# Energy Security of Thermal Energy Communities

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Javanshir Fouladvand

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## DISSERTATION

for the purpose of obtaining the degree of doctor at
Delft University of Technology
by the authority of the Prof.dr.ir. T.H.J.J. van der Hagen,
chair of the Board for Doctorates,
to be defended publicly on Friday 7 October 2022 at 12:30

by

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To all selfless and sagacious people who patiently,
continuously and collectively fight for a
diverse, equal and peaceful world

تا در طلب گوهر کانی کانی    تا در هوس لقمهٔ نانی نانی
این نکتهٔ رمز اگر بدانی دانی    هر چیز که در جستن آنی آنی

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*Javanshir Fouladvand, July 2022*

# CONTENTS

**Acknowledgements** **ix**

**Summary** **xxvii**

**Samenvatting** **xxxi**

**1. Introduction** **1**
- 1.1. Local thermal energy transition . . . 1
- 1.2. Energy security of thermal energy communities . . . 3
- 1.3. Research objective . . . 4
- 1.4. Research questions . . . 4
- 1.5. Research approach . . . 6
  - 1.5.1. ABMS as the computer simulation approach . . . 6
  - 1.5.2. Institutional analysis for studying collective socio-technical energy systems . . . 7
  - 1.5.3. The Netherlands as a research context . . . 8
- 1.6. Audience . . . 9
- 1.7. Thesis outline . . . 10

**2. Thermal energy communities** **11**
- 2.1. Introduction . . . 12
- 2.2. Theoretical background . . . 13
- 2.3. Research methods . . . 14
- 2.4. Overview of the TEC initiatives' literature . . . 16
- 2.5. Organising the literature using the IAD framework . . . 20
  - 2.5.1. Biophysical conditions . . . 20
  - 2.5.2. Attributes of communities . . . 22
  - 2.5.3. Rules-in-use . . . 23
  - 2.5.4. Action situation . . . 23
  - 2.5.5. Interactions and outcomes . . . 24
  - 2.5.6. Evaluative criteria . . . 25
- 2.6. Analysis and discussion . . . 26
- 2.7. Research agenda and future work . . . 27

**3. Simulating thermal energy communities** **31**
- 3.1. Introduction . . . 32
- 3.2. Thermal energy communities (TEC) . . . 33
  - 3.2.1. The thermal technology component . . . 34
  - 3.2.2. The stakeholder's component . . . 34

3.2.3. The institutional component . . . . . . . . . . . . . . . . . . . . . . . . 35
3.2.4. Social and governance settings . . . . . . . . . . . . . . . . . . . . . . . 35
3.2.5. The formation process of TEC initiatives . . . . . . . . . . . . . . . . . 36
3.3. Theoretical background . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 36
3.3.1. The four-layer model of Williamson . . . . . . . . . . . . . . . . . . . . 37
3.3.2. The Institutional analysis and design (IAD) framework . . . . . . . . . 38
3.3.3. Behavioural reasoning theory . . . . . . . . . . . . . . . . . . . . . . . . 39
3.4. Research methods . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 40
3.4.1. Agent-based modelling (ABM) . . . . . . . . . . . . . . . . . . . . . . . 40
3.4.2. Case study: the Netherlands . . . . . . . . . . . . . . . . . . . . . . . . 41
3.5. Model description . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 41
3.5.1. Model conceptualization . . . . . . . . . . . . . . . . . . . . . . . . . . 41
3.5.2. Rules-in-use . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 45
3.5.3. Evaluation criteria and outcomes (KPI models) . . . . . . . . . . . . . 46
3.6. Model parameters and input data . . . . . . . . . . . . . . . . . . . . . . . 48
3.6.1. Data for biophysical conditions - technology . . . . . . . . . . . . . . . 48
3.6.2. Data for the attributes of the community . . . . . . . . . . . . . . . . . 49
3.6.3. Natural gas price and $CO_2$ price . . . . . . . . . . . . . . . . . . . . . 50
3.6.4. Model input parameters . . . . . . . . . . . . . . . . . . . . . . . . . . . 50
3.6.5. Sensitivity analysis and experimentation analysis . . . . . . . . . . . . 51
3.6.6. Experimentation settings . . . . . . . . . . . . . . . . . . . . . . . . . . 51
3.7. Results . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 51
3.7.1. KPIs at the neighbourhood level . . . . . . . . . . . . . . . . . . . . . . 51
3.7.2. Impact of technical and institutional conditions . . . . . . . . . . . . . 55
3.7.3. Successful and unsuccessful neighbourhoods . . . . . . . . . . . . . . . 58
3.8. Discussion . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 58
3.8.1. Key insights from the applied theoretical angles . . . . . . . . . . . . . 59
3.8.2. Limitations . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 60
3.9. Conclusion . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 61

**4. Modelling collective energy security 65**
4.1. Introduction . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 66
4.2. Agent-based modelling in the energy transition literature . . . . . . . . . . 67
4.3. 4A's energy security concept . . . . . . . . . . . . . . . . . . . . . . . . . . . 68
4.4. Research methods and data . . . . . . . . . . . . . . . . . . . . . . . . . . . 68
4.4.1. Agent-based modelling (ABM) . . . . . . . . . . . . . . . . . . . . . . . 68
4.4.2. Parameterising using Dutch data and sensitivity analysis . . . . . . . 69
4.5. Model conceptualisation and implementation . . . . . . . . . . . . . . . . . 69
4.5.1. Modelling purpose . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 69
4.5.2. Entities and state variables . . . . . . . . . . . . . . . . . . . . . . . . . 69
4.5.3. Interactions, network and adaptation . . . . . . . . . . . . . . . . . . . 69
4.5.4. Model initialisation and narrative . . . . . . . . . . . . . . . . . . . . . 70
4.5.5. 4As as key performance indicators (KPIs) . . . . . . . . . . . . . . . . . 71
4.5.6. Technical assumptions and model inputs . . . . . . . . . . . . . . . . . 72
4.5.7. Model parameters and experiment settings . . . . . . . . . . . . . . . . 72

4.6. Results . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 73
4.6.1. Overview of each KPI individually . . . . . . . . . . . . . . . . . . . . . 73
4.6.2. Most and least successful energy security performances based on all 4 KPIs . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 75
4.7. Discussion, conclusions and recommendations . . . . . . . . . . . . . . . . . 76

**5. Energy-secure thermal energy communities 79**
5.1. Introduction . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 80
5.2. Using ABMS to study energy systems and CESs in particular . . . . . . . . . . 82
5.3. Theoretical background . . . . . . . . . . . . . . . . . . . . . . . . . . . . 83
5.3.1. Conceptualizing energy security for community energy systems . . . 83
5.3.2. Community Energy Systems as a collective action problem . . . . . . 84
5.3.3. Modelling individual behaviour: Social value orientation (SVO) theory 85
5.4. Modelling context . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 86
5.4.1. Thermal applications in CESs . . . . . . . . . . . . . . . . . . . . . . 86
5.4.2. The Netherlands as a case study . . . . . . . . . . . . . . . . . . . . . 87
5.5. Model conceptualization . . . . . . . . . . . . . . . . . . . . . . . . . . . . 88
5.5.1. Agents in the model . . . . . . . . . . . . . . . . . . . . . . . . . . . . 88
5.5.2. Biophysical conditions . . . . . . . . . . . . . . . . . . . . . . . . . . 89
5.5.3. Attributes of community . . . . . . . . . . . . . . . . . . . . . . . . . 90
5.5.4. Related institutions . . . . . . . . . . . . . . . . . . . . . . . . . . . . 90
5.5.5. Action situation and interactions . . . . . . . . . . . . . . . . . . . . 90
5.5.6. Evaluation criteria and outcomes (model's KPIs) . . . . . . . . . . . 96
5.5.7. Sensitivity analysis and experimentation analysis . . . . . . . . . . . 98
5.5.8. Parameters and experimentation settings . . . . . . . . . . . . . . . 98
5.6. Results . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 99
5.6.1. General security performance of CES . . . . . . . . . . . . . . . . . . 99
5.6.2. Technical and institutional conditions of high energy security performance . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 102
5.7. Discussion and conclusions . . . . . . . . . . . . . . . . . . . . . . . . . . 104
5.7.1. Energy security of energy communities . . . . . . . . . . . . . . . . . 104
5.7.2. Limitations and further work . . . . . . . . . . . . . . . . . . . . . . 106
5.7.3. Recommendations . . . . . . . . . . . . . . . . . . . . . . . . . . . . 107

**6. Towards collective energy security of thermal energy communities 109**
6.1. Answers to the research questions . . . . . . . . . . . . . . . . . . . . . . . 109
6.2. Research contributions . . . . . . . . . . . . . . . . . . . . . . . . . . . . 113
6.2.1. Scientific contribution . . . . . . . . . . . . . . . . . . . . . . . . . . 113
6.2.2. Societal contribution . . . . . . . . . . . . . . . . . . . . . . . . . . . 115
6.2.3. Limitations and directions for further research . . . . . . . . . . . . 116
6.2.4. Final remarks . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 119

**Appendix A 163**
A.1. Overview of documents . . . . . . . . . . . . . . . . . . . . . . . . . . . . 163

**Appendix B** **177**
B.1. Households attributes . . . . . 177
B.1.1. Drivers to Join . . . . . 177
B.1.2. Household SVO . . . . . 178
B.1.3. Pay-back time (PBT) & Willingness to pay (WTP) . . . . . 179
B.1.4. $CO_2$ emissions . . . . . 179
B.1.5. Other parameters . . . . . 180
B.2. Arrangement of the neighbourhoods . . . . . 180
B.2.1. Number of neighbourhoods & number of households . . . . . 180
B.2.2. Neighbourhood structure and dynamics . . . . . 181
B.2.3. Share of neighbourhood . . . . . 181
B.2.4. Household interactions in neighbourhood . . . . . 182
B.3. District heating technology . . . . . 184
B.4. Data on collective heating technology . . . . . 184
B.5. Data on individual heating technology . . . . . 186
B.6. Environmental attributes and other data . . . . . 187
B.7. Value-based multi-criteria decision-making procedure . . . . . 187
B.7.1. Financial criteria . . . . . 187
B.7.2. Environmental criteria . . . . . 188
B.7.3. Independence criteria . . . . . 189
B.7.4. Criteria calculation . . . . . 189
B.7.5. Criteria rating . . . . . 190
B.7.6. Criteria weighting . . . . . 190
B.7.7. Alternative scoring . . . . . 191

**Appendix C** **193**
C.1. Model's KPIs . . . . . 193
C.1.1. Availability: Average voluntary discomfort percentage: . . . . . 193
C.1.2. Affordability: Average cost . . . . . 193
C.1.3. Accessibility: Diversity index . . . . . 193
C.1.4. Acceptability: $CO_2$ reduction per household . . . . . 194
C.2. Assumptions and input data . . . . . 194
C.3. Sensitivity analysis . . . . . 194

**Appendix D** **197**
D.1. Input data . . . . . 197
D.1.1. Data for attributes of the community . . . . . 197
D.1.2. Collective heating technology . . . . . 198
D.1.3. Individual heating technology . . . . . 199
D.1.4. Distribution of energy labels in the Dutch context . . . . . 200
D.1.5. Other data . . . . . 200
D.2. Calculations of seven energy security KIPs . . . . . 200
D.2.1. Availability: Average voluntary discomfort percentage: . . . . . 200
D.2.2. Energy prices: average cost per household: . . . . . 201
D.2.3. Environmental: Average $CO_2$ emission per household: . . . . . 201
D.2.4. Infrastructure: average diversity of infrastructure: . . . . . 201

    D.2.5. Energy efficiency: average thermal insulation per household: . . . . . 201
    D.2.6. Governance: Establishment duration of energy communities . . . . . 201
    D.2.7. Societal effect: average community benefit . . . . . . . . . . . . . . . . . 202
  D.3. Assumptions and input data . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 202
  D.4. Sensitivity analysis . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 202

**List of Publications** **205**

**Curriculum Vitae** **207**

# LIST OF FIGURES

1.1. Relationship of research questions . . . . . . . . . . . . . . . . . . . . . . . . . . 6

2.1. IAD framework [110] . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 13
2.2. Prisma Flow diagram literature search . . . . . . . . . . . . . . . . . . . . . . . . 15
2.3. Timeline of published documents . . . . . . . . . . . . . . . . . . . . . . . . . . . 16
2.4. Overview of research disciplines and approaches . . . . . . . . . . . . . . . . . 17
2.5. Percentages of worldwide distribution of case studies of articles . . . . . . . 18
2.6. Level of geographical urbanization . . . . . . . . . . . . . . . . . . . . . . . . . . . 18
2.7. Distribution of energy sources and carriers in the body of literature . . . . . 20
2.8. Overview of findings on TEC initiatives literature . . . . . . . . . . . . . . . . . 28

3.1. The four-layer model of Williamson [319] . . . . . . . . . . . . . . . . . . . . . . . 37
3.2. The IAD framework [110] . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 38
3.3. BRT [320] . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 39
3.4. Overview model structure . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 47
3.5. Accumulated $CO_2$ emission reduction . . . . . . . . . . . . . . . . . . . . . . . . 52
3.6. The duration of forming TEC initiatives . . . . . . . . . . . . . . . . . . . . . . . . 52
3.7. Neighbourhood distribution for share of support from households . . . . . 53
3.8. Neighbourhood distribution for share of participating households . . . . . . 53
3.9. Neighbourhood distribution for technologies . . . . . . . . . . . . . . . . . . . . 54
3.10. Share of the households' contribution to the total investment . . . . . . . . . 55
3.11. Neighbourhood distribution per technology scenario . . . . . . . . . . . . . . 56
3.12. Influence of training policy on municipality $CO_2$ reduction . . . . . . . . . . 56
3.13. Influence of training policy on municipality participation . . . . . . . . . . . 57
3.14. Influence of municipality strategy on municipality participants . . . . . . . 57
3.15. Influence of municipality strategy on $CO_2$ emission reduction in the municipality . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 58

4.1. Model conceptual flowchart . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 71
4.2. Overview of KPIs . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 75
4.3. Most and least successful energy security performances . . . . . . . . . . . . 76

5.1. IAD framework, adapted from [110] . . . . . . . . . . . . . . . . . . . . . . . . . . 84
5.2. Model conceptual flowchart . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 95
5.3. Distribution of collective and individual energy sources combinations . . . 100
5.4. Average natural gas consumption . . . . . . . . . . . . . . . . . . . . . . . . . . . 100
5.5. Overview of normalized KPIs vs number of thermal energy communities overall runs . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 101
5.6. Parameters for 60% high and low energy security performances . . . . . . . 103

5.7. Type of leadership and percentage of collective energy generation in the high energy secure communities . . . . . . . . . . . . . . . . . . . . . . . . . . . . 104

A.1. Dominating topics of 134 documents . . . . . . . . . . . . . . . . . . . . . . . . . 175

B.1. Sensitivity analysis outcome for the share of the neighbourhood ($C0_2$ emission reduction) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 182
B.2. Sensitivity analysis outcome for the share of the neighbourhood (household participation) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 182
B.3. Neighborhood participation in the Netherlands . . . . . . . . . . . . . . . . . . 183
B.4. The sensitivity analyses results . . . . . . . . . . . . . . . . . . . . . . . . . . . . 183

C.1. OFAT sensitivity analysis results for the duration of the information exchange period . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 195

D.1. Sensitivity analysis results . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 203

# LIST OF TABLES

1.1. Research questions and their methods . . . . . . . . . . . . . . . . . . . . . . 8

2.1. Used keywords . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 14
2.2. Overview of topics in the studied literature . . . . . . . . . . . . . . . . . . . . 19

3.1. Key performance indicators used to evaluate the model outcomes . . . . . . 46
3.2. Agents, their roles and characteristics . . . . . . . . . . . . . . . . . . . . . 47
3.3. Data for collective technology . . . . . . . . . . . . . . . . . . . . . . . . . 48
3.4. Data on individual heating technology . . . . . . . . . . . . . . . . . . . . . 49
3.5. Criteria for attributes of the community . . . . . . . . . . . . . . . . . . . . 49
3.6. Data for Natural gas price and $CO_2$ price . . . . . . . . . . . . . . . . . . . 50
3.7. Model's parameters and data . . . . . . . . . . . . . . . . . . . . . . . . . . 50
3.8. Experimentation settings . . . . . . . . . . . . . . . . . . . . . . . . . . . . 51
3.9. Households' investment per chosen technology (in Euros) . . . . . . . . . . . 54
3.10. Average level for the TEC boards' value priority for the chosen technologies 56
3.11. Comparison of successful and unsuccessful neighbourhoods . . . . . . . . . 59

4.1. Experimental settings . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 73

5.1. Dimensions and indicators of energy security, adapted from [76] . . . . . . . 83
5.2. Indicators of energy security in the model . . . . . . . . . . . . . . . . . . . 86
5.3. General KPIs . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 97
5.4. Sensitivity analysis results . . . . . . . . . . . . . . . . . . . . . . . . . . . 98
5.5. Experimentation settings . . . . . . . . . . . . . . . . . . . . . . . . . . . . 99
5.6. General conditions of high and low energy security performances . . . . . . 102

A.1. Thermal energy community literature . . . . . . . . . . . . . . . . . . . . . 163
A.2. The list of dominating topics of 134 documents . . . . . . . . . . . . . . . . 172

B.1. Mean and standard deviation values for drivers used to model the values system of households in the model . . . . . . . . . . . . . . . . . . . . . . . 177
B.2. Percentage of the neighbourhood population that is initially related to each point in the scale for each value type . . . . . . . . . . . . . . . . . . . . . . 178
B.3. Example of initial SVO distribution for an average Dutch neighbourhood, given the model output . . . . . . . . . . . . . . . . . . . . . . . . . . . . 178
B.4. Example of initial SVO distribution for an average Dutch neighbourhood, given the model output . . . . . . . . . . . . . . . . . . . . . . . . . . . . 179
B.5. Other variables assigned to households in the model . . . . . . . . . . . . . 180
B.6. District heating systems . . . . . . . . . . . . . . . . . . . . . . . . . . . . 184

B.7. Collective bio-energy data . . . . . 184
B.8. Collective aqua-thermal energy storage (ATES) data . . . . . 184
B.9. Collective residual heat from surface water (TEA) data . . . . . 185
B.10. Collective heat pump data . . . . . 185
B.11. Individual heat pump systems . . . . . 186
B.12. Individual solar thermal systems . . . . . 186
B.13. Data on environmental attributes and other data . . . . . 187
B.14. Data input for subsidy coverage sub-criteria for each collective technology alternative . . . . . 188
B.15. Data input for land use sub-criteria for collective technology alternatives . . 188
B.16. Score given for level of social awareness to each heating technology . . . . . 189
B.17. Calculation of data input on each sub-criteria . . . . . 189
B.18. Results for normalisation of sub-criteria information for each collective technology alternative . . . . . 190
B.19. Results for normalisation of sub-criteria information for each collective technology alternative . . . . . 191

C.1. Assumptions and input data . . . . . 194
C.2. Parameters' ranges for the OFAT sensitivity analysis . . . . . 195
C.3. Sensitivity analysis results . . . . . 195

D.1. Assumptions related to the attributes of community . . . . . 197
D.2. Assumptions and input data for bioenergy . . . . . 198
D.3. Assumptions and input data for ATES . . . . . 198
D.4. Assumptions and input data for Electric boiler . . . . . 198
D.5. Assumptions and input data for Heatpump . . . . . 199
D.6. Assumptions and input data for Solar PVT . . . . . 199
D.7. Assumptions and input data for Woodpellet . . . . . 199
D.8. Distribution of energy labels in the Dutch context . . . . . 200
D.9. Other data . . . . . 200
D.10. Assumptions and input data . . . . . 202
D.11. Parameters' ranges for the OFAT sensitivity analysis . . . . . 203

# SUMMARY

One of the possible approaches to enlarge the share of renewable energy resources at the local level is the establishment of community initiatives for renewable energy technologies (RETs), namely energy communities. As an overarching term, ’energy community’ is a term that encapsulates all local joint efforts and collective action of individuals for renewable energy generation, distribution and consumption. The recent academic literature and real-world practices on energy communities are mainly dominated by studies on specific renewable electricity technologies, namely solar photovoltaic (solar PV) and wind turbines. However, the community energy literature largely neglected thermal energy, which covers 75% of non-transport energy consumption for applications such as space heating, cooling, bathing, and showering. Given this large share, establishing renewable thermal energy communities (TECs) could drastically impact the energy transition.

Renewable thermal energy technologies which can be used in a community setting (e.g. geothermal wells, heat pumps and bio boilers) are well developed. Yet, it is unclear whether these technologies and their applications would result in different institutional and behavioural dynamics in collective and community settings when compared with their electricity-driven counterparts. Neglecting the unique characteristics of thermal communities may result in energy supply shortages, institutional misalignment and conflict, high energy prices for community members, and low social participation. These issues undermine the energy security for the communities, which has also received minimal attention in the energy community literature. As one of the focal points in the energy-related literature and a concerning point for different actors of energy communities, the energy security of energy communities requires further investigation, given the collective action and decentralised nature of these local systems. In this line, this research aims **to support the design and implementation of energy-secure thermal energy communities by investigating their technical, behavioural and institutional settings through a collective action perspective.**

Different technical, behavioural and institutional settings, including the TEC initiatives’ characteristics as a collective energy system and the surrounding (exogenous) conditions that affect and shape the establishment and functioning of such initiatives, are investigated in this study. This study approaches TEC initiatives through the collective action perspective, using theoretical frameworks such as the Institutional Analysis and Development (IAD) framework, the institutional layers coined by Williamson and Social Value Orientation (SVO) theory as the theoretical basis. The study uses agent-based modelling and simulation (ABMS) and Dutch data to investigate the energy security of thermal energy communities through a collective action perspective. The following paragraphs summarise the main findings of this research.

### Technical, behavioural and institutional characteristics of thermal energy communities

A comprehensive literature review was conducted to outline the technical, behavioural and institutional TEC initiatives' characteristics and their surrounding conditions. According to the state-of-the-art literature, seven categories of characteristics are particularly associated with TEC initiatives. From a technical point of view, these were thermal energy resources (e.g. geothermal) and associated technologies (e.g. district heating and thermal insulation). Also, ambient temperature and indoor air quality were distinctive criteria when establishing TEC initiatives compared to electricity-driven communities. Typical behavioural and institutional characteristics were consumers' norms for final thermal application (e.g. heating and cooling), heat regulations and heat market analysis (e.g. natural gas price reforms, cost reduction by thermal insulation, and other thermal energy policies). Also, trade-offs between health issues and thermal applications (e.g. trade-off between indoor/ outdoor air pollution and using bio-energy heaters) were identified as influential in decision-making processes for establishing TEC initiatives. Finally, thermal performances and heat costs were the main criteria for evaluating the performance of TEC initiatives.

### Thermal energy communities' establishment and functioning processes

Using agent-based modelling, the impact of identified characteristics from the previous research step on the establishment and functioning of TEC initiatives is explored. The results demonstrate the considerable importance of behavioural and institutional settings on the establishment and functioning of TEC initiatives. Similar to electricity-driven communities, empowering the community-board as a project leader, allocating available subsidies based on the projects' degree of environmental friendliness, and including the environmental and social considerations along with economic concerns have a considerable positive impact on the establishment and functioning of TEC initiatives.

