Contents

Acknowledgements i

Contents iii

Zusammenfassung vii

Abstract ix

1 Introduction 1

1.1 Emissions, lowEx and current research 1

1.2 Research Objective 3

1.2.1 Serial heat pumping 3

1.2.2 Research questions 4

1.3 Organization of this work 4

2 Evaluation and performance assessment of heat pumps and heating systems 5

2.1 System description 5

2.2 Heating system analysis and performance 6

2.2.1 Energy balance 6

2.2.2 Performance 8

2.2.3 Exergy analysis 10

2.2.4 Seasonal performance 11

2.3 Heat pumps and their performance 13

2.3.1 Temperature lift 13

2.3.2 Efficiency of vapor compression heat pumps 17

2.3.3 Efficiency of other types of heat pumps 20

3 Introduction to serial heat pumping **23**
3.1 Literature review 23
3.2 Performance of heat pump combinations 28
3.2.1 Heating and hot water production 28
3.2.2 Cooling 32
3.3 Advantages and disadvantages of serial heat pumping 33
3.3.1 Performance 33
3.3.2 Influence on the main heat pump and the heating system . . 35
3.3.3 Costs 36
3.3.4 Control and complexity 37
3.3.5 Conclusion 38

4 Serial heating **39**
4.1 Introduction 39
4.1.1 Motivation 39
4.1.2 Configurations 42
4.1.3 Operation and control of the system 43
4.2 Methods and analysis 46
4.2.1 Considered cases for analysis 46
4.2.2 Building and heating system 47
4.2.3 Analysis 50
4.3 Results 56
4.3.1 Supply and return temperatures 56
4.3.2 Performance of heat pumps 58
4.3.3 Comparison of the performance of case 1 and case 2 60
4.3.4 Pump electricity consumption 65
4.3.5 Performance of the total system considering auxiliary energy 68
4.3.6 Sensitivity of parameters 71
4.4 Technology 80
4.4.1 Requirements 80
4.4.2 Available heat pump technology 82
4.5 Discussion 85
4.5.1 Boundary conditions 85
4.5.2 Absolute consumption 88
4.6 Conclusion 89
4.6.1 Summary of findings 89

4.6.2 Outlook 90

5 Serial hot water production **93**

5.1 Introduction 93

5.1.1 Reducing exergy demand of hot water production 93

5.1.2 Literature review 94

5.1.3 LowEx systems 97

5.1.4 System considered 97

5.2 Methods and assumptions 100

5.2.1 Hydronic system 100

5.2.2 Energy analysis 102

5.2.3 Model assumptions and boundary conditions 108

5.2.4 Heating and hot water system 113

5.2.5 Thermal comfort 122

5.3 Results of dynamic model 124

5.3.1 Solar gains and room temperature 125

5.3.2 Operation time and cover ratio 128

5.3.3 Performance of heat production 134

5.3.4 Performance with auxiliary energy 143

5.4 Discussion 154

5.4.1 Boundary conditions and assumptions of model 154

5.4.2 Comparison with reported performance values in standards and literature 161

5.4.3 Costs of set-up 165

5.4.4 Limitation of concept 166

5.5 Conclusion 168

5.5.1 Summary of findings 168

5.5.2 Outlook 170

6 Conclusion and outlook **171**

6.1 Conclusion 171

6.2 Outlook 174

6.2.1 Methodology 174

6.2.2 Additional aspects and applications 175

6.2.3 Implementation 176

A Serial heating and cooling **179**

A.1 Mathematical derivations for decentralized heat pump 179

A.1.1 Temperature lift of the decentralized heat pump for heating . 179

A.1.2 Return temperature of the decentralized heat pump 180

A.1.3 Electrical power and heating capacity of the decentralized heat pump 181

A.2 Model parameters 182

A.2.1 Pressure drops 182

A.2.2 Representation of the heat pump and the circulation pumps within the model 183

A.3 Parameters for the estimation of the heat loss in the distribution system 184

B Serial hot water production **187**

B.1 Parameters of TRNSYS building model 187

B.2 Hot water demand and draft profile 189

B.3 Technical systems 189

List of figures **197**

List of tables **201**

Nomenclature **203**

Bibliography **205**

Curriculum vitae **223**