Contents

Copyrights vi

Abstract xiii

Credits xv

Acknowledgments xvii

Introduction 1

I Tomorrow's distribution power grid

1 New challenges for the power grid 11

1.1 The shift to renewable energy sources 13

1.1.1 Increase of power imbalances 14

1.2 Increase in amount and complexity of the consumption . . . 15

1.2.1 Demographic growth 15

1.2.2 The emergence of new electric loads 15

1.3 Specific challenges for the distribution grid 18
1.3.1 The need for storage and demand flexibility 21

2 Definition of a framework 23

2.1 Demand-side management 24
2.1.1 Demand-side management programs 25
2.1.2 The choice of a program 25
2.2 Demand response 27
2.2.1 Demand response programs 27
2.2.2 The choice of a program 29
2.3 Dynamic pricings for residential customers 31
2.3.1 Time-of-use pricing 32
2.3.2 Critical peak pricing 33
2.3.3 Real-time pricing 33
2.3.4 Prosumer pricing for customers producing electricity 33
2.3.5 Inclining block rates 35
2.3.6 Choosing a pricing structure 35
2.4 The distribution grid in Belgium 38
2.4.1 Distribution system operators 38
2.4.2 The current legal framework 39
2.4.3 Pricing structures in Belgium 40
2.4.4 Current load flexibility 42

3 The smart grid to the rescue 45

3.1 The smart grid 46
3.2 ... and the smart meter 46
3.3 Towards a smart distribution grid in Belgium 48
3.3.1 The smart meter roll out 48
3.3.2 Political incentives 49
3.4 An attempt to an exhaustive state of the art 49
3.4.1 The potential of the residential area 50
3.4.2 Optimization objectives for the future power grid 51
3.5 Objectives and added-value of the current work 54

II Problem statement, solving and results

4 Design of the residential area model 61
4.1 Distribution grid topology 62
4.1.1 Thermal model of the medium-to-low voltage transformer 63
4.1.2 Communication network infrastructure 65
4.2 Human behaviors 68
4.2.1 Electricity-related practices 68
4.2.2 Participation willingness to demand response programs 69
4.3 Houses 71
4.3.1 Electric configuration 72
4.3.2 Thermal configuration 73
4.4 The autonomous energy management system 74
4.4.1 The smart meter 76
4.4.2 Communication protocols 76
4.4.3 Real-time control 78
4.5 Electric loads 81
4.5.1 Non-controllable loads 82
4.5.2 Non-interruptible loads 83
4.5.3 Electric vehicles 84
4.5.4 Thermal loads 86
4.6 Distributed energy sources 97
4.6.1 Solar panels 98
4.6.2 Other renewable sources of electricity 99
4.7 Pricing structures 100
4.7.1 Bihourly pricing 101
4.7.2 Real-time pricing 101
4.7.3 Prosumer pricing 103

5 Formulation of the optimization problem 105
5.1 Computational optimization methods 106
5.1.1 A quick review of optimization methods 107
5.1.2 A brief history of linear and integer programming 108
5.1.3 Canonical problem forms 109
5.2 Bilevel parametric MILP formulation 112
5.2.1 Sets and indices 112
5.2.2 Parameters and other constants 113
5.2.3 Control and state variables 114

5.2.4 Constraints . . . 115
5.2.5 Objective functions . . . 118
5.2.6 Alternatives to non-linearities . . . 120
5.2.7 From a bilevel to a sequential problem . . . 121
5.2.8 Robustness to strict constraint violations . . . 121
5.3 Problem solving algorithms . . . 123
5.3.1 The Branch-and-cut algorithm . . . 124
5.3.2 The Cutting-plane method . . . 124
5.3.3 The Branch-and-bound algorithm . . . 125
5.4 Stochastic aspects . . . 126
5.4.1 The Monte Carlo method . . . 126
5.4.2 Monte Carlo Sampling . . . 128
5.4.3 Error estimation using the Monte Carlo method . . . 129
5.4.4 Generation of scenarios to optimize . . . 129

6 Simulation and results . . . 131
6.1 Simulation backbone . . . 132
6.1.1 Creation of a block area along with household characteristics . . . 134
6.1.2 Scenario generation using Monte Carlo Sampling . . . 138
6.1.3 Tools for solving the programming problem . . . 144
6.1.4 Simulation parameters and assumptions . . . 147
6.2 Introductory examples for the optimization results . . . 148
6.2.1 Examples of electricity pricings . . . 149
6.2.2 Optimized power load of a 100-household block area . . . 150
6.3 Benefits for the distribution grid . . . 153
6.3.1 Optimization of the peak-to-average ratio . . . 153
6.3.2 Financial benefits for residential clients . . . 157
6.3.3 Impact on the distribution transformer's lifetime . . . 163
6.3.4 Participation to ancillary services . . . 166
6.4 Sensitivity and robustness analysis . . . 167
6.4.1 Dispersion of the peak-to-average ratio . . . 167
6.4.2 Monte Carlo error . . . 169
6.4.3 Penalty activations . . . 171
6.5 Macroeconomic analysis . . . 172
6.5.1 Welfare of the distribution grid . . . 173
6.5.2 Elasticity of the residential demand . . . 176

Final words 177
6.6 Conclusions 179
6.7 Future work 182
6.7.1 Impact of elasticity on the wholesale market price 182
6.7.2 Participation to ancillary services 183
6.7.3 Real life application 183
6.7.4 Heuristics as alternative optimization methods 183

III Appendix

A Additional data 187
A.1 The transmission grid 187
A.2 Electric vehicles 189
A.3 Creating PDFs from Belgian data 189
A.3.1 Houses surfaces and envelope insulation 190
A.3.2 Electric vehicle models 191
A.3.3 Hot water tank sizes 193
A.3.4 Solar panel installation 193

B Additional result analysis 195
B.1 Time synchronization of the price and the base load power 195
B.2 Relative values of the peak-to-average ratio 196
B.3 Financial benefits 198

End matter

List of references 224
List of figures 228
List of tables 229
Index 229