### Modelling the energy security of a collective energy system

An agent-based model is developed to explore the energy security of energy communities and simulate the collective decision-making processes of individual households. This model is the first of its kind to investigate and measure collective energy security by considering the heterogeneity of actors' motivations and the complexities of decision-making processes within a community energy system. The energy security dimensions considered in this modelling exercise are availability, affordability, accessibility and acceptability, referred to as the 4As. To explore the energy security of a collective energy system, four parameters are selected from the literature that are potentially influential for energy security, namely: natural gas prices, energy demand, investment size and willingness to compensate. The modelling results demonstrate that all energy communities have a high energy security performance overall. The results substantiated the potential of energy communities to reduce CO2 emissions while being affordable and accessible over a long time horizon. The amount of investment showed the most significant influence on the collective energy security of energy communities, while energy communities' performance did not show considerable sensitivity to changes in natural gas prices.

**Establishment and functioning of energy-secure thermal energy communities**

The findings from previous research steps are combined to investigate the energy security of TEC initiatives. An agent-based model capturing the technical, behavioural and institutional settings (including characteristics and surrounding conditions) of TEC initiatives is built to explore the energy security of such collective energy systems. This modelling exercise conceptualises energy security based on seven dimensions: energy availability, infrastructure, energy price, environment, societal effects, governance, and energy efficiency. The simulation results confirm that TEC initiatives can contribute to the energy security of individual households. Similar to the previous model that used a different definition of energy security and community energy system in general (rather than focusing particularly on TEC initiatives), the simulation results demonstrate the substantial potential of TEC initiatives in CO2 emissions reduction (60% on average) while being affordable in the long run. However, unlike the previous model results, project leadership (particularly municipality leadership), available subsidy and connection to a national natural gas grid are factors that substantially influence the energy security of TEC initiatives. Individual households' thermal energy demand reduction also positively impacted the establishment and functioning processes of energy-secure TEC initiatives.

**Conclusions and contributions**

This thesis aims to support the design and implementation of energy-secure thermal energy communities by investigating their technical, behavioural and institutional settings through a collective action perspective. The thesis concludes that energy-secure TEC initiatives are collective energy systems with particular characteristics and surrounding conditions. Considering insights from all research questions, the thesis demonstrated that behavioural and institutional settings (e.g. role of the leadership, environmentally friendly behaviour and subsidy allocation strategies) are relatively more influential than technical settings (e.g. available renewable thermal technologies and resources) for establishing and sustained functioning of energy-secure collective thermal energy systems. Particular RETs combinations, namely aquifer thermal energy storage with heat pumps, showed a positive impact on TEC initiatives' energy security. The most crucial technical requirement, as might be anticipated for the energy security of TEC initiatives, is a connection to a natural gas grid. Reducing the individual households' thermal demand also positively influences TEC initiatives' energy security. The thesis recommends that individual households initiate their own (thermal) energy communities, and policy-makers support such initiatives.

# SAMENVATTING

Een van manieren om het aandeel hernieuwbare energiebronnen op lokaal niveau te vergroten is het oprichten van duurzame energiecoöperaties. De term "energiecoöperatie" betreft alle lokale gezamenlijke inspanningen en collectieve acties van individuen voor de opwekking, distributie en het gebruik van hernieuwbare energie. De recente academische literatuur over en de praktijk van energiecoöperaties worden hoofdzakelijk gedomineerd door hernieuwbare elektriciteits technologieën, namelijk fotovoltaïsche zonne-energie (PV) en windturbines. In de literatuur over energie in coöperaties wordt echter nauwelijks aandacht besteed aan thermische energie, die 75% van het niet transportgebonden energieverbruik uitmaakt voor toepassingen als ruimteverwarming, koeling, baden en douchen. Gezien dit grote aandeel zou de oprichting van hernieuwbare thermische energiecoöperaties (Thermal Energy Communities, TECs) een drastische impact kunnen hebben op de energietransitie.

Hernieuwbare thermische energietechnologieën die in een coöperatie kunnen worden gebruikt (b.v. geothermische bronnen, warmtepompen en biobrandstofketels) zijn goed ontwikkeld. Toch is het onduidelijk of deze technologieën en hun toepassingen leiden tot een andere institutionele en gedragsdynamiek in coöperaties in vergelijking met hun door elektriciteit aangedreven tegenhangers. Het verwaarlozen van de unieke kenmerken van thermische coöperaties kan leiden tot tekorten in de energievoorziening, institutionele scheefgroei en conflicten, hoge energieprijzen voor de leden van de coöperatie, en geringe sociale participatie. Deze kwesties ondermijnen de energiezekerheid voor de coöperaties, die ook in de literatuur over energiecoöperaties minimale aandacht heeft gekregen. Energiezekerheid is tot nu toe vooral bestudeerd voor gecentraliseerde systemen, en de energiezekerheid van energiecoöperaties vraagt verder onderzoek, gezien de gedecentraliseerde aard van deze lokale systemen. In deze lijn beoogt **dit onderzoek het ontwerp en de implementatie van energiezekere thermische energiecoöperaties te ondersteunen door hun technische, gedragsmatige en institutionele settings te onderzoeken vanuit een collectief actieperspectief.**

Verschillende technische, gedragsmatige en institutionele kenmerken, met inbegrip van de kenmerken van de TEC-initiatieven als een collectief energiesysteem en de omringende (exogene) omstandigheden die de oprichting en het functioneren van dergelijke initiatieven beïnvloeden en vormgeven, worden in deze studie onderzocht. Deze studie benadert TEC-initiatieven vanuit het perspectief van collectieve actie, waarbij theoretische kaders zoals het 'Institutional Analysis and Development (IAD)' raamwerk van Ostrom, het institutionele-lagen-model van Williamson en 'Social Value Orientation (SVO)' theorie als theoretische basis worden gebruikt. De studie maakt gebruik van agent-based modelling en simulatie (ABMS) en van Nederlandse data. De volgende paragrafen vatten de belangrijkste bevindingen van dit onderzoek samen.

### Technische, gedragsmatige en institutionele kenmerken van thermische energiecoöperaties

Er is een uitvoerig literatuuronderzoek verricht om de technische, gedragsmatige en institutionele kenmerken van TEC-initiatieven en hun randvoorwaarden in kaart te brengen. Volgens de meest recente literatuur kunnen hierin zeven categorieën worden onderscheiden die in het bijzonder met TEC-initiatieven worden geassocieerd. Vanuit technisch oogpunt waren dit thermische energiebronnen (b.v. geothermische energie) en bijbehorende technologieën (b.v. stadsverwarming en thermische isolatie). Ook de omgevingstemperatuur en de kwaliteit van de binnenlucht waren onderscheidende kenmerken bij het opzetten van TEC-initiatieven in vergelijking met coöperaties die werken op elektriciteit. Typische gedrags- en institutionele kenmerken waren de normen van de consument voor de uiteindelijke thermische toepassing (b.v. verwarming en koeling), de warmteregelgeving en de warmtemarkt (b.v. hervormingen van de aardgasprijs, kostenvermindering door thermische isolatie, en ander beleid inzake thermische energie). Ook de afweging tussen gezondheidskwesties en thermische toepassingen (bv. afweging tussen luchtvervuiling binnenshuis/buitenshuis en gebruik van bio-energieketels) werd als invloedrijk aangemerkt in besluitvormingsprocessen voor het opzetten van TEC-initiatieven. Ten slotte waren thermische prestaties en warmtekosten de belangrijkste criteria voor de evaluatie van de prestaties van TEC-initiatieven.

### Oprichting en werking van thermische energiecoöperaties

Aan de hand van ‘agent-based modeling’ wordt nagegaan welk effect de in de vorige onderzoeksfase vastgestelde kenmerken hebben op de totstandkoming en het functioneren van TEC-initiatieven. De resultaten tonen het aanzienlijke belang aan van gedragsmatige en institutionele kenmerken op de totstandkoming en werking van TEC-initiatieven. Net als bij elektriciteitscoöperaties hebben het versterken van het coöperatiesbestuur als projectleider, het toekennen van beschikbare subsidies op basis van de mate van milieuvriendelijkheid van de projecten, en het opnemen van milieu- en sociale overwegingen naast economische overwegingen een aanzienlijk positief effect op de totstandkoming en het functioneren van TEC-initiatieven.

### Modellering van de energiezekerheid van een collectief energiesysteem

Er is een agent-based model ontwikkeld om de energiezekerheid van energiecoöperaties te onderzoeken en de collectieve besluitvormingsprocessen van individuele huishoudens te simuleren. Dit model is het eerste in zijn soort dat collectieve energiezekerheid kan onderzoeken en meten waarbij rekening wordt gehouden met de heterogeniteit van de motivaties van de actoren en de complexiteit van de besluitvormingsprocessen binnen een coöperatie. De energiezekerheids¬dimensies die in deze modellering aan bod komen zijn beschikbaarheid, betaalbaarheid, toegankelijkheid en aanvaardbaarheid, ook wel de 4A’s genoemd. Om de energiezekerheid van een collectief energiesysteem te onderzoeken, werden uit de literatuur vier parameters geselecteerd die potentieel van invloed zijn op de energiezekerheid, namelijk: aardgasprijzen, energievraag, investeringsomvang en bereidheid tot compensatie. De modelresultaten tonen aan dat alle energiecoöperaties over het algemeen een hoge energiezekerheid hebben. De resultaten staven het potentieel van energiecoöperaties om de CO2-uitstoot te verminderen en tegelijk betaalbaar en toegankelijk te zijn over een lange tijdshorizon. De omvang van de investeringen bleek de grootste invloed te hebben op de collectieve energiezekerheid van energiecoöperaties, terwijl de prestaties van energiecoöperaties niet erg gevoelig bleken voor veranderingen in de aardgasprijzen.

**Oprichting en werking van energiezekere coöperaties voor thermische energie**

De bevindingen van de vorige onderzoeksstappen werden gecombineerd om de energiezekerheid van TEC-initiatieven te onderzoeken. Met behulp van een agent-based model dat de technische, gedragsmatige en institutionele kenmerken (inclusief omgevingsfactoren) van TEC-initiatieven simuleert, werd de energiezekerheid van dergelijke collectieve energiesystemen onderzocht. In deze modelleringsexercitie werd energiezekerheid geconceptualiseerd op basis van zeven dimensies: beschikbaarheid van energie, infrastructuur, energieprijs, milieu, maatschappelijke effecten, governance en energie-efficiëntie. De simulatieresultaten bevestigen dat TEC-initiatieven kunnen bijdragen tot de energiezekerheid van individuele huishoudens. Vergelijkbaar met het vorige model, dat een andere definitie van energiezekerheid en het energiesysteem van de coöperatie hanteerde (in plaats van specifiek te focussen op TEC-initiatieven), tonen de simulatieresultaten het substantiële potentieel van TEC-initiatieven aan voor de vermindering van de CO2-uitstoot (gemiddeld 60%), terwijl ze op lange termijn betaalbaar zijn. In tegenstelling tot de vorige modelresultaten zijn projectleiderschap (met name leiderschap van de gemeente), beschikbare subsidie en aansluiting op een nationaal aardgasnet factoren die de energiezekerheid van TEC-initiatieven aanzienlijk beïnvloeden. De vermindering van de vraag naar thermische energie van individuele huishoudens had ook een positieve invloed op de totstandkoming en het functioneren van energiezekere TEC-initiatieven.

**Conclusies en bijdragen**

Deze dissertatie beoogt het ontwerp en de implementatie van energiezekere thermische energiecoöperaties te ondersteunen door hun technische, gedragsmatige en institutionele kenmerken te onderzoeken vanuit een collectief handelingsperspectief. De dissertatie concludeert dat energiezekere TEC-initiatieven collectieve energiesystemen zijn met bijzondere kenmerken en omgevingscondities. Rekening houdend met de inzichten uit alle onderzoeksvragen, toonde het proefschrift aan dat gedragsmatige en institutionele kenmerken (bijv. de rol van het leiderschap, milieuvriendelijk gedrag en subsidietoewijzingsstrategieën) relatief meer invloed hebben dan technische kenmerken (bijv. beschikbare hernieuwbare thermische technologieën en hulpbronnen) voor het opzetten en duurzaam functioneren van energiezekere collectieve thermische energiesystemen. Bepaalde combinaties van duurzame energietechnologieën, namelijk opslag van aquifer thermische energie met warmtepompen, bleken een positief effect te hebben op de energiezekerheid van TEC-initiatieven. De meest cruciale technische vereiste is een aansluiting op een aardgasnet. Het terugdringen van de warmtevraag van individuele huishoudens heeft ook een positieve invloed op de energiezekerheid van TEC-initiatieven. De dissertatie beveelt aan dat individuele huishoudens hun eigen (thermische) energiecoöperaties initiëren, en dat beleidsmakers dergelijke initiatieven ondersteunen.

# 1

# INTRODUCTION

## 1.1. LOCAL THERMAL ENERGY TRANSITION

Today, the energy transition is one of the main challenges for the energy sector worldwide [1]. The energy transition's main goal is to reduce greenhouse gas (GHG) emissions [2]. The deployment and installation of renewable energy technologies (RETs), such as solar panels, geothermal wells and wind turbines, could facilitate and lead to achieving the energy transition goals [2]. In order to drive the energy transition and specifically to support the deployment of RETs, various plans and actions have been executed on different scales: international (e.g. Paris climate agreement), transitional (e.g. European Commission targets on renewable energy consumption), national (e.g. Dutch renewable energy policies) and at the local level [3]. Community initiatives for RETs, or energy communities, are considered key elements of the energy transition at the local level [4].

An 'energy community' is an overarching term used to represent initiatives that aim to generate, distribute and consume renewable energy collectively for locally involved participants [5]. Although there are various definitions for energy communities in the literature (e.g. the ones presented in [6], [7], [8], [9], [10], [11], [12]), in a broad sense, energy communities are defined as a group of individual local actors in a neighbourhood, who invest in RETs jointly and consume the energy they generate [1] (with energy-saving measures) [13], and/or sell excess energy to stakeholders outside the community. Such collective energy systems are gaining momentum [14], and the number of established energy communities is increasing [15], [16]. The main reasons for this momentum of energy communities are:

- (Inter)national targets and incentives to increase the share of renewable energy generation and consumption [3], specifically for the built environment and among individual households [17];
- improvements in the technical and institutional system design of decentralized renewable energy systems [18] (mainly due to developments in decentralized renewable energy systems [19], [20]);

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[1] Energy generation and energy production are used as synonyms in the literature and they refer to processes related to transformation of different energy forms to each other (e.g. heat and electricity).

- recognizing the importance of stakeholder participation in the decision-making processes (mainly due to new governance arrangements for decentralized renewable energy systems) [21];

- attempts of different stakeholders to preserve energy in the residential area [22], especially policy-makers and individual households [11] (due to different reasons such as the energy crisis in the 1970s [23], [24]).

The number of energy communities is increasing, and the majority of the established energy communities use renewable *electricity* technologies (e.g. solar photovoltaic and wind power) [15]. This is also reflected in the academic literature, as recent literature on the establishment and governance of community energy systems is dominated by studies on specific renewable electricity technologies, namely solar photovoltaic (solar PV) and wind turbines (e.g. [11], [25], [26]). However, thermal energy systems, which are used for heating, cooling, bathing, and showering [27], are understudied within the energy communities context [28], [29], [30]. This knowledge gap contrasts with the importance of thermal energy at the community level, as heat and cold cover approximately 75% of households' non-transport related energy consumption [31], [32]. This contrast is problematic, as to foster local energy transition and reduce $CO_2$ emission, it is essential also to include energy communities for thermal energy applications [33], [34].

To facilitate the establishment of thermal energy communities (TEC), some lessons can be learned from the energy community literature as a whole. However, due to some unique characteristics of TEC initiatives as compared to electricity initiatives, such as higher energy demand (approximately 75%) [31], [32], different consumption patterns (e.g. due to building occupation and seasonal changes) [31], [32], and more considerable required investment (e.g. investment on collective district heating) [35], [36], and considering their technological differences (e.g. geothermal, bioenergy, heat pump and solar thermal) [27], there is a need to study TEC initiatives, in detail. Zooming into the scarce literature body on TEC initiatives reveals that this literature is dominated by studies that focus on technological aspects (e.g. [32], [37], [38], [39]). However, according to [30] and [40], this is problematic because the adoption of local heating renewable energy systems is challenged by the current institutional context, stakeholder interactions, and behavioural attitudes. These barriers are not only blocking the establishment of TEC initiatives processes but are also potentially undermining their energy security, which is a crucial consideration for energy communities, like any other energy system [41], [42]. In the broader context of the (thermal) energy transition, in which (thermal) energy communities are seen as key local components, energy security is also a crucial consideration [43], [44].

Energy security (loosely defined in this introduction as uninterrupted access to affordable and acceptable energy), is a very fundamental issue as it is one of the main concerns of participants in any kind of energy community, including TEC initiatives [45], [46]. In this line, studies such as [47] and [48] argued that energy security concerns become more crucial in the context of energy communities, as such decentralised energy systems are based on individuals' collective action for energy generation and distribution based on RETs. Thus, the behaviour and institutional settings become more influential for the energy security of energy communities. Therefore, to understand and facilitate the establishment of energy-secure TEC initiatives, these community energy systems and their technical and institutional conditions need to be studied, as the further establishment of TEC initiatives would contribute to the energy transition as a whole.

## 1.2. ENERGY SECURITY OF THERMAL ENERGY COMMUNITIES

In the energy community literature, various topics such as technological design (e.g. [32], [49], [50], [51], [52]), integration of technologies (e.g. [20], [53], [54]), social acceptance (e.g. [18], [21], [26], [29], [55]), willingness to participate (e.g. [56], [57], [58]), and institutional design (e.g.[4], [59]), are explored. Nevertheless, discussions around energy security and how to study and measure the energy security of energy communities are very limited.

As one of the focal points in the energy-related literature, energy security is a complex concept [60]. Different disciplines such as economics, engineering and public policy contribute to the literature and the definition of energy security [61], [62]. There are more than 45 definitions for energy security. For instance, one of the most used definitions, the Asia Pacific Energy Research Center (APERC) definition is: “The ability of an economy to guarantee the availability of energy resource supply in a sustainable and timely manner with the energy price being at a level that will not adversely affect the economic performance of the economy” [63].This definition and other ones in the literature (e.g. the definitions presented in [64], [65], [66], [67]), availability [68], affordability [69], and sustainability [70], to define and assess energy security.

However, these definitions, mainly focus on conventional energy systems, namely centralized, fossil-fuel-based and (inter)national energy systems [60], [64]. In this vast body of literature, there are only a few studies (e.g. [71], [72], [73]) with a focus on the energy security of energy communities. These studies mainly take into account the traditional notion of security of supply to study energy security (e.g. [74], [75]). Nonetheless, as mentioned earlier in this chapter, this is different from the current energy security literature, which has shifted and has adopted a more comprehensive approach and has included more diverse dimensions, such as efficiency [76], acceptability [69], and affordability [77].

The traditional notion of security of supply is useful for studying conventional energy systems; however, it is not capable of capturing the key characteristics of energy communities, such as decentralized renewable energy generation [12], a collective action approach [12], [13], participatory decision-making processes and financial distribution [14]. More specifically, energy may not be available in the community at all times, especially when the system is not connected to the national grid [73], and energy may not be accessible at all times, given the intermittent nature of renewable energy systems [74]. Community energy may not be affordable for everyone given the upfront investment costs, among other factors [14]. At the same time, the energy efficiency and environmental-friendliness of energy communities are also other challenges in this context [78]. There are few studies (e.g. [79], [80], [81]) that considered such topics to study energy security of energy communities; however, they analyse these topics in isolation rather than in integration and combination with each other.

To summarize, the literature does not provide any particular definition or approach to studying and investigating the energy security of collective energy systems, such as TEC initiatives. Also, the technical, institutional and behavioural settings that influence the establishment and functioning of TEC initiatives are not very well understood. In this line, understanding such settings, along with studying the dynamics, decision-making processes, and trade-offs related to energy security, is essential for (thermal) energy communities. As the establishment and functioning of energy-secure TEC initiatives lead to enlarging the share of renewable energy and fostering the energy transition as a whole, it is essential to bridge these knowledge gaps. Especially considering the noticeable thermal energy demand at the community level, energy security concerns are becoming more critical in the TEC initiatives context [65].

## 1.3. RESEARCH OBJECTIVE

The current literature on community energy systems does not focus on thermal energy applications (i.e. TEC initiatives) nor on the energy security of such collective energy systems. To overcome these gaps, as explained in Section 1.1 and Section 1.2, the objective of the research is *to support the design and implementation of energy-secure thermal energy communities by investigating their technical, behavioural and institutional settings through the collective action perspective.*

Given the decentralized nature of these systems, a collective action perspective provides an opportunity to look at energy-secure TEC initiatives from behavioural and institutional angles and allows one to pay attention to how members arrange and manage these decentralized systems [82]. Therefore, this research investigates different technical, behavioural and institutional settings related to energy-secure TEC initiatives to facilitate their establishment and functioning. This research entails integrating insights from two separate scientific fields: community energy systems and energy security.

To fulfil this objective, several research gaps will be addressed. First, TEC initiatives as the underlying collective energy system will be studied. This step includes identifying and conceptualising TEC initiatives' technical, behavioural, and institutional settings. Second, methods and approaches will be deployed to study and investigate these settings and their influence on TEC initiatives' establishment and functioning processes. Lastly, the study will study and propose an approach to explore and measure the energy security of collective energy systems and then apply such an approach to TEC initiatives' context. This step entails capturing the collective decision-making processes and investigating the influence of technical, institutional and behavioural settings on the establishment and functioning of energy-secure TEC initiatives.

## 1.4. RESEARCH QUESTIONS

In order to investigate and achieve the goal of this research, different technical, behavioural and institutional settings and their influence on the establishment and functioning of energy-secure TEC initiatives will be investigated. These technical, behavioural and institutional settings include the characteristics of the TEC initiatives as a collective energy system and the surrounding (exogenous) conditions that affect and shape the establishment and functioning of such energy-secure TEC initiatives.

The following research questions are formulated:

*Research question 1: What technical, behavioural and institutional characteristics set thermal energy communities apart from electricity-driven communities?* Although thermal energy community is a type of energy community, its differences from electricity-driven communities are not clear yet. Therefore, an overarching view of the particular characteristics of TEC initiatives and their surrounding (exogenous) conditions is essential to address the main research objective. Answering this research question helps to identify and understand the technical, institutional and behavioural settings that could potentially influence thermal energy communities' establishment and functioning processes, which may have been missed in the general literature on energy communities. Desk research and a comprehensive literature review are conducted to answer this research question.

*Research question 2: How and to what extent do the identified technical, behavioural and institutional characteristics affect thermal energy communities' establishment and functioning processes?* After identifying the technical, behavioural, and institutional characteristics of TEC initiatives and their surrounding conditions in the previous research stage, the impact of such settings on TEC initiatives' establishment and functioning processes are needed to be investigated. Therefore, various complex technical, behavioural and institutional settings need to be studied over time. Since the real-world data is limited, simulation modelling, such as agent-based modelling, is used in this step (see Section 1.5).

