Nuclear Power Generation to Pioneering Solar Energy.....	90
16.4.2 A Strategy for Photovoltaic Power Generation.....	92
16.4.3 Solar Energy Strategies and Electric Restructuring.....	95

PART VII. DISTRIBUTED POWER GENERATION: CREATING A DECENTRALIZED ELECTRICITY SYSTEM

17. THE CONCEPT OF DISTRIBUTED GENERATION.....	98
17.1 The Decline of Economies of Scale in Electric Power Generation.....	98
17.2 Defining Distributed Power Generation	99
17.3 Distributed Generation with Renewable Energies.....	99
17.4 Utility Benefits from Distributed Electricity Generation	100
17.4.1 Economic Assets through Distributed Power Systems	100
17.4.2 Valuing Distributed PV Power Generation.....	103
17.4.3 Cost-Benefit Analyses in Deregulated Power Markets.....	105
17.5 Residential Customer Benefits from Distributed Electricity Generation.....	106
18. MICRO-GRIDS: ELECTRIC POWER GENERATION WITHOUT A CENTRAL GRID SYSTEM	107
18.1 Definition	107
18.2 Components of Micro-Grid Systems.....	107
18.3 Energy-Efficiency of Micro-Grids	109
18.4 Economics of Micro-Grid Systems	109

PART VIII. DYNAMIC MODELING - ASSESSING THE ECONOMICS OF PV POWER GENERATION IN REGULATED AND RESTRUCTURED ELECTRICITY MARKETS

19. STELLA DYNAMIC MODELING	112
19.1 STELLA II Software	112

<i>19.2 STELLA Programming Elements</i>	112
19.2.1 Stocks	112
19.2.2 Inflows and Outflows	113
19.2.3 Variables	113
19.2.4 Conveyors	114
19.2.5 Ghosts	114
19.2.6 Feedback-Processes	114
<i>19.3 STELLA Analysis Elements</i>	115
19.3.1 Tables	115
19.3.2 Charts	115
<i>19.4 Calculation Methods</i>	116
19.4.1 Time Runs	116
19.4.2 Sensitivity Runs	116
20. DYNAMIC MODELS	117
<i>20.1 The Economics of PV Power Generation in a Regulated and Vertically Integrated Electricity Market</i>	117
20.1.1 Utility PV Power Generation in a Regulated Environment	117
20.1.1.1 Deriving a Basic Model for Conventional Utility Cost Calculation	117
20.1.1.2 Model Assumptions	120
20.1.1.3 Sensitivity Analyses	123
20.1.1.3.1 Sensitivity Analysis on PV System Cost	123
20.1.1.3.2 Sensitivity Analysis on Balance of System Cost	125
20.1.1.3.3 Sensitivity Analysis on Discount Rate	126
20.1.1.3.4 Sensitivity Analysis on the Calculation Time Period	127
20.1.1.3.5 Sensitivity Analysis on Energy Output Data	128
20.1.1.4 Scenarios	130
20.1.1.4.1 New England Electric Services (NEES) Case Model	131
20.1.1.4.2 Sacramento Municipal Utility District (SMUD) Case Model	134
20.1.1.4.3 High-Cost Scenario Germany	137
20.1.1.4.4 Low-Cost Scenario Germany	140
20.1.1.5 Conclusions on Hypothesis 1.1	143
20.1.2 Residential Customer Power Generation in a Regulated Environment	144
20.1.2.1 Basic Model for Residential Customer Cost Calculation	144
20.1.2.2 Sensitivity Analyses	147
20.1.2.3 Assessing Multiple Benefits	153
20.1.2.4 Conclusions on Hypothesis 1.2	154
<i>20.2 The Economics of PV Power Generation in a Restructured and Liberalized Market Environment</i>	156
20.2.1 Modeling an Electric Utility PV Market Strategy	156
20.2.1.1 Basic Utility Model	156

20.2.1.2 Model Evaluation.....	165
20.2.1.3 Sensitivity Analyses.....	168
20.2.1.4 Assessing the Cost-Competitiveness of the Municipal's PV Strategy	170
20.2.1.5 Conclusions on Hypothesis 2.1	179
20.2.2 Residential Customer Power Generation in a Liberal Electricity Market.....	180
20.2.2.1 Basic Model for Residential PV Power Generation	180
20.2.2.2 Sensitivity Analyses.....	184
20.2.2.3 Conclusions on Hypothesis 2.2.....	187
20.3 <i>The Economics of Distributed Power Generation with Photovoltaic Technologies</i>	188
20.3.1 Basic Model of Distributed Power Generation	188
20.3.1.1 Cost-Benefit Analysis of Distributed Power Generation	188
20.3.1.2 Modeling the Economics of Distributed Power Generation.....	190
20.3.1.3 Sensitivity Analysis Results.....	194
20.3.1.4 Conclusions on Hypothesis 3.1	195
20.3.2 Model for Micro-Grid Economics.....	196
20.3.2.1 Micro-Grid Components	196
20.3.2.2 Modeling Micro-Grid Economics.....	198
20.3.2.3 Model Analysis	200
20.3.2.4 Conclusions on Hypothesis 3.2.....	203

PART IX. RESULTS AND OUTLOOK

21. RÉSUMÉ OF HYPOTHESES EVALUATION	206
21.1 <i>PV Economics in Vertically Integrated and Regulated Electricity Markets</i>	206
21.2 <i>PV Economics in Restructured and Liberalized Electricity Markets</i>	206
21.3 <i>PV Economics in Distributed Electricity Systems</i>	207
22. ECONOMIC PROSPECTS AND PROBLEMS FOR PHOTOVOLTAIC POWER GENERATION	207
22.1 <i>System Cost Reductions through Mass Production</i>	207
22.2 <i>New Utility Investment Calculation Methods</i>	208
22.3 <i>Electric Utility PV Strategy in a Deregulated Environment</i>	208
23. OUTLOOK	211
23.1 <i>The Scale Issue of Economic Activity</i>	211
23.2 <i>The Entropy Law and Solar Energy</i>	212
23.3 <i>Photovoltaic Power – Changing Our Energy Basis Toward Sustainability</i>	213

PART X. APPENDIX

24. UNITS OF MEASURE..... 216

25. GLOSSARY 217

26. REFERENCES..... 223

27. INDEX 232

 27.1 *Index of Figures*..... 232

 27.2 *Index of Tables*..... 233