

Table of Contents

Abstract V

Kurzfassung..... VII

Danksagung IX

Acknowledgements XI

Author’s Publications XIII

 Peer-reviewed Journal Publications XIII

 Publications in Proceedings of Scientific Conferences XIII

List of Supervised Theses XV

Table of ContentsXVII

AbbreviationsXXI

NomenclatureXXIII

Chapter 1: Introduction 1

 1.1 Motivation 1

 1.2 Background and Scope: Grid Planning with Active Power Curtailment (APC).. 2

 1.3 Objectives 4

 1.4 Approach and Structure 4

Chapter 2: Active Power Curtailment in Grid Planning and Grid Operation 7

 2.1 Objectives for APC Approaches 7

 2.2 Static APC Methods..... 8

 2.2.1 Static APC in Planning 8

 2.2.2 Static APC in Operation 10

 2.3 Dynamic Methods for APC Operational Simulation10

 2.3.1 Dynamic APC in Planning 10

 2.3.2 Dynamic APC in Operation 11

 2.4 Conclusion13

Chapter 3: A Time-Series-Based Approach for Target Grid Planning 15

 3.1 State of the Art: APC Planning Methods15

 3.1.1 Worst-Case-Based Planning with Reduction Factor 16

 3.1.2 Time-Series-Based Planning 17

 3.2 Bridging the Gap between CAPEX and OPEX Optimization19

3.3 Decoupled Time-Series-Based Planning Framework	20
3.3.1 Optimization Problem Formulation	21
3.3.2 Step 0: Input.....	23
3.3.3 Step 1: Planning with Heuristic Optimization	23
3.3.4 Step 2: OPF Time Series	25
3.3.5 Step 3: Cost-Benefit Analysis.....	26
3.4 Application and Benchmarking	26
3.4.1 Base Case Study	27
3.4.2 Benchmarking of Planning Frameworks	31
3.5 Summary and Conclusion.....	33
Chapter 4: A Time-Series-Based Multi-Year Planning Approach	35
4.1 Literature Overview.....	36
4.2 Development of a Multi-Year Planning Framework.....	40
4.2.1 Economic Analysis	40
4.2.2 Decision Tree Formulations	42
4.3 Case Study	45
4.3.1 Multi-Year Scenario	45
4.3.2 Economic Analysis of the Different Decision Trees.....	46
4.3.3 Equivalent Reduction Factor Analysis.....	49
4.3.4 Computational Effort	50
4.4 Summary and Discussion	50
Chapter 5: Impact Analysis of Curtailment Restriction, Reactive Power and Price...	53
5.1 Case Study Setup.....	53
5.1.1 Grid Model	53
5.1.2 Scenario Setup	54
5.1.3 Measure Setup.....	55
5.1.4 Operational Setup.....	56
5.2 Planning Assumptions for Target Grid Planning with APC	58
5.2.1 Curtailment Restriction Scheme.....	58
5.2.2 Reactive Power Control of RES Generators	59
5.2.3 Curtailment Price	60
5.2.4 Variant Overview.....	62
5.3 Economic Analysis of Reactive Power Control and Curtailment Restriction	62
5.4 Curtailment Price Sensitivity Analysis.....	70

5.4.1	Low Curtailment Price	70
5.4.2	Sensitivity Analysis	74
5.4.3	Evaluation of the Impact of the Curtailment Price	75
5.5	Summary and Conclusion.....	76
Chapter 6: Approach for Target Grid Planning under Uncertainty		79
6.1	Handling Uncertainties in Grid Planning – Motivation and Background	80
6.2	Method: Scenario-Based Cross-Checking Framework	82
6.2.1	Target Grid Cross-Checking Framework	82
6.2.2	Key Performance Indicators for Robustness and Robust Optimality.....	83
6.3	Case Study	85
6.3.1	Statistical Regret Evaluation	85
6.3.2	Analysis of No-Regret Measures	88
6.4	Summary and Conclusion.....	91
Chapter 7: Multi-Year Multi-Scenario Grid Planning Framework		93
7.1	Motivation: Why Multi-Year and Multi-Scenario Planning?	93
7.2	Multi-Year Multi-Scenario Grid Planning Method	95
7.2.1	Definition of Robust Optimal Transformation Paths	95
7.2.2	Cross-Checking Planning Framework.....	97
7.2.3	Preselection of Measure Sets	97
7.3	Case Study	98
7.3.1	Random Multi-Year Scenario Creation	98
7.3.2	Results: Multi-Year Multi-Scenario Transformation Paths with APC ...	101
7.3.3	Results: Cross-Checking Analysis of Transformation Paths	102
7.3.4	Measure Set Preselection for Robust Optimal Transformation Paths .	104
7.4	Summary and Conclusion.....	107
Chapter 8: Conclusion and Outlook.....		109
8.1	Summary and Conclusion.....	109
8.2	Outlook	111
8.2.1	Further Research and Methodical Enhancement.....	111
8.2.2	Significance for the Energy Transition	113
Appendix.....		115
A.	The <i>SpiN-AI</i> Planning Tool	115
A.1.	The <i>SpiN-AI</i> GUI	116
A.2.	Manual Workflow with <i>SpiN-AI GUI</i>	117

A.3.	Automated Workflow with <i>SpiN-AI</i> Backend	117
B.	<i>SimBench</i> MV Grid and Artificial Time-Series.....	119
B.1.	<i>SimBench</i> MV Grid	119
B.2.	Future Scenario Generation.....	120
B.3.	Artificial Time Series	121
B.4.	Grid Planning Measures	122
C.	Additional Results	123
C.1.	Chapter 4	123
C.2.	Chapter 5	125
C.2.1.	Low Curtailment Price.....	125
C.2.2.	Medium Curtailment Price	126
C.2.3.	Expenditures and Equivalent Reduction Factors	130
C.2.4.	Analysis of Equivalent Reduction Factors.....	135
C.2.5.	Curtailment Results	136
C.2.6.	Analysis of Solution Spaces	141
C.3.	Chapter 6	147
C.3.1.	Influence of the Curtailment Price on the Robustness Analysis.....	147
C.3.2.	Target Grid Measures per Scenario.....	149
C.4.	Chapter 7	150
C.4.1.	Multi-Year Scenarios	150
C.4.2.	Multi-Year Transformation Paths	152
C.4.3.	Measure Preselection	156
	List of Tables	160
	List of Figures.....	163
	References	169