*Research question 3: How can energy security of a collective energy system be modelled?* There are various optimization models for the energy supply security of energy communities. However, no model captures the multi-dimensional nature of energy security and the collective action towards the collective energy security of an energy system. As collective energy systems are based on the collective actions of individuals with different motivations and values, it is meaningful to investigate collective energy security. This approach is also in line with energy security literature, where energy security concepts are included in dimensions such as acceptability, affordability and availability. In order to capture such collective action in energy systems and study their energy security over time, simulation modelling, such as agent-based modelling, was used.

*Research question 4: How do technical, behavioural and institutional settings affect the establishment and functioning of energy-secure thermal energy communities?* After capturing the energy security of an energy community in a model, the concept of energy security can be expanded into a model of thermal energy communities. For thermal energy communities, collective energy security could be a potential consideration to assess their overall performance. The prevailing energy security concept should be expanded and include other dimensions of energy security, such as governance, energy efficiency and social effects. Therefore, by simulation approaches such as agent-based modelling, the energy security of thermal energy communities is investigated. Figure 1.1 illustrates the relationships between the research sub-questions.

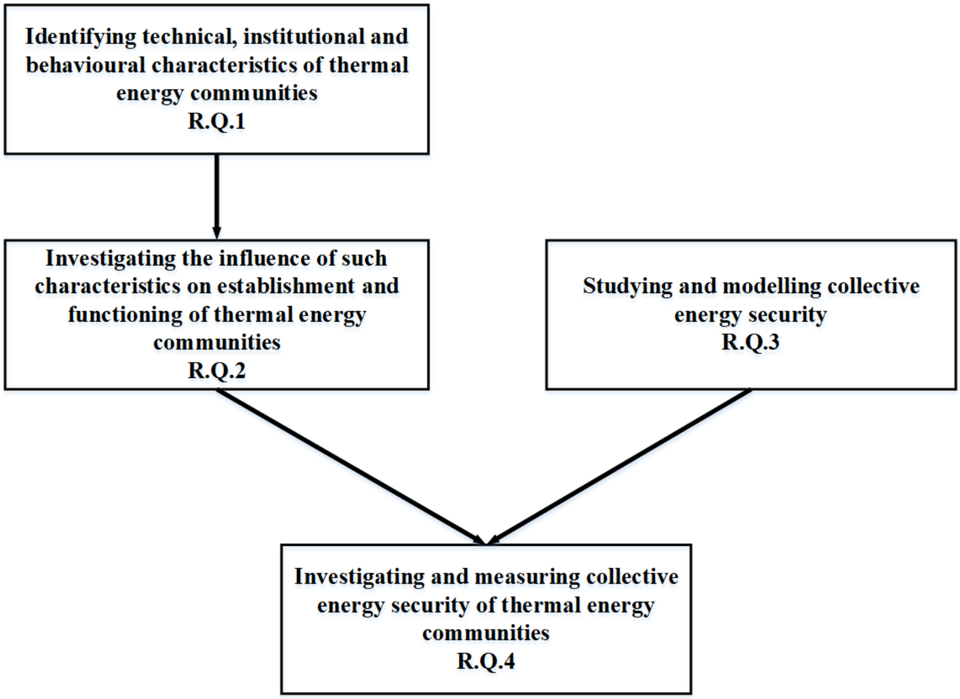

Figure 1.1.: Relationship of research questions

## 1.5. RESEARCH APPROACH

To capture the complexities of energy-secure thermal energy communities, they have been approached by agent-based modelling and simulation (ABMS). In order to have a conceptually rich representation of social structures and other components and methodologically analytical ABMS, institutional analysis is used as the theoretical backbone of this research.

### 1.5.1. ABMS AS THE COMPUTER SIMULATION APPROACH

Computational social simulation is a well-established field of research at the crossroads between technical design, social sciences, computer sciences, and mathematics [83], [84]. As performing real-world experiments would be time-consuming and costly, computer simulation is often used to conduct experiments in a virtual simulation environment [85], [86]. ABMS is specifically promising for this research as it facilitates the exploration of artificial societies of autonomous agents as representatives of the real-world [87], [88].

Like other modelling practices, ABMS represents a simplified version of reality [88]. In an ABMS, “An agent is the software representation of some entity that completes an action or takes a decision, by which it effectively interacts with its environment” [89]. Agents are heterogeneous, autonomous and individual decision-making entities (such as individual households) that can learn and interact with each other and their environment [87], [90]. In addition, to studying and capturing the behavioural choices of individuals, using ABMS also provides the opportunity to explore the emergent behaviour of the system [91]. Emergence relates to the idea of “the behaviour of the system”, which results from individual actors’ behaviour on lower levels and their interactions [91]. Institutional changes and policy interventions can also be analysed in ABMS by comparing different scenarios [30], [88]. This would help study different system levels’ complexities (e.g. macro-level and meso-level). Moreover, ABMS provides the ability to add the temporal scale, which allows for examining different scenarios throughout time [88], [91].

For these reasons, ABMS is considered a suitable approach for studying the dynamics and interactions within energy-secure renewable thermal energy communities. Given the bottom-up nature of (thermal) energy communities and the importance of individual characteristics, decision-making processes and interactions for measuring energy security of such collective energy systems, we use ABMS instead of other simulation approaches such as Equilibrium Modelling [92], System Dynamics [93], and Discrete Event Simulations [94]. Different studies argue for and use ABMS for studying different topics in the energy transition’s context, although considering the complexity of the real world, an ABMS cannot represent all the details of real-world decision-making processes. Studying value conflicts for acceptance of decentralized energy systems [95], simulating behavioural attitudes [96], and leadership in the energy communities [97], studying local heating systems [30], [98], indoor heating and cooling and built environment systems [99], [100], [101], modelling and simulating zero energy communities [102], [103], and studying renewable energy technology adoption [104], [105], renewable energy market design and price reforms [106], [107], are examples of these studies.

Besides computer simulation methods, approaches such as questionnaires, interviews, focus groups, and serious gaming were also possible as research approaches. However, using such methods relies heavily on high numbers of participants, and due to the slow thermal energy transition, there are not many experts with knowledge on both thermal energy transition (and TEC initiatives particularly) and energy security who are willing to participate in these methods. Furthermore, TEC initiatives are relatively new systems, and the real-world data lack their establishment and functioning processes. As only a few TEC initiatives were recently established, their data is insufficient to explore many technical, institutional, and behavioural characteristics over a more extended period.

### 1.5.2. INSTITUTIONAL ANALYSIS FOR STUDYING COLLECTIVE SOCIO-TECHNICAL ENERGY SYSTEMS

In social systems, institutions are human-constructed rules which shape social, political and economic interactions [108], or, more loosely, rules that govern the system [4], [109]. Institutions can be divided into two main categories: formal and informal institutions which together lead to the system’s governance [108]. Institutional analysis is commonly used to study socio-technical systems (e.g. [108], [110], [111]). Specifically in the context of energy communities, topics related to formal rules such as energy policies (e.g. [14], [112]), regulatory design (e.g. [4], [113], [114]), incentive mechanisms (e.g. [10], [8], [115]), pricing strategies (e.g. [98], [116], [117]), stakeholders’ behaviour and their indications (e.g. [85], [113], [118], [119]), are studied.

Among various frameworks (as are elaborated in studies such as [108], [120], [121], [122], [123]), the institutional analysis and development framework (the IAD framework) by Nobel Laureate Elinor Ostrom [110] describes various components of a socio-technical system and explains how they are related to institutions [124]. Even though the IAD framework has conventionally been applied for the study of traditional common pool resource management, such as irrigation and fishery, it has lately been extensively applied to energy systems (e.g. [125], [126]) and especially energy communities (e.g. [127], [128]). Therefore, the IAD framework aligns with our research objective and is an appropriate starting point to study thermal energy communities as a collective socio-technical system.

#### THEORETICAL BACKBONE OF SYSTEM DESCRIPTION FOR ABMS

Institutional analysis, particularly the IAD framework, is used as a theoretical backbone of the system description for our ABMS. Besides its analytical power for studying energy communities from a collective action perspective, the IAD has also been proven useful for building agent-based models [129], [130], as it can provide an opportunity (i) to explore the influence of institutions on enabling or restricting agents behaviours [88], [108], (ii) and to develop more tangible and structured assumptions about agent decision making processes and behaviour [88], [131]. Table 1.1 summarizes the overview of research questions and their related research methods.

Table 1.1.: Research questions and their methods

| Research questions | Research questions' objective | Research methods |
|---|---|---|
| R.Q.1 | Identifying technical, institutional and behavioural characteristics of TEC initiatives | Literature review and analysis |
| R.Q.2 | Investigating the influence of technical, institutional and behavioural characteristics on TEC initiatives establishment | ABMS and institutional analysis |
| R.Q.3 | Capturing and modelling collective energy security | ABMS |
| R.Q.4 | Investigating and measuring collective energy security of TEC initiatives | ABMS and institutional analysis |

### 1.5.3. THE NETHERLANDS AS A RESEARCH CONTEXT

In order to parameterize the ABMS, delineate reliable results and derive practical recommendations, we focus on the Netherlands. The country-level analysis is chosen because (i) the characteristics of energy systems differ per country, (ii) national statistical data are readily available, and (iii) it allows the study of institutions (both formal and informal rules) and behavioural attributes which are typically defined at a national level. For the thermal energy transition studied in this study, The Netherlands was selected because of the following reasons: the

- presence of a high number of energy communities as compared to other EU countries [11];
- presence of well-developed energy and specifically heating infrastructure [132];
- Dutch national ambitious $CO_2$ reduction targets which influence the heating sector [133];
- national norms for environmental concerns and sustainable development [134], [135];
- the sense of urgency for the heat energy transition due to natural gas-induced earthquakes [136].

In addition, energy security is an essential topic in the Dutch energy policy debates [24], [137]. Historically, the Netherlands has a strong performance in energy supply security [70], resulting from the Groningen natural gas field. However, as energy security has adopted more diverse dimensions, various studies have evaluated Dutch energy security differently (e.g. [24], [67], [70]). Furthermore, particularly in the thermal energy context, topics such as gas quakes [138], the geopolitics of natural gas imports/ exports [139], and energy prices [117], [140], contribute to the importance of energy security within the Dutch thermal energy context. The needed data on available renewable technologies, policy mechanisms and energy demand is collected through desk research (e.g. [141]) and Dutch national data sources such as Statistics Netherlands (CBS), and Netherlands Environmental Assessment Agency (PBL), "Stimuleringsregeling Duurzame Energie" (SDE++). The data from a survey among 599 Dutch citizens about their motivations for joining an energy community (i.e. [58]) is also used. In each chapter, the details of the data used are presented. The generalisability of the final results is discussed in Chapter 6.

## 1.6. AUDIENCE

This study addresses audiences in academia, practitioners and individual households. Firstly, in academia, this study offers insights for researchers that study the heat/thermal energy transition, particularly academics focusing on TEC initiatives, institutional design, collective action, technical, behavioural and institutional characteristics. Furthermore, academics with interest in energy security, particularly those interested in bottom-up and collective energy security, would also benefit from the findings of this research. Social simulation researchers, mainly agent-based modellers and institutional modellers, would also potentially draw valuable insights from this work, as it offers new conceptualizations and applications for such approaches.

The outcomes of this research can be beneficial for practitioners in the energy transition, specifically for policy-makers, municipalities and energy consultants. The results can assist them on subjects related to the institutional design of energy-secured TEC initiatives and the facilitation of their establishment process. These practitioners can gain insights into the impacts of various related institutions, behavioural attitudes and technological choices on the establishment process of energy-secured TEC initiatives. Finally, as the core participants in a (thermal) energy community, individual households and energy community's boards can benefit from this research. Individual households who need to act collectively for generating, distributing, and consuming renewable thermal energy can gain insights into different technical, behavioural and institutional conditions to coordinate themselves and establish their TEC initiatives more smoothly.

## 1.7. THESIS OUTLINE

Chapter 2 provides an overview of the thermal energy community concept. Also, it structures and dives into particular characteristics of TEC initiatives through literature analysis. Based on the results of the literature analysis, an ABMS model is developed to study these technical and institutional characteristics, which is presented in Chapter 3. Chapter 4 is dedicated to exploring and proposing an approach to model collective energy security of energy communities through an ABMS modelling process. Chapter 5 discusses an ABMS model for measuring and investigating the collective energy security of TEC initiatives. Answers to this study's research questions, reflections, conclusions, and contributions are presented in Chapter 6.

# 2

# THERMAL ENERGY COMMUNITIES

Energy communities are decentralized socio-technical systems where energy is jointly generated and distributed among a community of households locally. As the energy that is shared among the community is commonly electricity, the energy community's literature is dominated by electricity-systems and mostly neglects collective thermal energy as an alternative energy carrier for heating and cooling. The aim of this chapter is to organise the existing research on "community-based initiatives for heating and cooling" by using the Institutional Analysis and Development (IAD) framework, and based on this analysis, identify a future research agenda. The analysis reveals that the number of publications in this area has been growing fast recently, focusing on technological challenges. Fewer papers take an institutional point of view, in which they cover policies, price reforms and values. The institutionally oriented papers focus on solar thermal energy and bio-based thermal energy. Other thermal technologies, such as geothermal wells, are largely neglected in the literature, but are known to have different institutional constraints. Informal rules and values are mainly researched from a consumer perspective. Since energy communities often consist of consumers and prosumers, additional research is warranted into this area. Evaluative criteria for such communities are limited to economic aspects and greenhouse gas emissions, while indicators such as soil-pollution and spatial planning that may play an equally important role are neglected. The chapter explores the need for studying thermal energy communities as distinctive entities with their own unique characteristics, and it develops a research agenda for this purpose. [1]

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[1] This chapter has been published as J. Fouladvand, A. Ghorbani, N. Mouter, and P. Herder, "Analysing community-based initiatives for heating and cooling: A systematic and critical review," Energy Res. Soc. Sci., vol. 88, p. 102507, 2022. It has been slightly modified textually for alignment in this study. The first author has conceptualised and performed the research. The other authors have performed an advisory role.

## 2.1. INTRODUCTION

The effects of the global temperature rise on human and natural systems, such as the sea-level rise and the increase of the intensity and frequency of extreme weather events like droughts and floods, are well recognised [142]. According to the IPCC report, "worldwide, numerous ecosystems are at risk of severe impacts" [143]. Greenhouse gases (GHG) mitigation is essential in order to limit the consequences of these impacts [133], and special attention is being placed on transition in the energy sector since it is one of the main sources of GHG emissions worldwide [28]. The energy transition is executed at different scales: international, national, regional and local [144]. Energy communities (interchangeably also used as community energy systems (CES) in the literature) are considered key elements of the energy transition at the local level as they aim to locally generate and distribute renewable energy resources in order to meet the demands of local stakeholders [145].

Although there are many different definitions for CES in the literature (e.g. [5], [7], [9], [10], [11], [146], [147],[148]), in a broad sense, CES are defined as a community of actors in a local area, with renewable energy technologies that they have jointly invested on to generate, consume and/or sell renewable energy [13]. CES promote collective citizen action to address various aspects of the transition to a low carbon energy sector [12].

CES can be based on the generation of renewable electricity (e.g. [15], [149]), the generation of renewable heat (e.g.[27], [30]) or on a combination of the two energy carriers (e.g. [150], [151], [152]). However, the literature on CES does not address how differences in the energy carrier and the technologies that accompany them impact the social, institutional, and economic attributes of such collective energy communities. As electricity-generating communities seem to be currently mainstream in many countries (e.g. [146], [15], [149], [153]), this leads to more publications of often case-driven research. Despite the importance of heating and cooling [33], which covers approximately 75% of the non-transport related energy consumption among households [31], [32], community-based initiatives for heating and cooling, namely thermal energy communities (TEC), have received less attention in the literature.

In TECs, households collectively invest in renewable thermal energy systems (e.g. solar thermal, geothermal, bio-energy or heat pumps) to jointly generate and consume thermal energy [27]. Many of these thermal technologies are quite mature but are different from electricity-generating technologies [39], which leads to differences in the distribution and storage infrastructure (e.g. district heating instead of micro-grids [154], [155], and thermal storage systems instead of electrical batteries), consumption patterns [31], [39], initial investment costs [35], behavioural characteristics and collective arrangements [36], [156], among many other differences. For example, indoor air quality [157], and thermal comfort level [158], [159], along with specific biophysical characteristics of the community (e.g. ambient temperature, geographical place, level of urbanization, building characteristics and insulation) [158], [113], are issues unique to TEC initiative.

Our goal in this chapter is to outline the existing research on TEC initiatives in order to identify distinctive features of TEC initiatives that distinguish them from their electricity-generating counterparts, and propose areas for further research that require specific attention for this type of energy community. We do this by reviewing the existing body of literature on TEC initiatives. TEC initiatives can theoretically be seen as a form of collective action where actors join efforts to achieve shared goals on a common-pool resource dilemma [160]. Therefore, to provide a theoretical basis to analyse the existing literature and to be able to identify aspects that have not yet been addressed systematically, we use the Institutional Analysis and Development (IAD) framework of Ostrom [108]. The IAD framework is specifically designed for collective action problems [108] and has already been applied to study CES (e.g. [126], [161]). It has proven to be highly instrumental in this domain in particular because it explicitly addresses the formal and informal institutional challenges for such collective initiatives [162].

The structure of the chapter is as follow. The next section presents the theoretical background. Section 2.3 presents the methods that were used in this research. Section 2.4 discusses the literature. The literature analysis using the IAD framework is presented in Section 2.5. Further analysis and discussions are elaborated in Section 2.6. Finally, conclusions and research agenda are presented in Section 2.7.

## 2.2. THEORETICAL BACKGROUND

The Institutional Analysis and Development (IAD) framework (Figure 2.1) was specifically developed to study collective action in socio-ecological systems [108], particularly their related institutions. Institutions are human-constructed rules which shape social, political and economic interactions [120] or, more loosely, rules that govern the system [123], in this case, the (thermal) energy communities. Institutions can be discerned into formal and informal rules [108].

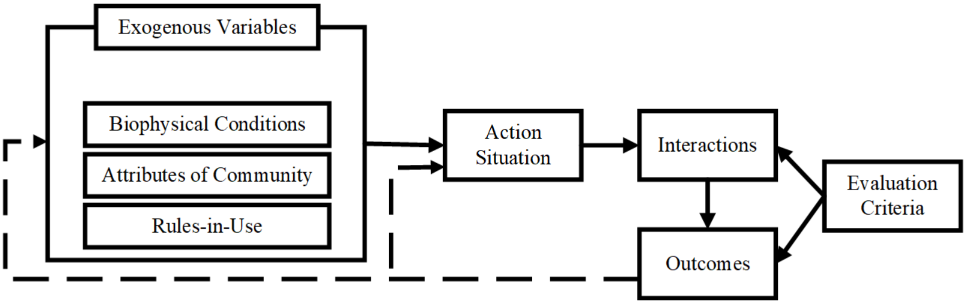

Figure 2.1.: IAD framework [110]

At the centre of the IAD framework is the “action situation” building block, where participants’ actions take place [123]. The action situation is “a conceptual space in which actors inform themselves, consider alternative courses of action, make decisions, take action, and experience the consequences of these actions” [108]. The action situation is described by variables such as the characteristics of the individual actors, their roles (position), the range of actions they can take and the potential outcomes, the cost and benefits of those actions and outcomes, the available information they have, the level of control over their decisions and choice/ participation mechanisms [120].

What happens in the action situation is influenced by a series of exogenous variables (biophysical conditions, community attributes and rules) and leads to patterns of interactions and outcomes that can be assessed on the basis of evaluative criteria [109]. In the end, there is feedback connecting the outcome of the action situation to the exogenous variables. The description of each exogenous variable is as follow:

- **Biophysical conditions:** natural surrounding and human-made infrastructure [161], including the physical and material resources and capabilities available within the system's boundaries [163];
- **Attributes of community:** informal rules and public perception [127], including the cultural norms accepted by the community. In other words, the values, beliefs and preferences about the potential outcomes of the action situation [123];
- **Rules in use:** formal rules and policies [127] that define what actions are allowed and which are not in an action situation [123].

Even though the IAD framework has conventionally been used to study traditional common pool resource management (e.g., irrigation and fishery), it has lately been applied to energy systems (e.g. [126], [125], [164]) and especially to CES (e.g. [161], [127], [128]). Since the framework is specifically aimed at analysing collective action settings such as those found in TEC initiatives, we also use it to analyse the literature in this research. By basing our analysis on this framework, we aim to address the literature with a focus on the social and institutional settings for these systems, given their highlighted importance [5], [30], [113]. Furthermore, using the IAD framework also adds value to studies such as [28] and [165], which studied CES literature from integration and sustainability angles.

## 2.3. RESEARCH METHODS

An extensive literature search was conducted on thermal energy communities (TEC). This literature review was based on material collected from www.webofknowledge.com and www.scopus.com that are published until the end of 2020, using combinations of keywords as presented in Table 2.1:

Table 2.1.: Used keywords

| Combination of the keywords | Number of articles |
|---|---|
| “heating” AND “energy community” | 55 |
| “heating” AND “energy cooperative” | 7 |
| “heating” AND “energy initiative” | 110 |
| “thermal” AND “energy community” | 65 |
| “thermal” AND “energy cooperative” | 7 |
| “thermal” AND “energy initiative” | 106 |
| “cooling” AND “energy community” | 25 |
| “cooling” AND “energy cooperative” | 6 |
| “cooling” AND “energy initiative” | 29 |

As the goal of the current study is to provide a critical overview and propose a research agenda for studying TEC initiatives (and as the literature on TEC initiatives is relatively small), the collected materials cover all different types of documents, including peer-reviewed articles and conference proceedings. The choice of keywords is to cover all research about thermal energy applications ("heating", "thermal" and "cooling") with collective action and bottom-up organizational structures ("energy initiative", "energy community", and "energy cooperative"). Since the goal of this study is to provide an overview of research on community-based initiatives that collectively invest in thermal technologies rather than thermal technologies themselves, we deliberately left out research that does not address the bottom-up and collective nature of these systems or only focus on specific technologies (e.g. solar energy, geothermal, and district heating). The keywords in Table 2.1 appeared in 410 documents. However, only 134 of them actually referred to the energy community as a local scale, collective action and bottom-up energy system. For instance, in some of these 410 documents, "energy initiative" referred to an official part of the government (energy initiative office/ plan), but not to the community-based energy initiatives (e.g. [166], [167], [168]). "EU energy community", "international energy community", "atomic energy community", and "East Asia energy community" are other examples of using the "energy community" keyword with a different meaning. Figure 2.2 elaborates on the processes of including and selecting documents.

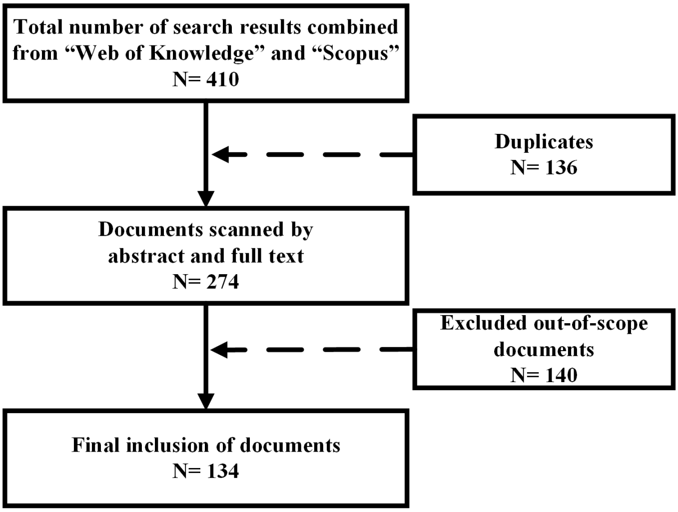

Figure 2.2.: Prisma Flow diagram literature search

Next, in order to provide a descriptive analysis of this literature, the dominating topics (i.e. common repeating words) in these 134 documents were explored using Vosviewer [169] with co-occurrence analysis of all keywords with minimum co-occurrence of 5. Vosviewer is a software tool for creating, visualizing and exploring maps based on network data (e.g. scientific publications and scientific journals), where these networks can be connected by co-authorship, co-occurrence, citation, bibliographic coupling, or co-citation links [169]. Therefore, in our study, any word in the abstracts, titles, and articles' suggested keywords, that has been repeated in at least five different articles is reported.

Lastly, we analysed and structured the literature in detail using the IAD framework. In order to do so, along with using the Vosviewer (i.e. common repeating words) for this purpose, careful discussion and extraction of the topics studied in each of the 134 documents also contributed. Therefore, all the topics that are discussed in the TEC initiatives literature are aligned with different building blocks of the IAD framework.

## 2.4. OVERVIEW OF THE TEC INITIATIVES' LITERATURE

This section presents an overview of articles on TEC initiatives (details of these 134 articles are presented in the Appendix A). The number of studies related to TEC initiatives has grown rapidly in recent years. As Figure 2.3 demonstrates, around 50% of all studies (66 studies) were published in the last 4 years from 2017 onwards.

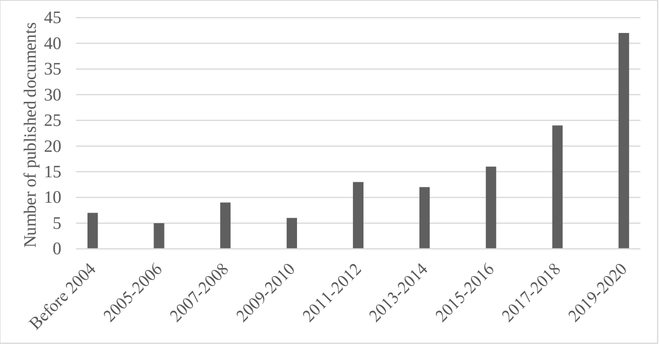

Figure 2.3.: Timeline of published documents

Although the focus of this study is limited to TEC initiatives and thermal applications, only 53 solely focus on heating and cooling energy generation. The other 81 studies also consider electricity generation in addition to thermal energy. These articles can be further divided into two categories: (i) those where electricity is generated and then used for thermal application purposes, such as for heat pumps (e.g. [170]), and (ii) the energy generation for both thermal energy and electricity, such as community-based (bio-)gas combined heat and power systems (e.g. [171]). Even in communities with both generation of heat and electricity (which is for thermal purposes), district heating remains the main technology for distributing the thermal energy among the households. Different thermal energy storage systems (e.g. thermal buffers), built environment efficiency (e.g. buildings' energy label) and thermal energy applications (e.g. space heating, air-conditioning and hot water) are also studied in the literature. These are unique topics for TEC initiatives and are discussed in detail in Section 2.5

Concerning the scientific discipline of these existing studies, following [28], five groups have been identified: technical, economic, environmental, behavioural/ institutional, and literature reviews. The technical discipline with 55% of the total share of these studies is the dominant discipline, including topics such as the technical design of renewable heat generation and distribution (e.g. district heating systems), optimization of heating energy systems, and integration of different renewable heating systems. For instance, [172], [173], [174] and [175] study different types of smart systems and their influence on thermal energy consumption at the community level. The relation between increasing domestic energy efficiency and thermal energy consumption in energy communities is presented in [176] and [177].

The second-largest discipline is the economic discipline (16%). Articles with a purely economic focus (e.g. [178], [179]), including topics such as market design, economic feasibility and cost-benefit analysis, cover 12% of the studies. Also, broader topics are addressed, such as [180], which explores socio-economic factors for small rural communities, while [181] studies technical and economic factors for renewable energy technology retrofits to single-family homes.

Environmental studies cover 14% of the literature. Different topics such as the influence of climate change on buildings' thermal energy consumption (e.g. [182], [183]) and the environmental sustainability of thermal energy systems (e.g. [184]) are related to this category. 9% of studies focus on behavioural and institutional aspects (e.g. stakeholder analysis, policy analysis and consumer behaviour). Bio-energy policy in Finland [185], the influence of institutional reforms on environmental aspects related to both the heating and electricity sector in Montenegro [186] and bio-energy policy in Chile [187] are examples of such studies. Lastly, 6% of studies provide a literature analysis, review, or opinion about a particular topic (e.g., thermal technology, policy, or economic consideration). Figure 2.4 illustrates the overview of research disciplines and approaches in the TEC initiatives literature.

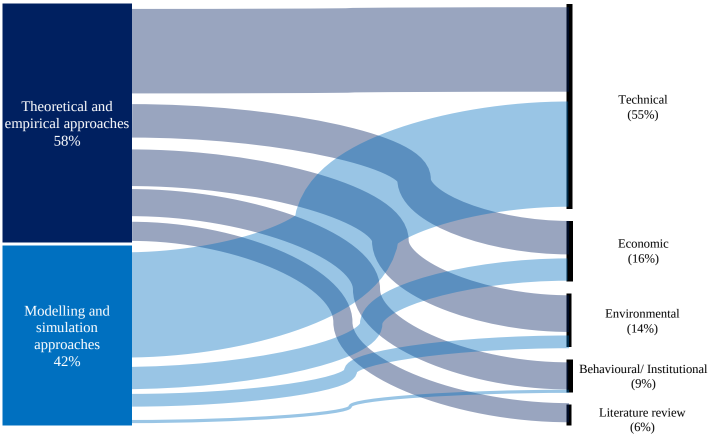

Figure 2.4.: Overview of research disciplines and approaches

Before going into the analysis, we first look at the geographical location of the studies. The geographical location of the studies can influence the research results, as different regions have their own background and exogenous variables (i.e. biophysical conditions, attributes of community and rules in use in the IAD framework). As Figure 2.5 shows, in the TEC context, most case studies are conducted in Asian and European countries, whilst the literature offers only a relatively small number of case studies in North America. This is relatively similar to the CES literature, dominated by studies focusing on European countries [153]. Figure 2.5 demonstrates the percentages of worldwide distribution of the case studies present in the literature.

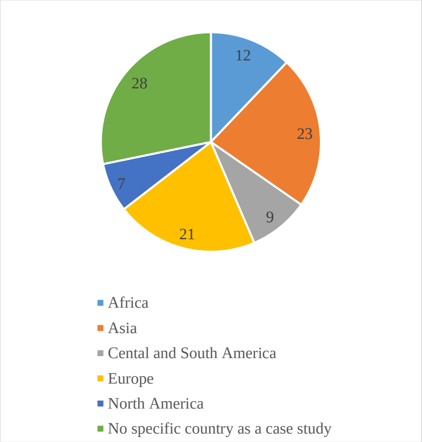

Figure 2.5.: Percentages of worldwide distribution of case studies of articles

Given the important level of geographical urbanization, namely differences between rural and urban settings (e.g. space availability) [128], we also investigate the distribution of the studies with this categorization. For instance, [180], [188] show that rural TEC initiatives have less (thermal) energy demand and make a smaller investment in comparison with urban TEC initiatives. However, 39% of the TEC initiatives' literature (52 studies) does not clearly distinguish between the urban and rural contexts. As Figure 2.6 shows, more studies investigated TECs in an urban context than in a rural context.

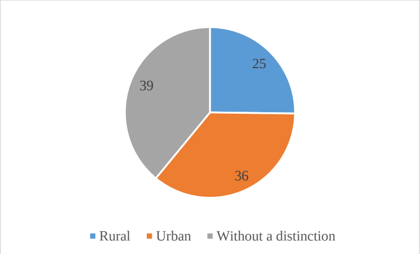

Figure 2.6.: Level of geographical urbanization

As a final part of the overview, we extracted the commonly repeated words of these research articles using Vosviewer [169], meaning words with minimum co-occurrence of 5 in all articles (more detail can be found in Appendix A). In total, the results of the analysis by Vosviewer showed 91 common repeated words, where we grouped them in suggested categories presented in Table 2.2 to provide a more abstract overview, which would potentially help the next steps of analysing and organizing the literature. The suggested categories have emerged from commonly repeated words themselves while considering studies such as [189] and [190]. These commonly repeated words and their overarching suggested categories could be used in organizing and analysing the literature further. Moreover, they bring more context to the literature disciplines (see Figure 2.4), as the repeated words are related to a certain discipline. For instance, the following five categories are associated with the technical discipline: (i) energy resources, (ii) energy generation technology, (iii) energy storage technology, (iv) energy distribution technology, and (v) final energy application.

Table 2.2.: Overview of topics in the studied literature

| Categories | Keywords |
|---|---|
| Energy resources | Solar power, Renewable energy resources, Biomass, Solar energy, Renewable energy, Fuels, Fossil fuels, Biogas, Solar radiation, Renewable energy source, Natural gas, Natural resources, Energy resources, Renewable resource, Alternative energy |
| Energy generation technology | Electricity generation, Solar water heaters, Photovoltaic system, Water heaters, Solar heating, Renewable energy technologies, Solar water heating, Power generation, Combustion, Photovoltaic cells, Heat pump systems, Solar collectors, Combined heat and power, Solar power generation, Electric power generation |
| Energy storage technology | Energy storage, Heat storage, Electric energy storages, Energy conservation |
| Energy distribution technology | District heating, Hot water distribution systems, Electric power transmission network, Smart power grids, Smart grid |
| Final energy applications | Cooking appliance, Air conditioning, Domestic Hot water, Heating equipment, Heating, Cooling |
| Formal institutions | Energy market, Energy policy |
| Environmental aspects | Water, Atmospheric pollution, Greenhouse gas, Carbon emission, Carbon dioxide, Gas emissions, Emission control, Greenhouse gases, Environmental impact |
| Buildings | Housing, Residential energy, Buildings, Residential building, Intelligent buildings |
| Research Approach | Design, Integer programming, Modeling, Cost benefit analysis, Optimization, Economic analysis |
| Economic and financial | Economics, Commerce, Costs, Investments |
| General keywords | Energy systems, Multi-energy systems, Multi energy, Thermal energy, Thermal power, Energy efficiency, Energy utilization, Heating system, Cooling systems, Sustainability, Sustainable development, Digital storage, Climate change, Household energy |

## 2.5. ORGANISING THE LITERATURE USING THE IAD FRAMEWORK

As elaborated in Section 2.2 and Section 2.3, we use the IAD framework to analyse the current literature on TEC initiatives. The keyword categories in Table 2.2 are also to determine which papers focus on which building block of the IAD framework.

### 2.5.1. BIOPHYSICAL CONDITIONS

For this building block of the IAD framework, we address the biophysical attributes of these systems and the technological and infrastructure attributes [124]. Therefore, the keywords related to energy resource, energy generation, energy storage and energy distribution technology fall within this building block of the IAD framework. This covers 40 out of 91 of all keywords identified and presented in Table 2.2, which shows the domination of this building block in the TEC initiatives' literature. Figure 2.7 illustrates the distribution of energy resources and technologies for heating purposes within the 134 documents.

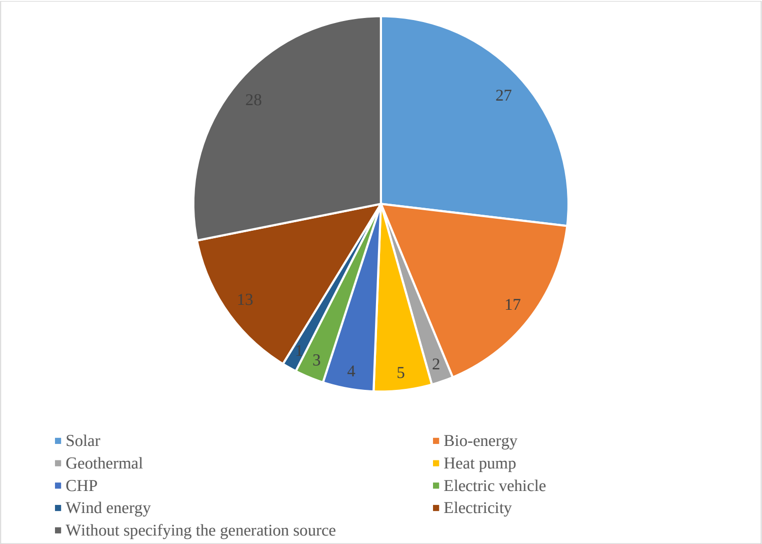

Figure 2.7.: Distribution of energy sources and carriers in the body of literature

Among the resources and generation technologies, solar energy plays a major role. Topics related to design of solar energy communities (e.g. [152], [150], [191], [192], [193], [194], [195]) and (technical, economical) feasibility study of solar energy communities (e.g. [196], [197], [198], [199], [200], [201]) are researched extensively. Both types of solar energy technologies, i.e., solar photovoltaic systems (e.g. [202]) and solar collectors (e.g. [191]), are explored in the TEC literature. However, unlike the mainstream CES literature, which is focused on available solar irradiation as a determining factor for solar photovoltaic electricity communities (e.g. [203], [102], [104]), TEC initiatives' literature also considers environmental surrounding factors such as ambient environment and seasonal temperature (e.g.[150], [191]), as these determine the performance of solar heating technologies, such as solar collectors. In addition to solar energy, various studies (including [204], [205], [206], [207], [208], [209], [210], [211], [113], [212], [213], [214]) address bio energy. [205], [207], [208], provide technical designs and models for bio-based energy communities. Studies such as [211], [213] and [214] study domestic availability of bio-energy (e.g. fuel wood and wood chips) and environmental surroundings (e.g. climate and temperature) as crucial factors for bio-based TEC initiatives.

These two specific RETs, solar and bio-energy, are by far the most studied sources of heat-generation in the literature, which is probably due to their considerable share in local renewable energy generation overall (see articles such as [10], [215]). Although there are few studies in our set (e.g. [216], [217], [218]) that perform research on geothermal energy, all of them also study other RETs in that same study (except [217] that only focuses on geothermal energy). For both solar and bio TEC initiatives, institutional design and economic topics, including market design, [219], [220], business models, [221], [222], [223], and socio-economic aspects [180], [210], [224], [225] are studied in the literature (elaborated in Section 2.5.2 and Section 2.5.3.As presented in Figure 2.7, other energy technologies, such as heat pumps (5% of studies), electricity (13% for both conventional and renewable electricity) and wind turbines (1% of studies), are also studied in the literature.

There are also a considerable number of articles (30% of the literature approximately) that study TEC initiatives without specifying the energy source or carrier. In these studies, the main focus is on district heating, as the distribution system (e.g. [226], [227], [228]) or on thermal applications (e.g. [229], [230]). District heating design is the focal point of many articles such as [217], [231], [232], [232], [233], [234]. The influence of storage systems on TEC initiatives is studied in [152], [188], [150], [191], [235], [236], [237]. [226] and [228] study integration of energy systems (e.g. electricity, heating, and cooling) for TEC initiatives, while [227] focuses on developing an integrated design approach for sustainable energy communities. [229] explores thermal applications (e.g. chillers, boilers and heat pipes) within TEC initiatives, and [173] studies monitoring households' energy consumption as an essential factor for TEC initiatives establishment. These topics, particularly district heating and thermal storage design, are only specific to TEC initiatives.

Regarding energy consumption technologies specifically, the TEC initiatives literature elaborates mainly on the optimal design and consumer interaction/ behaviour with the consumption technologies (e.g. [177], [184], [238]). In line with this, the literature's focus could be divided in three groups: (i) final consumption, such as providing hot water, air conditioning, and cooking (e.g. [238], [239]), (ii) control systems (e.g. [173], [174]), and (iii) efficiency and insulation (e.g. [177], [181], [240], [241], [242]). These consumption technologies are studied within the context of different kinds of buildings (e.g. residential, commercial, social, intelligent buildings, and smart homes). These applications and technologies are also specific to TEC initiatives and are different from the CES main body of literature that mainly focuses on electrical applications, such as lighting and household appliances.

Finally, it is worth highlighting that many biophysical and environmental surrounding attributes are specific to TEC initiatives and have been extensively studied in the literature. These include indoor air quality (e.g. [157]), and ambient temperature (e.g. [150], [191], [229], [243]). Specifically, studies such as [9], [170], [205], [244] focus on analysing the impact of climate, temperature, or location on TEC initiative establishment. These factors are important conditions for TEC initiatives' performance, as they influence system design, thermal efficiency, and indoor comfort. They also influence TEC initiatives institutional settings [245], [246], as we will study further in Section 2.5.4 and Section 2.5.6.

### 2.5.2. ATTRIBUTES OF COMMUNITIES

The 'attributes of communities' is one of the main building blocks of the IAD framework as it greatly influences the behaviour of the actors and, therefore, the action situations [123]. In this context, community attributes (such as norms, values and culture) influence motivations and behaviour towards the (thermal) energy communities. However, as it appears in the literature, minimal attention is given to this part of collective action in TEC initiatives (14 articles out of 134). Although there are no identified keywords related to this building block of the IAD framework in Table 2.2, a number of articles have studied some aspects related to the community attribute.

In this building block, two main lines of research stand out: 1) norms and values 2) community behaviour. Norms and values (e.g. environmental concerns and lifestyle) are mainly studied in relation to the final application and consumption side of TEC initiatives such as the ones related to cooking stoves and indoor air pollution [157], norms related to income level and energy consumption [247], and norms of single-family homes and relation to energy demand [181]. This is different from the mainstream literature of CES, where norms and values are commonly studied in relation to general motivations such as environmental concerns and financial benefits for participating and investing in CES initiatives (e.g. [14], [97]). Therefore, the norms and values of prosumers that received considerable attention in CES literature are missing from TEC initiatives' literature.

Secondly, the users' common behaviour in a specific community has been highlighted by several studies (e.g. [170]). The influence of users' behaviour on biogas generation (e.g. [210], [248]) and the impact of home efficiency upgrades on residents and tenants (e.g. [177]) are studied in the TEC literature. These studies explore the behaviour of households related to thermal energy applications. Furthermore, [249] observed and modelled social dynamics to explain uptake in energy-saving measures. This research line is similar to the CES body of literature, where studies such as [104], [97], [250], [251] also explore the overall behaviour and attributes of actors in CES initiatives.

In addition to the specific characteristics of TEC initiatives, other overall behavioural attributes of a community have also been studied in our TEC body of literature. Particularly [247] is focused on environmental and social impacts of solar water heaters in South Africa, and [252] dived into the influence of housing cooperatives and households attributes on buildings' heating systems and their costs. These attributes and the approach for studying them are similar to the ones studied in CES literature, such as willingness to pay (e.g. [253], [57]), awareness ( e.g. [58], [254]) and trust (e.g. [255], [256]).

### 2.5.3. RULES-IN-USE

In this building block of the IAD framework, we address the formal institutions (i.e., policies, regulations) that influence TEC initiatives [163]. Informal institutions (i.e. norms) were already discussed in Section 2.5.2 Within this building block, studies are mainly dominated by TEC initiatives' energy market and energy policy. Studies such as [219], [220] and [222] performed market analyses on solar and biomass energy resources. [219] specifically focused on solar water heaters, while [220] explores the biomass market. [178] also explored market diffusion of solar photovoltaic systems. Furthermore, [244] researched the influence of residential aggregators on market flexibility.

Price reforms [185], [186], bio-energy policy [185], [187], [224], and cost reduction [212], are examples of studies on energy policies related to TEC initiatives. [185] extensively elaborated on bio-energy in Finland and how policies and regulations evolve in this regard. Furthermore, studies such as [187], [212] and [224] also focus on policies related to bio-energy in other countries. Assessment of related energy policies is also studied in different researches (e.g.[225], [257]).

Another line of research, in addition to the ones that are mainly technology-driven, is about the relationship between policies, social and environmental aspects. For instance, [186] explains the environmental impacts of energy price reforms, and [258] studied the impact of energy exchange cost on TEC initiatives. [113] explored the role of institutional entrepreneurship in emerging TEC initiatives. However, these studies can be generalized to CES research, as they do not have dived into specificities of thermal energy applications of these communities.

The overall number of studies covering institutions is limited in our studied TEC literature (15 articles out of 134). However, we conjecture that the technological specificities of thermal energy may require specific institutional arrangements and regulations (such as institutions for district heating and underground thermal storage to avoid environmental impacts, including soil pollution) other than the ones that are extensively studied in CES literature. Examples of institutional research in CES include regulations and policies (e.g.[113] [37]), (self) governance (e.g. [78], [259]) and ownership (e.g. [260], [119]).

### 2.5.4. ACTION SITUATION

In the action situation building block, the focus is on the participants, their positions, responsibilities, possible actions, trade-offs, and participation rules [123]. Nevertheless, it has not received much attention in the CES literature as a whole, and particularly within TEC initiatives literature. There are only a few studies that are specifically related to this building block, and they can be divided into two main groups (i) participants, their roles and the participation rules (e.g. [214], [261], [262]), and (ii) trade-offs and decision-making processes (e.g.[212], [217]) in TEC initiatives.

For instance, [262] investigated sustainable energy project development (waste-to-energy initiative) with a public-private partnership organizational form in Nigeria. Along with the position of participants and their responsibilities, the study elaborates on technological, economic and environmental factors as well as the project's financial and work schedule data, which are related to the trade-offs and participation of actors. Social, economic and environmental aspects related to the fuelwood value chain in Burkina Faso are elaborated extensively in [214] and responsibilities and participation rules.

Regarding the trade-offs and decision-making processes, [157] focuses on trade-offs between human health and biomass usage for households. Therefore, health consideration-heating energy trade-offs are particularly related to TEC initiatives, as the households burn biomass (e.g. wood) indoors for heating and cooking purposes in their accommodation, which is different from electricity-driven communities. Studies about the trade-offs and decision-making processes related to living conditions, energy access and economic aspects are elaborated in [263]. Users' behaviour on biogas production through a technical and a social approach is the focus of [210]. Furthermore, [180] elaborately studied the influence of socio-economic profiles and level of development on energy consumption.

The current body of literature on TEC initiatives is limited to either households (as participants and prosumer/ consumer) or policy-makers (as government/ municipality who execute formal institutions). In contrast, in CES literature, the importance of other actors, such as prosumers, energy companies and community leaders/ cooperative committees, and their roles are highlighted. In addition to such actors, waste companies, farmers (i.e. manure production) [248] and building insulation companies [264] are also important actors that need further inclusion in TEC initiatives analysis given their importance in thermal energy provision. On top of this, further research on other topics in the action situation building block, such as possible actions (e.g. dropping-out process based on participants' satisfaction), need to be studied.

### 2.5.5. INTERACTIONS AND OUTCOMES

In the IAD framework, the "Action situation" leads to "Interactions" and "Outcomes" building blocks [108]. Considering the thermal technology specifications, topics discussed in these two building blocks have the most similarities with the main CES body of literature. In our literature on TEC initiatives, we found that interactions are diverse and include the ones that take place when developing a new energy community (e.g. [243], [265]), member and board settings (e.g. [266], [40]), and general participation in TEC initiatives (e.g. [244]). [243] is focused explicitly on geometric variables correlated with energy performance and providing guidelines for buildings in hot climates. It also explores the possible impacts and outcomes of such buildings and communities. An optimization model for home energy management systems focusing on internal interactions of energy technologies and users is presented from an aggregator's standpoint [244]. [229] explored the network synergies within energy communities and [265] developed a method to explore the energy cooperatives networks. Studies such as [30] and [132] suggest that there are 4 phases for (thermal) energy communities' establishment (namely: idea phase, feasibility phase, procurement and construction phase and expansion phase), where each phase has its own specific interactions and outcomes. These topics are similar to discussions within CES' literature.

The TEC initiatives' literature discussed that possible outcomes of TEC initiatives could be reduction of $CO_2$ emission (e.g. [9], [267]), more supportive structured policies for thermal energy transition (e.g. [185], [187]) and sustainable and healthy life-style (e.g. [247]). There are other studies, such as [217], [225] and [262], that took an integrated assessment approach (with emphasis on environmental impact) for measuring outcomes of energy communities in developing countries. Key performance indicators for energy communities and TEC in particular are addressed in most literature, but hardly systematically and explicitly. These indicators are input to the evaluative criteria to assess the performance of TEC, which will be elaborated on next.

### 2.5.6. EVALUATIVE CRITERIA

Evaluative criteria for TEC initiatives include technical feasibility measures, environmental performance measures, individual consumer satisfaction and economic benefit measures. Although various studies could potentially be related to evaluative criteria, 27 articles particularly explore and assess the performance of TEC initiatives. In this part of the literature, studies with a focus on measuring the environmental performance of TEC initiatives stand out (e.g. [9], [257], [262], [268]). These studies focus specifically on the greenhouse gas emission reduction by the establishment of TEC initiatives. [257], [262], and [268] and [165] used greenhouse gas emission reduction as the main indicator for analysing infrastructure for (thermal) energy communities, while [9] explored the greenhouse gas emission reduction potential for TEC initiatives. However, the environmental evaluation performance is more inclusive in the CES literature. In addition to greenhouse gas emission, the CES literature also evaluates CES based on community's waste and spatial issues [28], [149]. This is an essential consideration in the context of TEC initiatives as they could potentially have more significant environmental impacts due to their larger consumption share [145], [31], [32] in comparison with electric-generating communities. Furthermore, due to the technical design of TEC initiatives (e.g. district heating as distribution system, and geothermal energy and ground-source heat pump as generation systems), topics related to water and soil pollution could also become relevant.

In addition to the environmental oriented evaluation, there are also other ongoing discussions in the literature for evaluating TEC initiatives. Studies such as [198], [218], [227], and [269], investigate the energy performance of TEC initiatives. [218] specifically studies the energy performance of buildings within energy communities. The study presented an approach to achieve a nearly zero-energy community by assessing the energy performance of building design solutions and renewable energy systems. The literature also conducts various feasibility studies, which can be divided into 2 main categories, (i) technical and environmental feasibility measures (e.g. [182], [198]), and technical and economic feasibility measures (e.g. [196], [197]). Furthermore, [220] evaluated and explored the economic feasibility and market opportunities for thermal energy technologies. [258] studied the impact of internal energy exchange cost on TEC initiatives, while [184] and [270] assessed the techno-economic and economic-environmental performance of TEC initiatives. Finally, studies such as [217] [225], [226], and [271] have an integrated approach for evaluating TEC initiatives. Social, economic and environmental impacts of small scale bio-energy systems are elaborated in [225]. [217] developed a dashboard to support the decision making processes regarding the implementation of (thermal) energy communities.

## 2.6. ANALYSIS AND DISCUSSION

Energy communities or community energy systems (CES) are key entities in the energy transition. The body of literature on CES is dominated by electricity-based technologies, such as solar PV and wind turbines, but since thermal energy consumption in the built environment makes up a large portion of the transition challenge, thermal communities were the topic of our study. Given the technological differences between thermal energy and electricity, energy communities established on either of the two energy carriers are also expected to be different in institutional and social design. Hence in this study, a systematic literature review and analysis was conducted in order (i) to make a comprehensive overview of research on TEC initiatives and (ii) to identify key differences of TEC initiatives and electricity-based energy communities in order to build a research agenda for the future of TEC initiatives.

The literature review revealed that most of the papers in the TEC literature had been published within the last few years. The majority of articles in this literature (72 articles) focus on technical topics, with design, optimization and system integration approaches. District heating is the main distribution technology discussed in the literature. Renewable gas, a micro grid for direct electrical heating and individual renewable thermal energy systems are the alternatives that need further studies. Furthermore, in TEC initiatives' literature, considerable attention is given to the energy consumption of different types of buildings. This is particularly contextual in the TEC initiatives' literature, as different studies discuss how different building' types influence the thermal demand (e.g. heating, cooling and cooking).

In contrast, few studies on actor/ participants' analysis and institutional design. It can be concluded that institutions (both formal and informal rules) are largely neglected in this body of literature. Apart from providing a systematic literature review and a research agenda, this study provided an opportunity to dive into details of TEC initiatives based on the different building blocks of the IAD framework. Using the IAD framework for our literature review analysis revealed that, among exogenous variables, "Attribute of community" is neglected the most, in contrast to general CES literature, where "Attributes of community" gets relatively more considerable attention. This is problematic as TEC initiatives are formed when individuals act collectively, and therefore their attributes (e.g. values and norms) are influential in how TECs form and function. Thus, this hinders the deployment and implementation of TEC initiatives which may consequently hamper the energy transition as a whole. The literature on policies and regulations is dominated by research on specific technologies and resources (namely solar energy and bio-energy), focusing on pricing as an incentive mechanism. As discussed, research on policies and regulations that specifically address TEC initiatives needs to be expanded as they are substantially different from electricity-based communities in terms of land usage, investment, technology, building efficiency, among other factors.

Although the literature on "evaluative criteria" is well developed, it is dominated by technical and economic analyses and $CO_2$ emission reduction assessments. However, other important topics (e.g. soil pollution and public welfare) need to be included as evaluative criteria for TECs. The literature on building blocks "action situation", "interactions" and "outcomes" is relatively limited (and also different from mainstream literature on CES), and there is a need for further research on topics related to these building blocks in TEC initiatives context. For further elaboration, see Section 2.5.4, Section 2.5.5 and Section 2.5.6.

The current study sheds light on the TEC literature; however, it does not address certain technologies, locations or system designs. We deliberately excluded keywords related to specific thermal energy technologies (e.g. geothermal and district heating). For further work, as our analysis showed, there is considerable attention to particular technologies, such as solar energy, bio-energy and district heating. This is probably due to the historical maturity of such renewable thermal energy technologies compared to relatively new technologies such as geothermal wells and heat pumps. However, it would also be meaningful to focus on the literature of specific thermal energy technology, and while considering the collective nature of TEC initiatives, investigate the new insights, if any. Furthermore, the results showed that the number of studies focusing on TEC initiatives is increasing fast; therefore, it is also meaningful to add more recent studies (e.g. published 2021 onwards) in future reviews. It would also be meaningful to consider other keywords, such as thermal energy system, renewable thermal energy, collective action and collective decision-making, to collect a larger number of documents to validate and generalize current findings.

As TEC initiatives are based on the collective action of individuals, the collective action perspective and the IAD framework that we used in our analysis were highly instrumental in mapping out the current research and identifying gaps. As a future research avenue, it is meaningful to investigate the relationships and interactions between the building blocks of the IAD framework in the TEC initiatives context. Studies such as [272] hired such an approach. Other lenses (e.g. urban resilience) and other frameworks (e.g. innovation management and multi-level perspective) may provide additional insights related to resilience and different stages of technological diffusion of TEC initiatives.

## 2.7. RESEARCH AGENDA AND FUTURE WORK

This research aimed to study the body of literature on Thermal Energy Communities (TEC) to highlight state of the art and propose areas for further research. By taking a collective action perspective in our literature analysis, we paid special attention to the institutional and community attributes of these community-based initiatives. This perspective is less highlighted in the general body of literature on CES and even more so in the TEC literature. We used the IAD framework to map out areas of research that are relevant in the study of TEC initiatives from a collective action point of view. This is yet another contribution of the current study, as despite the IAD framework's proven instrumental analytical power for studying collective action resources and systems, this framework has not been used previously to analyse and structure energy communities' literature. Figure 2.8 summarizes the current, published, state-of-the-art in TEC initiatives research. We conjecture, in addition, that TEC initiatives have several unique characteristics, suggesting that these initiatives need to be studied specifically in addition to the general CES studies. These differences stem from the technological and infrastructure differences but are also related to differences in consumption behaviour of consumers and prosumers in addition to other types of institutions and behavioural attributes.

Below we discuss areas for future research in TEC:

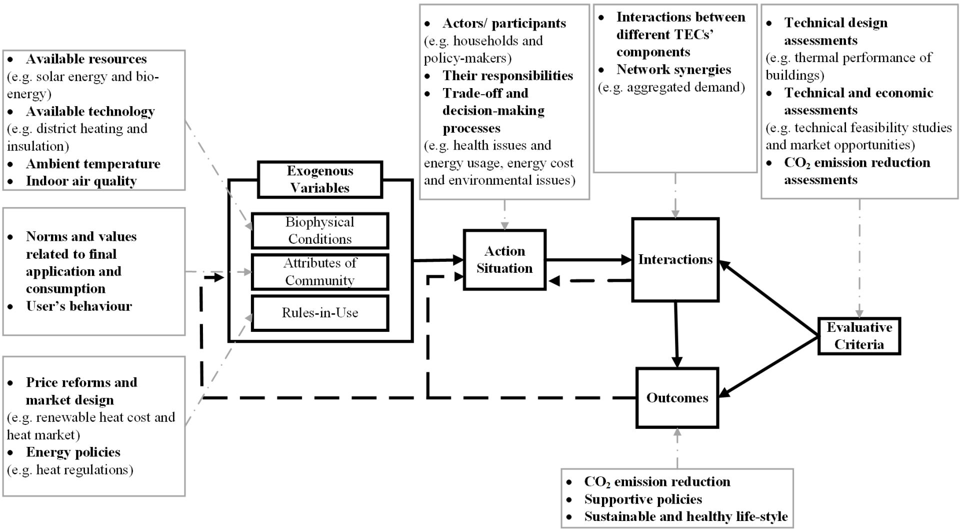

Figure 2.8.: Overview of findings on TEC initiatives literature

- Solar and bio energy are the main energy resources for TEC initiatives; however, several other heat resources can be shared and used on a community level and are worth further investigation. These include resources and technologies such as geothermal, heat pumps, and waste heat. Furthermore, different thermal energy applications (e.g. space heating and hot tap water) needs further investigation. Therefore, technical design and feasibility studies of other thermal technologies and resources are required.

- Unlike electricity-generating communities, biophysical conditions such as ambient temperature and indoor air quality in the context of TEC initiatives are essential factors influencing the establishment of these communities and their success (see Section 2.5.1). Specific thermal energy technologies such as geothermal energy and ground heat pumps influence the soil and ground water quality and would therefore need to be included in environmental assessments of TEC initiatives. Although there are a limited number of studies addressing these factors, more substantial inclusion in TEC research is needed. Performing life cycle assessments(e.g.[273], [274], [275]) could be useful in this regard.

- Institutions are essential in studying TEC initiatives to allow these community-based initiatives to flourish to the extent of their electricity-based counterparts. The institutional factors are both high level and formal such as the ones related to market mechanisms, but also informal, such as the ones that determine the internal functioning mechanisms of these initiatives and influence the type of interaction among community members. Particularly in TEC initiatives literature, there are few studies in this field. Conducting surveys and interviews with the assist of computer modelling (e.g. agent-based modelling [276]) could be helpful further to investigate institutions, both formal and informal rules. For instance, studies such as [245] that use behavioural attributes data to populate an agent-based model for studying the establishment of electricity-based energy communities could be an example for studying institutions in the TEC initiatives' context.

- The interactions' network (e.g. interactions between different actors), internal dynamics (e.g. dynamics and information exchange between households), desirable and possible outcomes (e.g. the number of participants) need to be explored for TEC initiatives. As presented in Section 2.4 it is also critical to study other actors. In this regard, as studies such as [134] and [118] suggest, approaches such as studying focused groups and organizing workshops of involved actors would bring new insights. Q-methodology [277] and serious gaming [278] would benefit such approaches.

- A methodological observation from this literature review was that the papers reported mainly mono-disciplinary studies focusing on the technical design or economic assessment. However, in order to facilitate TEC initiatives establishment, there is a need for multi-disciplinary research. Studies such as [30] and [34] [178] also argued for the need for multi-disciplinary in the heat energy transition as a whole.

In conclusion, substantial differences were identified between the TEC initiatives literature and electricity-generating energy communities. Their differences are in generation sources, distribution systems, and consumption applications from a technological standpoint. Furthermore, unlike the CES mainstream literature, studies related to attributes of community do not play a significant role in TEC literature, and the few studies in this regard are mainly focused on attributes related to thermal consumption applications. Due to all the differences, this study studied TEC initiatives as distinctive entities with their own unique characteristics.

# 3

# SIMULATING THERMAL ENERGY COMMUNITIES

Energy communities are key elements for local energy transitions, collectively generating, distributing and consuming energy using renewable energy technologies. As one type of energy community, thermal energy communities focus on thermal energy applications, such as heating, cooling, bathing, showering, and providing hot tap water. As thermal energy applications and systems receive increasing academic and policy attention, there is a need to understand better the formation processes they undergo. This chapter explores various technical, behavioural and institutional conditions that influence thermal energy community formation processes by using an agent-based modelling approach. The results show that technology selection is not the most crucial and determining factor for the success of thermal energy communities, yet the surrounding institutional conditions are. Key factors that influence these formation processes pertain to providing training so that the thermal energy community leaders become more skilled and allocating subsidies based on the projects' degree of environmental friendliness. For all stakeholders, finding the balance between all decision-making criteria is key to success. The results are useful for practitioners - and especially for policy makers - to develop more impactful policies and strategies to support the expansion of local thermal energy communities. [1]

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[1] This chapter has been published as J. Fouladvand, M. Aranguren, T. Hoppe, and A. Ghorbani, "Simulating thermal energy community formation: Institutional enablers outplaying technological choice," Appl. Energy, vol. 306, p. 117897, 2022. It has been slightly modified textually for alignment in this study. The first author has conceptualised and performed the research. The other authors have performed an advisory role.

## 3.1. INTRODUCTION

Among the multiple approaches to greenhouse gas mitigation in energy transition, the deployment of renewable energy technologies (RETs) is considered the primary strategy [2]. Energy transition has been discussed at different levels, namely, supranational, national, regional, and community [28], [144].

At the community level, in particular, energy communities are considered a key element for the deployment of RETs, as they contribute to their own energy generation, distribution and consumption [28]. Since households are responsible for around 25-30% of total energy consumption [279], [280], energy communities could potentially play a significant role in energy transitions. There are different definitions for the energy community in academic literature. This term can be defined, for instance, as "people in a neighbourhood, who invest in renewable energy technologies jointly and generate the energy they consume" [13]. Another definition works around installing one or more renewable energy technologies in or close to a rural community where community participation is a key factor [7], [8]. Schram et al. define an energy community as "a group of consumers and/or prosumers, that together share energy generation units and electricity storage" [9]. While energy communities are usually built on norms and values such as trust and the environmental and financial concerns of their participants [255], the more formal organisational-legal version of energy communities, i.e. energy cooperatives, are characterised as commercial organizations operating in a market environment [10], [281]. Overall, we conclude that the concept of energy community in the academic literature encapsulates initiatives that focus on collective generation, distribution and consumption of renewable energy for all community members [5], [147].

In the literature about energy communities, thermal energy applications are understudied [27]; however, thermal energy covers no less than 75% of total non-transport related energy consumption among households [33], [32]. Discussions mainly address either energy communities in the general sense of the concept (e.g. [28], [8], [29]) or, more particularly, electric energy communities (e.g. [25], [26], [53]). Within the scarce literature on thermal energy communities, studies are mainly focused on technological aspects (e.g. [32], [37],[38], [39]), and in particular, on district heating technology (e.g. [140], [117], [282]). For example, in Sweden, [283] and [284] have studied heat load patterns and the technical design of district heating. Studies such as [285] and [286] also provide an overview of Swedish district heating status and its benefits and risks. In this context, [287] and [288] discuss the overview of technical developments in Danish district heating. However, these studies do not explicitly focus on the thermal energy community and its collective action nature. Yet, according to [30] and [40], this is key to changing the institutional context, which is currently hindering the potential to overcome economic and technological challenges related to adopting local heat technology and the related infrastructure (e.g. high capital investment requirements and long installation time).

Overall, there is a lack of understanding about thermal energy community (TEC) initiatives, what their formation process entails and the institutional conditions needed for TEC initiatives to thrive. This hinders the deployment and implementation of TEC initiatives, which consequently hampers the energy transition as a whole. This study aims to explore and gain insights into the potential impact of various institutional and technological conditions on the formation process of TEC initiatives. In this regard, an Agent-Based Modelling (ABM) approach [91], [88] is considered to be a suitable tool for studying the complex dynamics and interactions within (thermal) energy community initiatives. ABM allows the exploration of the complexities of decision-making processes of an energy community and experimentation with alternative strategies within a virtual simulation environment. In fact, because of their usefulness in studying bottom-up social processes, several researchers have already used ABM for modelling community energy systems. For example, [102] uses ABM for studying zero-energy communities. Using ABM and considering the leadership role, the emergence of local energy initiatives for solar and wind energy is explored [104] use this approach for investigating the adoption of residential solar photovoltaic systems. [95] also developed an ABM for studying the conflict of values within local energy systems. [289] uses ABM to analyse local heating systems in the built environment in thermal energy applications. Policy interventions and business models related to heat network development in UK cities are studied in [30]. Although all these studies explore specific aspects of energy communities, none have explored the technical and institutional conditions for the formation of thermal energy communities.

The ABM model developed in this chapter is about technical (thermal) energy innovation that goes hand in hand with social innovation (in the form of energy community formation). It is used to look at how certain combinations of technical, behavioural and institutional conditions influence the formation of thermal energy communities. Furthermore, it proposes recommendations about the institutional changes required to foster the establishment of Dutch thermal energy communities. The model itself has the potential to serve as a simplified tool for stakeholders to explore how to foster thermal energy transitions in their local context. The results of this chapter exemplify how the model can be applied in the Dutch energy context, but this tool can be used in other contexts by adjusting the data.

The structure of this chapter is as follows: Section 3.2 provides insights into thermal energy communities. The theoretical background of the research is presented in Section 3.3. Research methods are introduced in Section 3.4. A model description, which entails the development and implementation of an agent-based model, is presented in Section 3.5. Section 3.6 then discusses model implementation and assumptions. Next, model results are presented in Section 3.7. Section 3.8 then presents the academic discussion. And finally, conclusions, implications and suggestions for further research are presented in Section 3.9.

## 3.2. THERMAL ENERGY COMMUNITIES (TEC)

To contextualise the modelling exercise of this study, the relevant literature on community energy systems in general, and TEC initiatives in particular, is presented in this section.

TEC initiatives, in particular, focus on providing sustainable energy for thermal applications, such as heating, cooling, bathing, showering and cooking [27]. As a sub-category of energy communities, TEC initiatives consist of three main components: (thermal) renewable energy technology, stakeholders involved and related institutions [27]. As elaborated in studies such as [42], [290], [291], these components interact with each other within the TEC initiatives system boundaries and with the environment outside the TEC initiatives system's boundaries.

### 3.2.1. THE THERMAL TECHNOLOGY COMPONENT

TEC initiatives involve the implementation of common local RETs which are used for thermal energy applications. In the existing literature, the technological component of TEC initiatives has been studied relatively more than the other two components (i.e. stakeholders and institutions) [30]. Regarding the technology, topics such as energy system design (e.g. [229], [292]), energy system integration (e.g. [293], [227]), demand-side management (e.g. [294], [51], [295]), and thermal storage (e.g. [296]), have received academic attention. According to [39], [152], [297], the technology components of TEC can be decoupled into three main elements: (i) generation (input); (ii) distribution (transition); and (iii) consumption (output).

- **Generation:** This encompasses the heat source and the thermal energy generating technology [39]. In addition to the renewable thermal energy resources and technologies, such as biomass, biogas, geothermal, solar thermal, and waste heat [298], [299], renewable electricity for thermal purposes (e.g. heat pumps) is also included in TEC initiatives [299].

- **Distribution:** This entails making the generated heat available for consumption through transportation from the heat source to the end-user [282], [50]. It consists of connections, heat exchangers, and the network of pipelines [38], [50].

- **Consumption:** This focuses on the thermal applications inside the households, such as space heating or cooling and hot tap water [39]. Therefore, besides demand-side management, studies such as [300] and [22] explore the influence of energy-saving measures for heat consumption. Energy labelling is another topic that is touched upon in the literature on thermal energy consumption (e.g. [280], [301]).

### 3.2.2. THE STAKEHOLDER'S COMPONENT

The second component of energy communities comprises participants within any energy community, e.g. TEC initiatives, their roles and responsibilities [27]. The role of different stakeholders on the level of social acceptance of community energy systems [118], the influence of leadership [97], [302], and vision building [302] on the establishment of energy communities are examples of topics explored in this regards. The division of financial responsibilities has also been studied as a key success factor in TEC initiatives [14], [11].

Recent research, however, has focused on exploring the participation motives [303], [304], willingness to invest [14], and trust [255], [58]. In this context, [144], [305], [306], focus on stakeholder involvement and engagement, [144], [119], discuss participants' norms and values, and [244], study participants' characteristics, such as willingness to participate.

### **3.2.3.** THE INSTITUTIONAL COMPONENT

Institutions are human-constructed rules that shape social, political and economic interactions or, more loosely, rules that govern the system, the local (thermal) energy system [123]. Institutions can be discerned into formal and informal rules [108], [120].

Research into formal rules influencing community energies looks into topics such as energy policies (e.g. [14], [112]), regulations (e.g. [307], [113], [114]), and incentive mechanisms (e.g. [8], [10], [115]). More particularly in the context of TEC initiatives, regulatory design [308], [309], [132], [310], and market design and pricing strategies [140], [117], [116] have received considerable academic attention.

On the other hand, informal institutions include norms and values that influence the behaviour of stakeholders [118], [311], [119] and interaction structures between them [113], [85]. In other studies, the role of values and behaviour in energy communities is addressed (e.g. [104], [161], [127], [312]). Other issues that have to do with public values, but also tap into informal rules held by community members and stakeholders, include trust [58], psychological factors [313], environmental concerns [314], [251], [315], and local energy autonomy [316].

### **3.2.4.** SOCIAL AND GOVERNANCE SETTINGS

Following the meta categorisation developed in [146] for solar energy communities on organisational and governance drivers that positively influence local energy initiatives, factors influencing community energy performance and their relative success can be divided into three different groups: (i) intra-organizational characteristics of an energy community ; (ii) interaction with the local community; and (iii) governance setting and linkage to government [146].

#### INTRA-ORGANIZATIONAL CHARACTERISTIC OF TEC INITIATIVES

Key factors influencing community energy performance include:

- The presence of especially committed actors to the project effectively provides direction to the group (i.e., ‘project champions’) [146].
- Having the required knowledge and expertise to overcome impediments and take the required actions to establish the energy communities [146], [317].
- Having access to funds [146], such as subsidies to cover (a fraction of) the required investment and increase the project’s affordability [11], [305].

#### THE INTERACTION WITH THE LOCAL COMMUNITY

Frequent interaction between project champions and the local community is essential to ensure a high level of local community involvement, which translates into a high willingness to participate and invest in the project [146]. This can be achieved through the early direct participation of the neighbourhood and open decision-making processes [318]. Active engagement of the local community could be ensured by aligning the needs, expectations and values of different stakeholders, including the local community and leaders [305]. The importance of other related factors, such as a high level of cohesion [245] and trust [255], [58], is also addressed in academic literature.

#### GOVERNANCE AND THE INVOLVEMENT OF EXTERNAL STAKEHOLDERS

It is critical to connect the external stakeholders to the project champions and local community [146] to achieve external support and complete the overall set of skills, capacities, information, and expertise required for the establishment of an energy community [305], [146]. Creating such a network facilitates information sharing, which is essential for enhancing learning from the experience of other energy communities [317]. Developing supportive policy frameworks that ease the provision of planning permits and provide external funding is another example of external stakeholders' influence on establishing an energy community [144], [114], [146]. Nevertheless, all these interactions and networks will only be successful if the different discourses and visions held among stakeholders are shared and aligned [245].

### 3.2.5. THE FORMATION PROCESS OF TEC INITIATIVES

The development of viable local heating networks requires the main actors to navigate through a series of project stages which are elaborated as follows [30], [233]:

- The idea phase: This phase focuses on the initial mobilization of TEC initiatives participants. The outcome of this phase is typically the shared approval of a vision and a first plan. Key issues in this phase concern: a vision, a new technology, a new partnership between the actors around the TEC initiative.

- The feasibility phase: This phase focuses on building consensus about the project's characteristics, considering that this is technically and financially feasible. An essential requirement is that the project is linked to both the region's spatial characteristics and the residents' socio-economic features. Additionally, the TEC initiative members need to agree on the financial and organisational arrangements during this phase.

- The procurement and construction phase: Once the consensus about the local heat network project has been reached, finance needs to be secured, customers contracts arranged, and the infrastructure built.

- The expansion phase: Lastly, this phase includes the daily operation of the local heat network once it is in place and its expansion to involve a larger share of the community.

## 3.3. THEORETICAL BACKGROUND

This section introduces the theories used as the backbone of our modelling exercise. We also use these theories to analyse our simulation results, as discussed in the following sections. While the four-layer model of Williamson [319] and the Institutional Analysis and Development framework [108] support the structuring of the elements of thermal energy communities, the Behavioural Reasoning Theory [320] supports the understanding of how these elements relate to each other.

### 3.3.1. THE FOUR-LAYER MODEL OF WILLIAMSON

The four-layer model of Williamson categorises institutions into four different layers [319], as presented in Figure 3.1. These four layers interact, provide feedback to each other, and have a temporal aspect since each level operates at its own pace [319], [321].

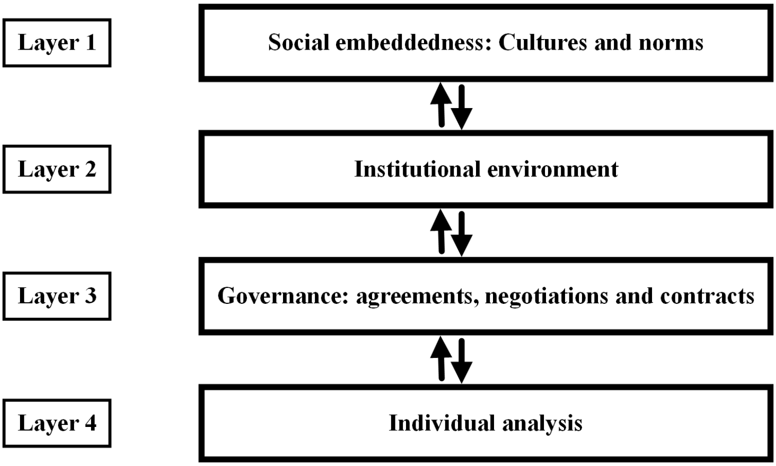

Figure 3.1.: The four-layer model of Williamson [319]

- **Level 1: Social embeddedness:** The highest layer includes the informal institutions of cultures and values, which operate at the lowest pace and require hundreds of years to change. However, they have a significant influence on the other layers. These institutions mainly have a spontaneous origin and have a lasting grip on society's behaviour.

- **Level 2: Institutional environment:** This level comprises the political, legal and governmental, more formal arrangements that shape the activities in the other levels. Changes in this level occur when there are windows of opportunity, such as a hard economic crisis. These formal rules are in the form of laws and regulations, which can come from a (supra)national and regional level. The time horizon of change in these institutions is in the order of a decade to a hundred years.

- **Level 3: Governance:** This layer looks into the modes of formal organisations with contracts and agreements that describe the division of roles and responsibilities across stakeholders. However, informal agreements based on trust and reciprocity can also be analysed on this level. The time horizon of change in these institutions is in the order of one year to a decade.

- **Level 4: Individual analysis:** This level accounts for the analysis of the operation and management of the system. It looks at what individuals take into consideration when making decisions and how they make these decisions. This is the fastest-changing level, continuously developing [319], [322].

The key element of Williamson's four-layer model concerns feedback loops [319], [110], illustrating the interconnectedness of institutions within a specific system using a system's perspective [322]. These loops show how developments and changes at a lower level are, on the one hand, steered and restricted by the institutional arrangements at higher levels. On the other, they open up paths for new arrangements at higher institutional levels [322].

The four-layer model of Williamson has traditionally been used to understand complex environmental issues. However, [59], [323], [324] argue that the four-layer model of Williamson also provides a useful platform to study and analyse energy systems.

In the present study, the four-layer model of Williamson is used to represent the stakeholders and their decision-making hierarchy in the ABM (See Section 3.5). The high-level meta-conceptualisation of the four-layer model of Williamson provides the structure to identify the key action situations within the decision-making processes of thermal energy communities' formation processes. Additionally, it supports the classification of these action situations into the different institutional layers. We leave the first layer out in the simulation to look at shorter time horizons.

### 3.3.2. THE INSTITUTIONAL ANALYSIS AND DESIGN (IAD) FRAMEWORK

The IAD framework developed by Ostrom (2005) enables the dynamic analysis of decision-making processes in a system by breaking them down and organising them into simpler, more manageable parts [123], [108] (see Figure 3.2).

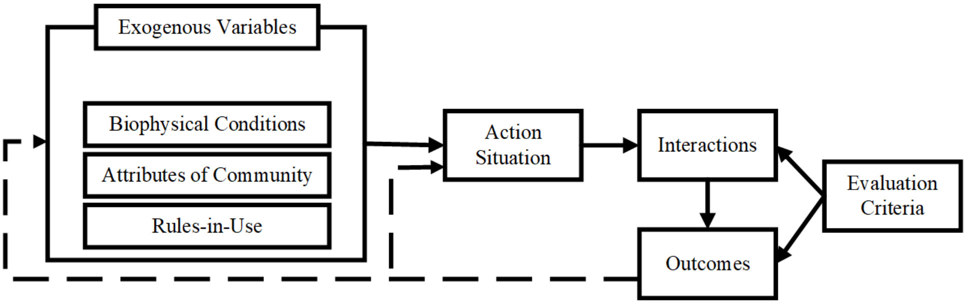

Figure 3.2.: The IAD framework [110]

The action situation is the main component of the IAD framework [108]. [163] describes the action situation as: "a conceptual space in which actors inform themselves, consider alternative courses of action, make decisions, take action, and experience the consequences of these actions". What happens in the action situation is influenced by exogenous variables classified into three main components: biophysical conditions, community attributes, and rules-in-use.

- The biophysical conditions include the physical and material resources and capabilities available within the system's boundaries. Resources include technology options, finance, population and available labour, for instance, [123], [163].

- The attributes of the community include the cultural norms accepted by the community. In other words, the values, beliefs and preferences about the potential outcomes of the action situation [123], [127].

- Lastly, there is the rule-in-use component, which is about the formal rules that govern the system. Ostrom categorises them into seven rules which influence the action situation: boundary, aggregation, scope, pay-off, position, information and choice [322], [110].

These exogenous variables and action situation components lead to patterns of interaction that generate specific outcomes. Based on evaluation criteria, these outcomes can be objectively assessed [108], [110]. In the end, there is a feedback loop that connects the outcome to the action situation and the exogenous variables [322], [110].

Even though the IAD framework has conventionally been applied to the study of traditional, common pool resource management, it has lately been extensively applied to energy systems (e.g. [125], [164], [126]) and the community energy system, in particular (e.g. [161], [127], [128]). In our simulation, the IAD framework will be used to model the interactions and decision-making processes of stakeholders in each layer of the four-layer model of Williamson. Once the key actions for forming thermal energy communities have been identified, the IAD framework supports a more in-depth analysis of these actions by identifying the components that shape them and the important external and internal conditions that influence them. This provides the required depth of understanding for adequately representing the action within the ABM model presented in this paper.

### 3.3.3. BEHAVIOURAL REASONING THEORY

The Behavioural Reasoning Theory (BRT) is used to analyse and guide how actors make decisions and behave [320], [325]. BRT focuses on understanding the personal factors that influence sustainable behaviour [326], [327].

As presented in Figure 3.3, BRT postulates that intentions are strong predictors of behaviour and that attitudes are a key antecedent of the adoption of these intentions [320], [250]. BRT then theorises that attitudes are a key antecedent of adopting behavioural intentions [320]. BRT includes the relevance of context-specific reasons for and against a decision as a key predictor of the attitudes, as well as of the final decision [320], [328]. In addition, BRT proposes that, most importantly, resulting from a desire for simplified information processing, people's processing of value information directly affects the reasoning for their expected behaviour. In this line, BRT argues that project leaders, when searching to make the right decision, scan their values and belief systems and find the action that aligns best [329].

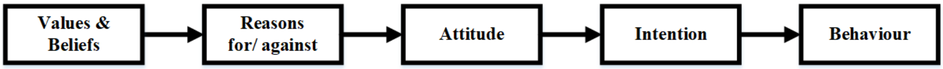

Figure 3.3.: BRT [320]

In the energy transition-related literature, several studies, such as [250], use BRT to analyse the deployment of RET. This study uses BRT to capture individuals' values, reasons, and attitudes concerning participation in TEC initiatives. BRT connects variables that are defined according to the two aforementioned frameworks: (i) how the community attributes within the IAD framework influence the action situation and, (ii) how the informal rules in the first layer of the Williamson framework influence the decisions made by the individuals in the fourth layer.

By building our ABM model on the theoretical grounding provided in this section, we aim to, firstly, analyse the way in which a particular combination of technical and institutional conditions influences the formation of thermal energy communities, and secondly, provide recommendations on the institutional change required to foster the establishment of TEC initiatives.

## 3.4. RESEARCH METHODS

### 3.4.1. AGENT-BASED MODELLING (ABM)

In ABM, agents are heterogeneous, autonomous and individual decision-making entities (e.g. any stakeholder, such as households, municipalities, companies and policy makers) that are able to learn and interact with each other and their environment [87], [90]. This allows the capture of individual behavioural choices while also allowing the understanding and analysis of the emergent behaviour of the system as a whole [91]. Moreover, institutional changes and policy interventions can be analysed in ABM by using different scenarios and comparing the emergent behaviours of agents that arise from them [30], [88].

For these reasons, ABM is considered a suitable approach for studying the behaviour of stakeholders, their decision-making process, and dynamics within a TEC initiative. In addition, ABM has the following key benefits:

- ABM creates a simplified representation of reality, easing the research while breaking free the constraints imposed by obtaining analytical solutions and mathematical formulations [88], [91].
- ABM can be applied to situations where the study of macro-level complexities is required, looking at the interaction of simple system components, which prompts the emergence of complex behaviour(s), using a bottom-up approach [131], [322].
- ABM provides the ability to add the time variable, allowing the examination of different scenarios to understand inputs, variables, and outputs with little effort, enhancing the investigative power [88], [91].

Considering the complexity of the real world, an ABM cannot represent all of the details of a real-world decision-making process. However, ABM can facilitate decision-making processes by equipping decision-makers with insights about crucial variables affecting such a process. In this research, ABM is used to approach and explore the technical and institutional conditions that influence the formation of TEC initiatives in urban districts.

### 3.4.2. CASE STUDY: THE NETHERLANDS

To parameterize the model, delineate reliable results and derive practical recommendations, we have used data from the Netherlands. A country-level of analysis has been chosen for the following reasons: (i) the characteristics of energy systems differ per country, (ii) the availability of national statistical data at the country level, and (iii) it allows the study of institutions (both formal and informal rules) with a broad view. The Netherlands was selected as the country for the case study in this research because of the following:

- Presence of a high number of energy communities as compared to other EU countries [11];
- Presence of a well-developed energy/heating infrastructure [132], [141];
- Ambitious Dutch national $CO_2$ reduction targets which have influenced the heating sector [133];
- National norms for environmental concerns and sustainable development [134], [135];
- Urge for (heat) energy transition due to gas quakes [136].

The Netherlands is used as a case study to populate the model based on real-world data. The data was collected from the 'Stimuleringsregeling Duurzame Energie' (SDE++) (in English: the Sustainable Energy Incentive Scheme; translation by the authors) and the Netherlands Environmental Assessment Agency (PBL).

## 3.5. MODEL DESCRIPTION

This section explains the agent-based model used to study institutional and technological factors that affect the formation of TEC initiatives.

### 3.5.1. MODEL CONCEPTUALIZATION

The model represents a city with multiple neighbourhoods. It assumes each neighbourhood can implement one thermal energy community. In each community, individual households collectively decide whether they are willing to generate and consume renewable thermal energy. As a government representative, the municipality has a limited budget per year (e.g. a subsidy) to facilitate the implementation of thermal energy communities in the city. The model conceptualization is based on the IAD framework as follows.

#### PARTICIPANTS: AGENTS

The agents included in the model are households, the board of energy communities and the municipality, each representing one of the four layers in Williamson's model (see Section 3.3.1).

- **Social embeddedness.** Each agent has a particular value system that guides their decision-making processes and level of involvement in forming thermal energy communities.

- **Institutional environment: the municipality.** This layer comprises the political, legal and governmental, formal arrangements, the “rules of the game” that shape the activities in the lower layers. In the model, the municipality, which represents the government departments responsible for the energy transition, is responsible for defining the formal institutions available to support the neighbourhoods’ transition from gas. Their tasks include setting eligibility requirements for subsidies and providing training for the energy community boards.

- **Governance: the TEC board.** This layer looks into the modes of organization that are formalised through contracts and agreements that describe the division of roles and responsibilities. In the model, it is assumed that, right from the start, there is already a group of people interested in leading the transition to a natural gas-free area in each neighbourhood that will take ownership of the project. The TEC board is responsible for gaining sufficient household support, organising the individuals who participate in TEC, the initial decision-making regarding collective technology, negotiating, and applying for subsidies as representatives of TEC. The TEC board also has a specific set of values that define its vision. It can participate in training courses to learn how to persuade more individuals to participate in the project.

- **Individual analysis: households.** These are the individual households forming the neighbourhood that initially use natural gas to cover the demand for thermal energy in the houses and hold a specific set of value preferences. At a later stage, they can adapt their value preferences when influenced by the preferences of their neighbours, and they can decide to participate in the TEC initiative by supporting the technology scenario, making the required investment and installing the technology.

### ACTION SITUATION AND INTERACTIONS: MODEL NARRATIVE

As representatives of participants, agents interact with each other and make decisions that follow a narrative based on the establishment process of the TEC initiatives. There are action arenas in which agents interact with each other based on various exogenous variables.

***Idea phase:***

- Individual households decide whether they support the TEC board in their role of leading and owning the TEC initiative, based on whether their visions align. Before the initiation of the community, the household agents use natural gas to cover their heating demand.

***Feasibility phase:***

- If training is available for the TEC boards and the TEC board has not yet had this training, the TEC board will take it to gain skills and learn how to better communicate and connect with the households within the neighbourhood.

- When the TEC board has sufficient household support, it goes through a value-based multi-criteria decision-making process (MCDM) to select the collective system that will be implemented in the neighbourhood. In MCDM, different criteria, such as financial gain and environmental concerns, will be used to make the final decision. The MCDM results are reported to the TEC board supporters (first MCDM).

- When TEC board supporters receive the information about the TEC board's MCDM, they evaluate this option through an individual MCDM process. Individuals might value criteria such as financial gain and environmental concerns differently than the TEC board. If households have the same perception of the collective system, they will support it (second MCDM).

- Once there is sufficient support for the collective technology, households go through a second MCDM process to select their preferred individual technology option to complement the collective system (third MCDM).

The details of the three MCDMs are presented in Section 3.6 and Appendix B.

***Procurement and building phase:***

- The TEC board considers which scenario has the most support and conducts a technical and investment feasibility analysis for the collective and individual components of the selected scenario. For the technical feasibility, energy generation (input energy), $CO_2$ intensity technology, and average capacity and load hours are used. For the investment feasibility, criteria such as lifetime, investment costs, operation costs and availability of subsidies are used.

- Based on the investment required and the total amount the technology supporters are willing to invest, the TEC board calculates how much subsidy they need to request to cover the entire investment. If this amount does not exceed the maximum amount the government is willing to give to one neighbourhood, the TEC board sends the request.

- The municipality receives the subsidy requests and considers the TEC initiatives that have applied for the subsidy once a year. The municipality ranks the requests based on their own subsidy distribution strategy and provides the subsidy to those that meet their criteria until all the funding has been used.

- After receiving the subsidy, the thermal energy community goes into the construction phase for half a year. Once the infrastructure is in place, the community is considered to be set up.

***Expansion phase:***

- After the initial set-up of the community, “non-supporters” can re-evaluate their participation: check if they support the TEC board and the selected energy scenario. If their willingness to pay is equal to or lower than the investment required per person in the neighbourhood, they will be willing to make the changes and connect to the community.

- Depending on the participation policy of the TEC board, households will be able to make the required changes at any time (i.e. under individual participation policy), or they will have to wait until they have gathered enough neighbourhood support for the expansion of the TEC initiative to connect to the district heating infrastructure (i.e. under a collective participation policy).

### BIOPHYSICAL CONDITIONS TECHNOLOGY

As described in Section 3.2, biophysical conditions include natural surroundings and human-made infrastructure, which, in this study, has focussed on thermal energy technologies. There are several technology scenarios from which the households, TEC boards, and the municipality can choose. For simplification, although in reality, the district heating (DH) infrastructure can be of low or medium heat, in this ABM, it is assumed that only one alternative is possible. The Heat Expertise Centrum (ECW, 2020) has identified eight key sustainable heat sources for the Netherlands: aqua thermal energy storage, geothermal, residual heat from surface water, green gas, bioenergy, residual heat, hydrogen and solar heat. Among all these sustainable heating technology alternatives, aqua thermal energy storage (ATES), residual heat from surface water (TEA), and bioenergy are the heat sources included in this ABM modelling exercise of the present study. This was done for the following reasons:

- They are the alternatives that are currently more readily available and the ones that need to overcome the least barriers for implementation;

- In currently used top-down implemented district heating systems, these are the dominating sustainable thermal technologies; moreover, these technologies fit well with neighbourhood size heating systems and are already used successfully or are tested in pilots with the aim to scale them in the short term;

- The scope and scale of the model (i.e. one community in one neighbourhood) do not allow for the generation and consumption of green gas and hydrogen; hydrogen is technologically not ready yet for use in neighbourhoods; green gas is not feasible to deploy in most neighbourhoods (with a few exceptions) for logistic and financial-economic reasons;

- Residual heat is often troublesome because of dependence on residual heat suppliers that are privately owned. The owners find it too risky to commit themselves to long-term heat supply contracts. Moreover, residual heat is not a 100% renewable energy source in practice.

Solar thermal (ST) and individual heat pumps (HP) are considered for individual applications. Therefore, among the eight sustainable heat sources, four of them are included in this modelling exercise. The information and data regarding these technologies are presented in Section 3.6.1. Limitations regarding these choices are also explained in detail in Section 3.8.2. Besides the technology, another condition would be the size of the city, which is translated as the number of neighbourhoods in the model. According to Netherlands Environment Assessment Agency (PBL) [330], [331], on average, each neighbourhood has 660 households, and the majority of Dutch municipalities have 7 neighbourhoods or less. Although this scale is relatively small (as it does not represent the metropolitan areas), it is insightful to explore the municipality's size in the context of TEC initiatives.

#### ATTRIBUTES OF COMMUNITY

It is assumed that the neighbourhoods are not connected to each other. As a result, each neighbourhood forms a network independent of each other. To simulate the social structure of each neighbourhood, the model uses a small-world network [332], [333]. Within this approach, the nodes represent households, and the edges connect households that interact with each other.

Following the BRT, norms and values are at the core of the factors that influence the final intention and decision-making of an actor. [58] concluded that the key values to consider when studying energy community systems are environmental concern, energy independence, and sense of community. To these, a fourth one has been included, which is financial concern [8], [21]. As a result, all agents in the model have a perception of their own internal values and how they are ranked with respect to each other.

Regarding the dynamics within the neighbourhood, the ABM assumes that all households in one neighbourhood can interact with each other. It is assumed that households interact in monthly residents' meetings, where it is assumed that 10% of the neighbourhood participate. The dynamics occur based on the following principle as argued in [97]: When two households interact, one will tend to slightly lean towards the opinion of the another, attempting to simulate peer pressure. Lastly, it is assumed that households with very extreme values (either high or low) will not be peer pressured and hence will not be influenced by the interaction. presents the data related to the attributes of the communities used in the simulation.

### 3.5.2. RULES-IN-USE

The regulations and subsidies related to each technology are implemented in accordance with the 'Stimuleringsregeling Duurzame Energie' (SDE) and the Netherlands Environmental Assessment Agency (PBL).

As studies already mentioned, such as [302] and [146], training leadership skills is considered a municipality's policy. If the municipality provides training finances for the TEC initiative's boards, then as skilled boards, they will persuade more households to join the TEC initiative. Also, it is essential to find out the participation policy for individual households who will join the community after it has been created. The two options for participation policy are: (i) participating instantly after the household decides to join, (ii) household will join a buffer (i.e. a waiting list), and when the buffer is full (i.e. enough households are willing to join), all of them will join the TEC initiative. These two options represent the individuals' joining processes for energy community initiatives, which are discussed in studies such as [40], [6], [334].

As the municipality's budget is limited each year, one of the most important rules for decision making is how the municipality will decide to allocate the available subsidy. Further to studies such as [30], [297], [172], the model has four available policies for community initiatives: economy (least economic burden for the municipality), environment (most $CO_2$ reduction option), social (most participants) and trade-off (a balance between the three). Lastly, the amount of the municipality's budget is essential. For PBL, the limit is 4 million Euros per municipality.

### 3.5.3. EVALUATION CRITERIA AND OUTCOMES (KPI MODELS)

To understand and measure the performance of the simulations, key performance indicators (KPIs) are defined, and presented in Table 3.1.

Table 3.1.: Key performance indicators used to evaluate the model outcomes

| KPI | Unit | Description |
|---|---|---|
| Cumulative $CO_2$ emission reduction | % | Percentage reduction of the total $CO_2$ emissions after 10 years compared to the reference scenario where 100% of the neighbourhood uses natural gas for heating the houses |
| Final share of neighbourhood TEC board support | % | Percentage of the neighbourhood households that supports the thermal energy community after 10 years, irrespective of whether they are connected or not |
| Final share of neighbourhood participation in TEC initiative | % | Percentage of the neighbourhood households that are connected to the district heating infrastructure after 10 years |
| Duration of the formation process | months | The time that it takes from the moment the TEC board is established to when the thermal energy community starts generating |
| Collective technology selection | - | The collective technology that the neighbourhood has selected and installed in the neighbourhood (biogas, ATES, heat recovery from wastewater) |
| Individual technology selection | - | The individual technology that the neighbourhood has selected and installed in the neighbourhood (nothing, heat pump, solar thermal) |
| Average household investment | € | The average amount a household in the neighbourhood is willing to invest in establishing a thermal energy community |
| Share of community investment | % | Share of total investments covered by the neighbourhood. The rest is assumed to be covered by the subsidy granted by the municipality |

Table 3.2 summarises the key characteristics of the agents in the model, as well as the essential tools they have to influence the decision-making process simulated in the ABM. Figure 3.4 also illustrates the model's narrative.

Table 3.2.: Agents, their roles and characteristics

| | Municipality | TEC board | Households |
|---|---|---|---|
| Role | $CO_2$ emissions monitoring and policy implementation | TEC project decisions and leadership | Level of project participation and investment |
| Biophysical conditions | Municipality size | Skills | Annual heat consumption and $CO_2$ emissions |
| Attributes of the community | Heat vision objective: cost minimisation, autonomy maximisation, participation maximisation, and emission minimisation | Values ranking: environmental concern, energy independence and financial concern | Values ranking: environmental concern, energy independence, and financial concern. Social value orientation: Payback time and willingness to pay |
| Rules-in-use | Subsidy schemes, Subsidy allocation strategy, Provision of workshops, $CO_2$ tax | Technology decision policy, Minimum neighbourhood participation policy,Process duration policy, Expansion policy, Household persuasion | Technology decision policy, Investment decision strategy |

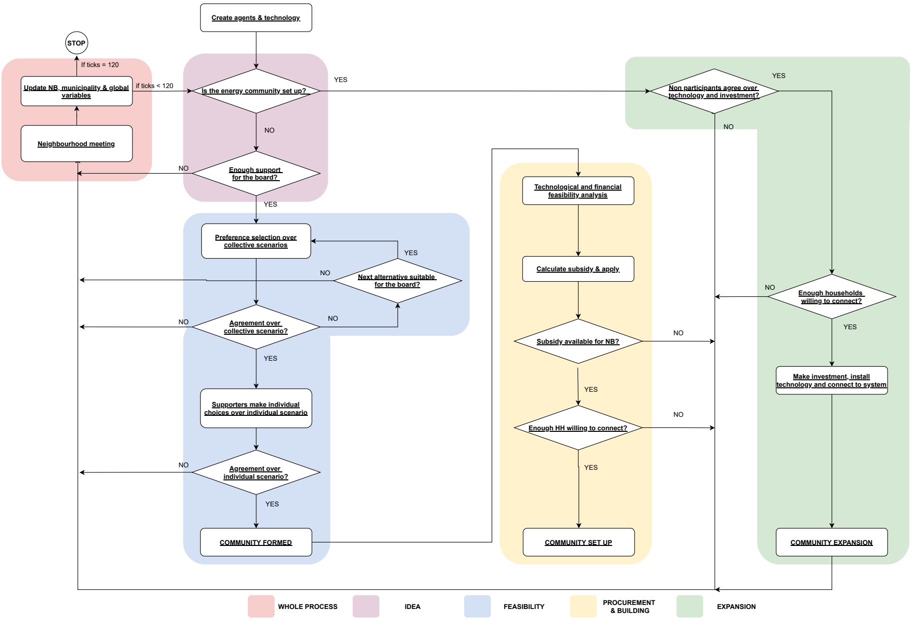

Figure 3.4.: Overview model structure

## 3.6. MODEL PARAMETERS AND INPUT DATA

In this section, first, the assumptions and data from the case study in the Netherlands are presented. Next, the sensitivity analysis results are explained. Finally, all the inputs for the simulation experiment are summarised.

### 3.6.1. DATA FOR BIOPHYSICAL CONDITIONS - TECHNOLOGY

In this section, we provide data on the technological choices that are included in the model. As mentioned above, the technology is divided into two categories: (i) collective technologies: bio energy, aqua thermal energy storage (ATES) and residual heat from surface water (TEA), and (ii) individual technologies: Solar thermal and heat pump.

#### COLLECTIVE HEATING TECHNOLOGY

For the collective thermal energy technology, stakeholders choose one of the three options according to their own values (see Appendix B). Information about each of these technologies is summarised in Table 3.3. The information is provided based on the 'Stimuleringsregeling Duurzame Energie' (SDE++) (PBL, 2020). The SDE++ provides financial incentives to renewable energy projects, either community energy initiatives or via other organisations, improving the energy price for generating energy. Following studies such as [335], [336] and [337], in this modelling exercise, the three collective thermal technologies are bio wood pellet boilers, ATES and TEA technologies. Table 3.3 provides an overview of the data related to collective heating technologies.

Table 3.3.: Data for collective technology

| | Investment costs (€/kW) | Operation costs (€/kW/year) | $CO_2$ intensity of technology (kg/kWh) | Average capacity (kW) | Electricity consumption (kWh/year) | Load hours (hour/year) |
|---|---|---|---|---|---|---|
| Bio pellet boiler | 415 | 25 | 0.26 | - | - | 3000 |
| ATES | 2401 | 113 | 0.152 | 800 | 994000 | 3500 |
| TEA | 2364 | 170 | 0.138 | 10000 | 1935000 | 6000 |

According to [338], for all three collective technologies, the peak energy demand is considered to be 10%, and the $CO_2$ intensity of electricity consumption is 0.429 Kg/kWh. Furthermore, the lifetime of the technologies is 30 years. For further information on collective heating technologies, see Appendix B.

#### INDIVIDUAL HEATING TECHNOLOGY

As mentioned in Section 3.5.1, after choosing and agreeing on the collective technology, households have three options: (i) use the collective technology to cover 100% of their consumption; (ii) combine the chosen collective technology with an individual ground-source heat pump (i.e. brine to water), and (iii) combine the chosen collective technology with individual solar thermal (i.e. flat plate solar collector). Information about each of these individual technologies are extracted from [102], [339] and [340] is summarized in Table 3.4. For further information on heating technologies see Appendix B.

Table 3.4.: Data on individual heating technology

| | Investment costs (€/kW) | Operation costs (€/kW/year) | Average capacity (kW) | Lifetime (years) | Load hours (hour/year) | Total cost (€) |
|---|---|---|---|---|---|---|
| Ground-source heat pump | 1770 | 35.4 | 1 | 20 | 1500 | 4602 |
| Flat plate solar collector | 1666 | 22.5 | 2 | 30 | 700 | 4680 |

According to [341], $CO_2$ intensity is assumed to be 0.14 kg$CO_2$/ kWh for the heat pumps. For calculating the $CO_2$ intensity of the solar thermal systems, it was assumed that a solar water heater would supply hot water 80% of the time, and the remaining 20% would be supplied by an electric water heater. By calculating 20% of the grid's $CO_2$ intensity, we arrive at a $CO_2$ intensity for the water heater systems of 0.086 kg $CO_2$/kWh.

### 3.6.2. DATA FOR THE ATTRIBUTES OF THE COMMUNITY

As presented in Table 3.5, the following criteria are used in a MCDM process by stakeholders to make decisions about the TEC initiatives, as described in Section 3.5.

Table 3.5.: Criteria for attributes of the community

| Criteria | Sub-criteria | Unit | Description | Reference |
|---|---|---|---|---|
| Financial criteria | CAPEX | € | Investment costs | [342] |
| | OPEX | € | Operational and maintenance costs during the lifetime of the system | [343] |
| | Payback time | Years | Years for the investment and maintenance cost to equal the accumulated energy savings from the change | [344] |
| | Subsidy coverage | % | Percentage of the capital costs covered by the subsidy (in the present study, this would be the SDE++ subsidy) | [343] |
| Environmental criteria | $CO_2$ emissions | kg $CO_2$eq | The $CO_2$ emission intensity of technology, based on capacity | [345] |
| | Land use | HA | Amount of land use required for technology, based on capacity | [342] |
| | Social acceptance | 1 to 10 | The degree to which that technology is accepted, recognized and implemented | [343] |
| Independence criteria | The energy input to the system | kWh | Amount of energy input required for the technology to produce the heat to cover the neighbourhood heat demand | [345] |

### 3.6.3. NATURAL GAS PRICE AND $CO_2$ PRICE

As studies such as [133], [346] and [347] explain, the price of natural gas is influential for the deployment of renewable thermal energy technologies and district heating systems. A policy that will have a significant impact on the future gas price if it finally gets implemented is the application of a $CO_2$ tax. [348] states that a $CO_2$ tax set at 50 Euros will increase the gas price by 30%. Therefore, the following prices have been chosen for the model (pertaining to the Dutch context) (see Table 3.6).

Table 3.6.: Data for Natural gas price and $CO_2$ price

| | Price (€/kWh) | Growth (€/kWh/year) |
|---|---|---|
| Gas | 0.096 | 0.003 |
| $CO_2$ tax (22 EUR + 2.5 EUR/yr) | 0.106 | 0.004 |

### 3.6.4. MODEL INPUT PARAMETERS

Table 3.7 presents an overview of all parameters and the data used in the model.

Table 3.7.: Model's parameters and data

| Parameter | Type | Value |
|---|---|---|
| Months | Numeric | 120 |
| Number of neighbourhoods | Range | 1-7 |
| Minimum neighbourhood participation | % | 10 |
| Number of households per neighbourhood | Numeric | 660 |
| Household interactions | % | 10 |
| Environmental concern | Distribution | 1-10 |
| Cost concern | Distribution | 1-10 |
| Energy independence concern | Distribution | 1-10 |
| Sense of community | Distribution | 1-10 |
| Social Value Orientation | Range | 1-4 |
| Payback time | Range | 5-20 |
| Annual heat demand per household | Numeric | 13510 |
| Insulation heat demand reduction | % | 50 |
| Hot water heat demand share | % | 16.5 |
| Municipality subsidy | Numeric | 4000 |
| Municipality subsidy policy | Options | Environment, social, economic, trade-off |
| Municipality subsidy dispatch frequency | Numeric | 1 |
| Gas price | Numeric | 0.0965 |
| $CO_2$ price | Numeric | 22 |
| Gas price increase | Numeric | 0.003 |
| $CO_2$ price increase | Numeric | 2.5 |
| TEC board value ranking: environment | Random | 1-3 |
| TEC board value ranking: social | Random | 1-3 |
| TEC board value ranking: economic | Random | 1-3 |
| Collective technology decision time limit | Numeric | 12 |
| Individual technology decision time limit | Numeric | 6 |
| Technology installation time | Numeric | 6 |

### 3.6.5. SENSITIVITY ANALYSIS AND EXPERIMENTATION ANALYSIS

A sensitivity analysis [349], [350] was conducted to explore different experimental configurations for various model parameters. This was done by following the one-factor-at-a-time (OFAT) approach [350], [351]. All the parameters were fixed at a specific value, and only the value of the study was altered [351], [352]. For each parameter, the model was run 30 times. The sensitivity analysis is presented in Appendix B.

### 3.6.6. EXPERIMENTATION SETTINGS

The experiments include a total number of 96 different combinations of institutional conditions (3*2*2*2*4=96), as presented in Table 3.8. Each combination was repeated 100 times; hence, the experimentation resulted in a total number of 9600 runs. Table 3.8 summarises the experimentation settings for the simulation. The duration of the experiments is 10 years.

Table 3.8.: Experimentation settings

| Parameter | Value | Unit |
|---|---|---|
| Number of neighbourhoods per municipality | 1, 4, 7 | - |
| Participation policy | A/B | - |
| Training availability | No/Yes | - |
| Municipality subsidy amount per neighbourhood | 3, 4 | M€ |
| Municipality subsidy policy | Environment, social, economy, trade-off | - |

## 3.7. RESULTS

In this section, we present the results of the simulation analysis. These results are discussed at three levels: (i) KPIs, (ii) the impact of institutional conditions, (iii) successful and unsuccessful neighbourhoods.

### 3.7.1. KPIs AT THE NEIGHBOURHOOD LEVEL

In the simulation, the size of a municipality is the number of neighbourhoods per municipality (1, 4, 7). In this part, the results are discussed for all of the neighbourhoods, regardless of the size of their municipality.

#### $CO_2$ EMISSION REDUCTION

Figure 3.5 presents the $CO_2$ emission reduction in the neighbourhoods. The neighbourhoods with 0% are the ones that had not formed a thermal energy community by the end of the simulation time.

As Figure 3.5 presents, although in the majority of simulation runs, the neighbourhoods reduced their $CO_2$ emissions, few of them (less than 5% of all simulation runs) achieved more than 20% $CO_2$ emission reduction.

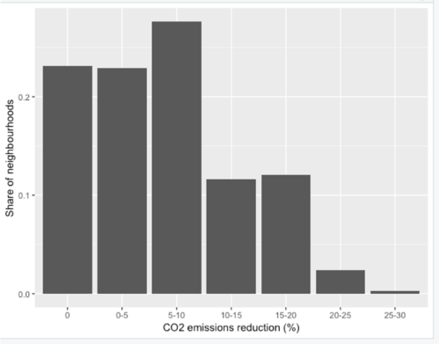

Figure 3.5.: Accumulated $CO_2$ emission reduction

### FORMATION PROCESS DURATION

Figure 3.6 presents the duration of TEC initiative formation. The red line represents the average duration of establishment, and the blue line the share of neighbourhoods (Y-axis) that successfully formed a TEC initiative before the month indicated in the X-axis.

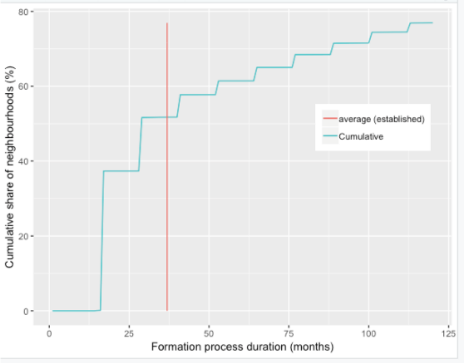

Figure 3.6.: The duration of forming TEC initiatives

The average duration for forming a TEC initiative is 37 months (roughly 3 years), and around 40% of all neighbourhoods have formed a TEC initiative within less than two years. These results show that stakeholders can quickly reach a consensus and establish thermal energy community projects.

### NEIGHBOURHOOD SUPPORT AND PARTICIPATION

While neighbourhood support accounts for the share of households that agree with the project plans, neighbourhood participation only accounts for those households that finally invest and connect to the district heating system. Figure 3.7 and Figure 3.8 show the distribution of neighbourhoods, based on the level of neighbourhood support and participation, respectively.

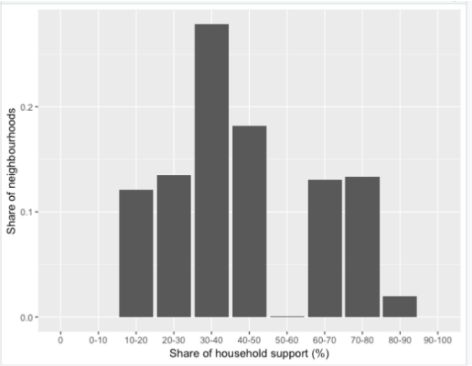

Figure 3.7.: Neighbourhood distribution for share of support from households

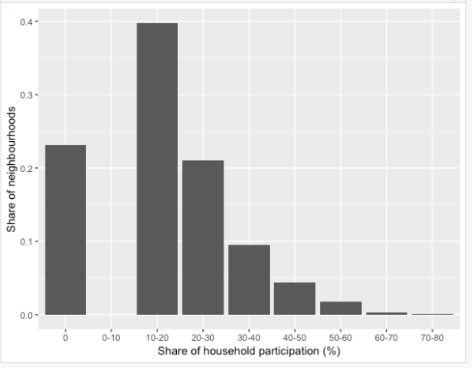

Figure 3.8.: Neighbourhood distribution for share of participating households

The average level of neighbourhood support for established TEC initiatives is around 50%, and the maximum is 85%. Concerning neighbourhood participation (i.e. connection to the thermal energy community), the average level is 22%, the maximum level is 77%. The results for neighbourhood support are quite positive, yet participation can be considered low since only 30% of the neighbourhoods achieve the participation of more than 25%. In other words, the gap between the number of supporters and participants is significant. This means that a large share of homeowners are interested and supportive of the project, but the project does not meet their financial expectations, and they end up not participating in the TEC initiative. The zero-value gaps in Figure 3.7 and Figure 3.8 are the model's assumptions. The modelling exercise assumes that for a community to be considered established, at least 10% of the households are required to participate. If the community is not formed, the participation is zero. Therefore, the runs with zero value in Figure 8 present the communities that were not established.

### COLLECTIVE AND INDIVIDUAL TECHNOLOGY SELECTION

Figure 3.9 presents the frequency distribution of each selected technology scenario. The bars indicate the collective heating technology and the colour the individual heating systems.

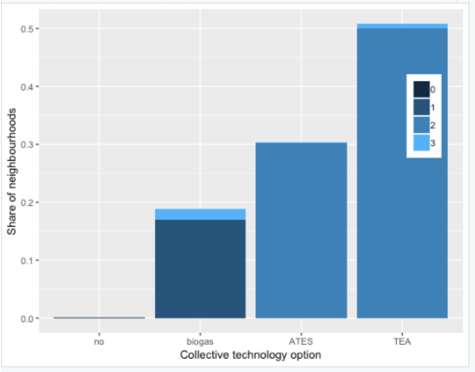

Figure 3.9.: Neighbourhood distribution for technologies

It can be observed that agreement over the technology scenario can be reached fairly easily since a decision is reached in almost every run. Regarding the collective generation technologies, residual heat from surface water (TEA) systems are preferred over the others (50% TEA, 30% aqua thermal energy storage (ATES), 20% biogas). In addition, regarding the combination of collective technologies with individual technologies, there is a clear preference for combining the ATES and TEA systems with solar thermal systems and the biogas system with heat pumps. As combinations of ATES and TEA with solar thermal systems are the most environmentally-friendly options among the combinations of technologies, these are the options that are most targeted by environmentally-friendly neighbourhoods. However, the most environmentally-friendly options, which are the fully collective systems (e.g. fully collective ATES), were not very popular and were only selected around 5% of the time. This is mainly due to their higher initial investment requirements.

### SHARE OF COMMUNITY INVESTMENT AND AVERAGE HOUSEHOLD INVESTMENT

Figure 3.10 presents how much households invest in the TEC as a proportion of the total required investment. Also, Table 3.9 shows how much households invested per chosen technology for those thermal energy communities that are already established.

Table 3.9.: Households' investment per chosen technology (in Euros)

| Technical scenario | Bioenergy | ATES | TEA |
|---|---|---|---|
| Fully collective | 14,000 | 23,000 | 20,000 |
| Collective + individual | 18,000 | 26,000 | 22,500 |

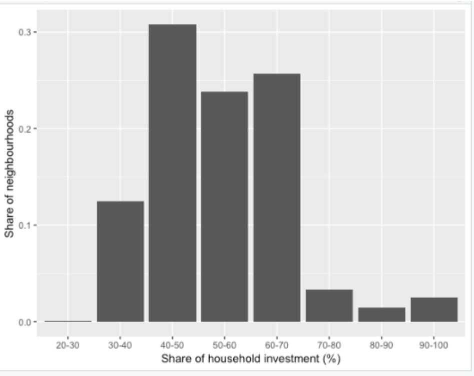

Figure 3.10.: Share of the households' contribution to the total investment

Figure 3.10 shows that the range of the neighbourhoods' contribution to the total investment is quite large. On average, residents are willing to cover 55% of the total investment in the neighbourhoods, and only a few neighbourhoods were capable of fully covering the investment without external support. It can be concluded that it is unrealistic to request households to cover more than 70% of the costs, which means that for projects to succeed, municipalities will need to cover at least 30% of the project costs. Moreover, from Table 3.9 it can be observed that, overall, households are willing to invest, on average, around 20,000 Euros in a timeframe of 10 years. In other words, they are willing to invest approximately 1,000 Euros per year on heating transition. However, it is higher for those scenarios with ATES systems, followed by TEA and then bio-energy wood pellets. Additionally, scenarios including individual generation technologies are costlier for households.

### **3.7.2.** IMPACT OF TECHNICAL AND INSTITUTIONAL CONDITIONS

This section presents the results of the three most relevant institutions and factors modelled: (i) TEC boards' technology selection, (ii) training policy, and (iii) subsidy strategy policy.

#### TEC BOARDS' TECHNOLOGY SELECTION

As mentioned in Section 3.5 and Section 3.6, the TEC board has a particular value upon which decisions are made. Figure 3.11 illustrates the leading value of TEC boards under each chosen technology. Table 3.10 presents the specific data on the average level of environmental, financial and independence concerns of the TEC boards per selected technology scenario in more detail.

#### TRAINING POLICY

Training policy is about the training that the municipality provides for TEC boards to have more fruitful, effective and appealing communication skills with the households.

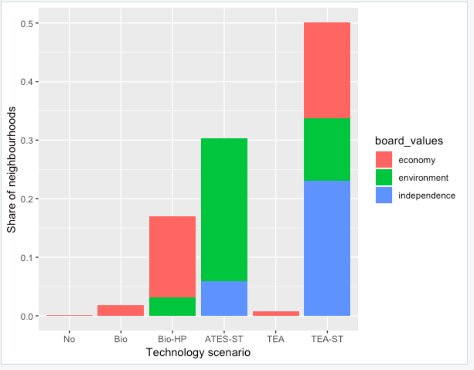

Figure 3.11.: Neighbourhood distribution per technology scenario

Table 3.10.: Average level for the TEC boards' value priority for the chosen technologies

| TEC board value priority | Technology scenario | Average environmental concern | Average economic concern | Average independence concern |
|---|---|---|---|---|
| Economy | No | 4.0 | 8.0 | 1.0 |
| | Bio-HP | 3.7 | 8.1 | 2.5 |
| | Bio | 3.8 | 8.4 | 2.9 |
| | TEA-HP | 4.3 | 7.9 | 6.3 |
| | TEA | 3.9 | 7.6 | 5.9 |
| Environment | Bio-HP | 8.0 | 7.2 | 1.5 |
| | ATES-ST | 8.0 | 3.1 | 4.4 |
| | TEA-ST | 7.7 | 6.7 | 5.5 |
| Independence | ATES-ST | 7.0 | 1.9 | 8.3 |
| | TEA-ST | 3.6 | 4.6 | 8.0 |

The graphs show the impact of the training policy on the level of $CO_2$ emission reduction and the level of household participation at the municipal level.

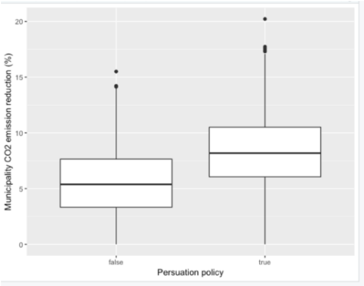

Figure 3.12.: Influence of training policy on municipality $CO_2$ reduction

According to Figure 3.12 and Figure 3.13, it can be observed that providing training

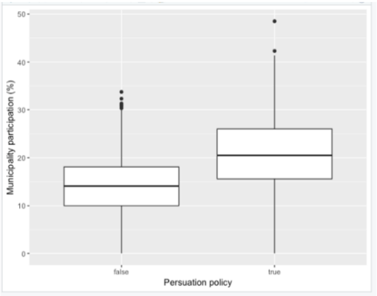

Figure 3.13.: Influence of training policy on municipality participation

sessions to the TEC board members to improve their cooperation and communication with the neighbourhoods has a positive impact on the success of TECs regardless of the municipality size. In particular, the availability of training increases both the level of $CO_2$ emission reduction and household participation by 5% on average.

### SUBSIDY STRATEGY POLICIES

Subsidy policy is about how the municipality decides to allocate financial support, considering the limitation of the subsidies. There are four available policies: (i) economy (least economic burden for the municipality), (ii) environment (most $CO_2$ reduction option), (iii) social (most participants), and (iv) trade-off (a balance between the three), which are presented in Figure 3.14 and Figure 3.15.

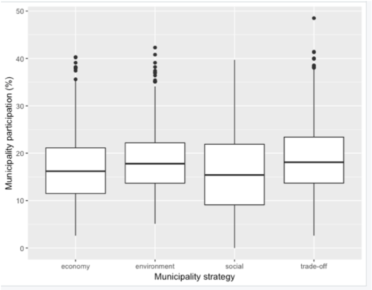

Figure 3.14.: Influence of municipality strategy on municipality participants

The results show that the municipality's strategies that lead to a better outcome in terms of $CO_2$ emission reduction and participation level are the environmental and the trade-off policies. The economic policy (only assessing the TECs based on their cost) is clearly the least effective one in smaller municipalities, as the reason might be that the neighbourhood overall has very high environmental and social concerns, so when the municipality implements an economic policy, this is misaligned with the value system of the neighbourhood. Therefore, it is less effective.

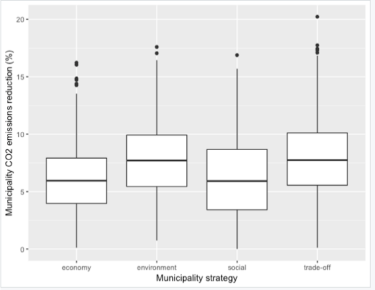

Figure 3.15.: Influence of municipality strategy on $CO_2$ emission reduction in the municipality

### 3.7.3. SUCCESSFUL AND UNSUCCESSFUL NEIGHBOURHOODS

To further understand the influence of technical and institutional conditions on the formation of TEC initiatives, we focused on the most successful and unsuccessful TEC initiatives. First, it is essential to define what a "successful neighbourhood" and "unsuccessful neighbourhood" is.

We define success with the range of simulation outcomes, i.e., their performance using the three key performance indicators: cumulative reduction of $CO_2$ emissions, duration of the formation process, and share of neighbourhood connections. For each of these KPIs, thresholds were defined for the highest 10% of the neighbourhood for each KPI. For the reduction of $CO_2$ emission percentage, for the highest 10% of neighbourhoods, this was set at a reduction of 17% or higher, the share of neighbourhood connections was 39%, and the duration process of TEC formation was 17 months or less. When combining these three criteria, the data set of the neighbourhoods that comply with it account for 5% of the total number of neighbourhoods. The unsuccessful neighbourhoods are defined as those that did not form a TEC initiative within the timeline of the models' run. Consequently, the parameters for the most successful and least successful neighbourhoods were more closely studied (See Table 3.11).

As Table 3.11 presents, the most successful communities are those whose municipality has the trade-off or environmental subsidy policy and provides training workshops. Also, the values of their TEC boards are balanced with the environmental concerns as their leading value. In contrast, the emphasis is on economic conditions and concerns within the municipality and the board for the unsuccessful communities.

## 3.8. DISCUSSION

As presented in the Introduction, this study and the results seen from the models complement existing models that explore specific aspects within thermal energy systems, (e.g. value conflicts for social acceptance of sustainable heating systems [289], and policy interventions and business models for the emergence of district heating networks [30]). Our model adds to this literature by providing insights into technical and institutional conditions relevant to the formation of TEC initiatives as a collective action ap-

Table 3.11.: Comparison of successful and unsuccessful neighbourhoods

| | | Successful neighbourhood | Unsuccessful neighbourhood |
|---|---|---|---|
| Municipalities | Subsidy policy strategy | Trade-off, Environment | Economy |
| | Training | Providing workshops for TEC board members | No workshop for TEC board members |
| TEC boards | Technology scenario | TEA +ST | ATES +ST |
| | Values | Balanced values with environmental concerns as highest | Focus only on a value (mostly economy and social) |
| | Subsidy | Yes | No |
| Households | Support | 75% | < 50% |
| | Investment | 25000 | 15000 |

proach for thermal energy generation and consumption. The results from Section 3.7 are translated into detailed discussions and recommendations as follows:

## 3.8.1. KEY INSIGHTS FROM THE APPLIED THEORETICAL ANGLES

### INSTITUTIONAL LAYERS

As presented in Section 3.7 (e.g. in Table 3.9), it can be concluded that technology selection itself is not the most crucial and determining factor for the success of thermal energy communities as much as the institutional conditions surrounding it are. These institutions can be located on the different layers of Williamson's framework [319], which correspond with different stakeholder groups:

- **Layer 1 – Cultures:** The alignment of the values held by the municipality and TEC board with those of the neighbourhood is a key condition for success;
- **Layer 2 – Institutional environment:** It is crucial to have fiscal policies, such as national subsidy and loan schemes, available that support the initial investment requirements of these communities;
- **Layer 3 – Governance:** Sharing responsibilities with the citizens themselves by ensuring active household participation is a key factor;
- **Layer 4 – Individual:** Gathering neighbourhood support is significant. It can be achieved by actively engaging with the neighbourhoods and integrating them in the design process by taking their preferences into account.

### TECHNOLOGICAL VS INSTITUTIONAL CONDITIONS

The IAD framework [110] is applied to the model's outcome to study the effect of exogenous conditions on the successful establishment of TEC initiatives:

- **Biophysical conditions:** Considering the model's simplification regarding the techno-economic aspects of the heating technologies, the results show that technology selection itself is not the most crucial and determining factor. Collective technologies are both economically and environmentally more feasible: Aqua thermal energy systems (ATES) and residual heat from surface water options are the most popular collective technological solutions and the ones that lead to a higher level of household participation and more significant $CO_2$ emissions reduction levels (see Section 3.7).

- **Attributes of the community:** Although the environmental concerns are the main driver for the successful establishment process, the model outcome shows that it is more effective to focus on visions built on a balance between economic, environmental and social considerations (see also Section 3.7);

- **Rules-in-use:** The model showed that the policy that led to the best outcome is the trade-off strategy; in addition, providing a platform to train the TEC board is considered necessary.

#### BEHAVIOURAL REASONING

The Behavioural Reasoning Theory (BRT) [320] is used to explore the relevance of context-specific reasons for and against a decision as a key predictor of the attitudes, as well as of the final decision, of the agents in the model. When examining the extent to which the values held by the TEC board are able to explain the success of the TECs, the results show that understanding the general attitude of the TEC board (i.e. whether they prioritise environmental concerns, costs minimisation or becoming energy independent) does not provide much information. Nonetheless, when delving deeper into understanding how the TEC boards specifically value different concerns (i.e., context-specific reasons), a better explanation of how internal values lead to a specific scenario preference can be provided.

### 3.8.2. LIMITATIONS

Although this study brought interesting insights to light about the formation of TEC initiatives, it has certain limitations that can be developed further. The first limitation concerns the application and conceptualisation of TEC initiatives using the theoretical concepts used in this study. The decision to use Ostrom's IAD framework together with the four-layer model of Williamson has provided a specific lens through which TECs have been researched. Despite the benefits this offers, it is crucial to keep in mind that there are also other theoretical frameworks, such as the Socio-Ecological System framework by Ostrom [120], that when applied to the same issue, system and processes, could potentially provide different insights. For example, Ostrom's Collective Action theory [108] or Theory of Planned Behaviour [353] could have derived different insights regarding the importance of building inter-actor trust in thermal energy community projects.

The second limitation is the selection of the case study. Although the Netherlands provides an opportunity to explore the TEC initiatives (See Section 3.4.2), due to the nature of the domestic heating sector, the choice of the Netherlands is a limitation. This influences data collection and the chosen technical and institutional conditions to conceptualize in the model and then investigate (e.g. input data on heat pumps and solar thermal energy systems). Even though the model relies on the input data from the Netherlands, the results and recommendations are to some extent generalizable as they are seen in relative rather than in absolute terms. More importantly, the results and findings of this study are in line with findings from empirical and theoretical studies from other European countries, like [14], [4], [113]. It would be still insightful to adapt the model's inputs to fit the context of another country (e.g. Sweden, Denmark or Germany) and to compare the differences in the outcomes of the model and its relation with the differences in the initial conditions of multiple countries.

Furthermore, a previous study showed that for modelling heating transitions at the local level, information is missing in the heating transition data ecosystem [354]. This mainly pertains to empirical data on collective heat generation and distribution. However, more general empirical data on the thermal energy community is scarce. Therefore, more empirical research, both explorative and descriptive, is needed; for instance, case study research about ongoing TEC initiatives in a number of (Dutch) cities can be beneficial. The national statistical data was used in this study, while empirical data from actual local initiatives would have led to more practical and applicable insights.

Moreover, the modelling approach itself has limitations. Models are representations of a selected aspect of the world. Therefore, by definition, models cannot include all the details of the objects they represent and have their own specific limitations [355]. As such, our model's assumptions and structure can be improved. More specifically, technological aspects are simplified in this study's modelling exercise. The reason for this was to focus on institutional design insights rather than to explore the techno-economic feasibility of TEC initiatives and to provide insights on technical design. Therefore, as long as these simplifications and limitations are considered, they do not jeopardize the results and outcome. The model could be coupled with a technical optimization model to overcome these limitations for the technical outcome to be completer and more conclusive. The model presented in this study explores the fully renewable thermal energy system, however, it is also meaningful to explore thermal energy communities that are based on using both renewable and natural gas as energy sources. Finally, further research on the stakeholders' roles could improve the model's insight. For example, the model has extensively studied the role of the municipality as a resource supporter, while in reality, their function is much more complex than this.

## 3.9. CONCLUSION

The number of community energy projects in Europe is rapidly growing and is expected to impact the energy sector on this continent significantly. Energy communities are key elements of the energy transition at the local level as they aim to generate and distribute energy based on renewable energy technologies. This research aimed to investigate the technical and institutional conditions that influence the formation process of energy communities with thermal applications (TECs); in particular, to speed up the transition to a sustainable heating sector. The focus was on understanding which conditions enhance (i) the fastest formation process, (ii) the higher degrees of community participation, and (iii) the higher $CO_2$ emission reduction levels, as three indicators for analysing the formation of TECs. To do so, an agent-based model was built, using the Netherlands as a case study to populate the model based on real-world data.

TECs consist of three main components: (thermal) renewable energy technology, stakeholders, and related institutions. TECs can include either collective and individual heating components, or both, simultaneously regarding the technological conditions. The analysis results show that households prefer scenarios combining collective and individual technologies. Aqua thermal energy systems (ATES) and residual heat from surface water options are the most popular collective technological solutions and the ones that lead to a higher level of household participation and a more considerable reduction of $CO_2$ emissions. However, the model also showed that technology selection itself is not the most crucial and determining factor for the successful establishment of TEC projects. Instead, it is the institutional conditions surrounding TECs. Considering this study's modelling simplifications and limitations (see Section 3.5 and Section 3.8), the overall results indicated that TECs could potentially be formed on average within three years with a high level of support from the households (e.g. approximately 50% on average). Although few runs are fully covered, financially, by households, municipalities would be required to invest at least 30% of the project costs, in reality.

Regarding the institutional context, the model demonstrates that projects are likely to be successful when stakeholders share a common vision that highly and equally values: (i) developing energy independent communities; (ii) using environmentally-friendly heating generation technologies; and (iii) providing heat at an affordable price for the consumers. Lastly, the results demonstrate that it is crucial to have supportive institutional conditions responsive to the local context and local needs. To develop such an enabling institutional environment in the Dutch context, based on the results of this study, we recommend (i) sharing decision-making and financial responsibility among all actors involved in the design and implementation of municipal heat plans; (ii) designing fiscal structures that focus on supporting those TEC projects that are able to balance out project costs with their potential environmental impact; and (iii) developing programmes that improve the marketing capabilities of TEC boards to increase residents' knowledge about the heating transition and their participation in TECs. These actions and policies have been widely used in the Netherlands to facilitate renewable energy communities. However, we suggest this is also needed to help TECs build capacities. In the Dutch context, platforms such as 'Buurtwarmte' [356] (in English: Neighbourhood heat; translation by the authors), set up by the Dutch community energy branch association 'Energie Samen', are helpful initiatives as they seek to help individuals who want to form their own TEC initiatives and facilitate the formation process.

These results provide new insights for stakeholders, especially policy-makers, municipalities and households, with technical and institutional conditions to enhance the development of TEC initiatives that contribute to the local energy transition. The model and results presented in this research are based on certain assumptions and theoretical background (see Section 3.3, Section 3.5 and Section 3.6) for exploring TECs within a Dutch context. As presented in Section 3.8.2, it would be insightful to use other theories and countries as a case study to further generalise the insights provided by this research for further research. Furthermore, a more detailed consideration of housing insulation in the model, instead of a modelling parameter, can also provide extra insights into how households at a community level can achieve more sustainability. All these would further support the exploration of the most supportive technical and institutional conditions for TEC initiatives with different starting conditions. Also, more reliable empirical data is needed to have more insightful outcomes. Conducting surveys and expert interviews would be helpful for this. Finally, other computer modelling approaches, such as optimization and equilibrium modelling, would be useful for studying other topics related to TEC initiatives.

# 4

# MODELLING COLLECTIVE ENERGY SECURITY

Energy communities as decentralised renewable energy systems, where energy is jointly generated and distributed among a community of households, are gaining momentum in the energy transition context. Given the distributed and collective action nature of energy communities, energy security of these local energy systems is more than just security of supply and is related to issues such as affordability and acceptability of energy to community members. This chapter presents an agent-based model of energy communities based on solar photovoltaic assisted heat pumps, as the most commonly used technologies in this context, to explore their energy security challenges. The security dimensions that are considered are availability, affordability, accessibility and acceptability, referred to as the 4A's energy security concept. The results confirmed that there is always a trade-off between all four dimensions and that although it is difficult to achieve a high energy security performance, it is feasible. Considering the heterogeneity of households' motivations and attributes, the community energy systems demonstrated substantial potential to reduce $CO_2$ emissions while being affordable over a long-time horizon. Results also showed that the community's investment plays the most significant role among factors influencing energy security. [1]

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[1] This chapter is expansion of the work published as J. Fouladvand, D. Verkerk, I. Nikolic, A. Ghorbani, (2022). Modelling Energy Security: The Case of Dutch Urban Energy Communities. In: Czupryna, M., Kamiński, B. (eds) Advances in Social Simulation. Springer Proceedings in Complexity. Springer, Cham. The first author has conceptualised and performed the research. The other authors have performed an advisory role.

## 4.1. INTRODUCTION

The energy sector has the most significant potential to reduce greenhouse gas (GHG) emissions [143]. Shifting from centralised energy systems to decentralised renewable energy technologies (RETs) is expected to fundamentally contribute to energy transition goals [144]. Therefore, local community initiatives, namely energy communities, are gaining momentum as one of the possible approaches to enlarging the share of local RETs [144].

Community energy systems (CESs) (interchangeably also used as energy communities) contribute to the local generation, distribution and consumption of RETs [27]. Although there are different definitions of CESs in the literature, a CES can be defined as "people in a neighbourhood, who invest in RETs jointly and generate the energy they consume." [6]. This definition and other ones in literature (e.g. [5], [8], [7], [9], [10], [11], [146], [147]), all emphasize on collective action of individuals in decision-making processes and actions within CESs [13].

A crucial topic for CESs is the energy security of these energy systems [357], [188]. Energy security is a complex concept [62], and various disciplines such as public policy, economics, and engineering contribute to its definition [64]. Traditionally, the main focus of energy security was only on the security of supply (i.e. availability) [60]; however, this has changed, and energy security approaches have become more comprehensive with several other dimensions [76].

As a result, the energy security literature has included environmental aspects and cost [76] as energy security dimensions. For instance, Asia Pacific Energy Research Centre (APERC) energy security definition is: "The ability of an economy to guarantee the availability of energy resource supply in a sustainable and timely manner with the energy price being at a level that will not adversely affect the economic performance of the economy" [60]. This definition and other ones in the literature (e.g. [60], [76] [18]) are developed mainly for conventional energy systems, namely centralised, fossil-fuel-based and national energy systems [60]. These definitions have not yet been explored in the CESs context to match the unique characteristics of CESs (such as being based on collective renewable energy generation and distributed RETs). Thus, in this chapter, we explore the energy security of CES using Agent-Based Modelling (ABM), given the bottom-up and collective nature of these energy systems. Although there are already many existing models of CESs (e.g. [27], [97], [30], [102]), none have addressed the security of these systems and, as a matter of fact, collective energy security in general. The goal of the model is to explore the impact of various parameters on the energy security of such collective energy systems, namely energy communities. The ABM is developed based on the 4As energy security concept [60].

The structure of this chapter is as follows: Section 4.2 provides an overview of ABM in the energy transition context. The 4A's energy security concept, as the backbone of the energy security concept in our modelling exercise, is presented in Section 4.3. Research methods are introduced in Section 4.4. Model conceptualisation and implementation, which entails the description and development of an ABM, is presented in Section 4.5. Section 4.6 is dedicated to results. Finally, discussions, conclusions and recommendations are presented in Section 4.7.

## 4.2. AGENT-BASED MODELLING IN THE ENERGY TRANSITION LITERATURE

Many studies employ agent-based modelling (ABM) to study energy communities in the fast-growing literature on energy communities. Studying value conflict for acceptance of decentralised energy systems (e.g. [95]), policy interventions for scaling-up RETs' infrastructure (e.g. [30]), and renewable energy technology adoption (e.g. [104]), are examples of the topics that are explored by using ABM in the energy community context. Although there are overlaps, the overarching topics explored in these models can be divided into three main categories: behavioural attitudes, institutional design, and technical system design.

The behavioural attitude of individuals and the role of leadership in the formation of energy communities is studied in [97]. Consumers' behaviour and the demand-side of the energy system are discussed in [104]. A multi-agent model to analyse the energy-saving behaviour of urban residents in China is presented in [96]. Also, Consumers' behaviour and the demand side of the energy system are discussed in [358]. Using ABM, [95] also explores five types of value conflict of individuals within energy communities. Another example is the model presented in [359], which focuses on prosumers' behaviour, including technological and spatial constraints. A model for analysing urban energy networks is also studied in [360]. Bellekom et al. explore energy exchange between prosumers and consumers to observe how the presumption affects the self-consumption of a neighbourhood [361].

The influence of regulatory framework on the adoption of renewable technology is explored in [104]. This study examines how additional rebates (i.e. partial refund of an item's cost) for low-income households and changes in the rebate amount affect the adoption of solar photovoltaic (solar PV) in Texas. [102] also explores the adoption of solar PV and its related institutions (e.g. pricing and ownership). Studies such as [27], [30], [289] are focused explicitly on thermal energy systems, where the generation, distribution and consumption of heating energy for communities is the core. [27] explores four main factors that influence TECs' formation, while [30] diving into regulations and institutional conditions for TECs' operation. [289] studies value conflict and social acceptance of sustainable heating systems. The model by Lee & Hong [362] allows to explore the effect of five factors on solar PV adoption: building-related physical factors, population-related demographic factors, PV system-related technical and economic factors, and social factors (i.e. number of neighbouring adopters). Insights for both institutional design and infrastructure planning are brought by [363], where various involved stakeholders and the physical solar PV system are modelled. A control system for decentralised energy systems using ABM is developed in [364]. [365] studies distributed energy grid systems on a larger scale.

Along with these studies, review studies such as [366] (with focus on buildings demand and indoor environment), [365] (with an emphasis on climate-energy policy), [367] (with an emphasis on technology adoption), [368] (with focus on socio-technical energy transition), provide a literature review on various developed ABMs for studying energy systems. Nevertheless, none of these studies and models has explored the energy security of energy communities.

## 4.3. 4A'S ENERGY SECURITY CONCEPT

Along with their energy security definition, APERC also proposed the 4As' energy security concept: availability, accessibility, affordability and acceptability [66]. The 4As concept provides room to capture the collective nature and decentralised characteristic of CESs and is therefore selected as the core definition of energy security for this modelling exercise.

- **Availability** is about the physical existence of the energy resources to be used for the energy system [16]. An indicator to measure availability is the domestic energy generation per capita of an energy system (either by fossil or renewable energy) [66]. Another indicator is the shortage percentage, which occurs when there is a mismatch in demand-supply and individuals are disconnected from energy supplies [369].
- **Affordability** is related to the costs of the energy system and whether it is affordable or not [66]. Among different affordability indicators, energy price is the most common [62]. The size of investments made to improve energy security [64] is another affordability indicator in the literature.
- **Accessibility** can be defined as having sufficient access to commercial energy to promote an equal society [66]. Diversification of energy resources is a popular indicator to increase and measure accessibility [62]. Diversity indexes quantify the diversity in energy supply to eliminate supply risks [62]. Multiple integrated diversity indicators are presented in the literature, such as the Shannon index [62].
- **Acceptability** refers to the social opinion and public support toward energy sources [62]. This is often linked to societal elements such as welfare, fairness and environmental issues [76]. Although APERC uses an economy's effort to switch away from carbon-intensive fuels as an indicator for acceptability [66], carbon content and the $CO_2$ emission of an energy system as a whole are also suggested as indicators for acceptability [62].

## 4.4. RESEARCH METHODS AND DATA

### 4.4.1. AGENT-BASED MODELLING (ABM)

In the CESs' literature, optimisation is the primary computational approach for studying energy security (e.g. [75]). Such studies do not capture the complexities and trade-offs of decision-making processes regarding collective energy security. However, as CESs are based on the collective action of individuals who have different motivations and criteria to make decisions, it is meaningful to study such decision-making processes. ABM provides the opportunity to capture individual agents' behavioural choice and their collective actions, while agents are heterogeneous, autonomous and individual decision-making entities (such as households) [87]. ABM also allows the time variable to be added [91], which allows for examining different energy security scenarios. This is important, as individual decisions, the trade-offs related to energy security, and the ability to adapt and learn from each other towards collective energy generation influence every four dimensions of energy security of CESs.

### 4.4.2. PARAMETERISING USING DUTCH DATA AND SENSITIVITY ANALYSIS

Data from Netherlands Environmental Assessment Agency (PBL) and Statistics Netherlands (CBS) are used to parameterise the model (e.g. [141]). To model agents' decision-making processes, data from the survey among 599 Dutch citizens about their motivations for joining CESs [58] is used, which will be further explained in Section 4.5.2 and Section 4.5.3. Furthermore, a sensitivity analysis [351] was conducted for various model parameters to explore different experimental configurations to explore the uncertainties systematically. This was done by following the one-factor-at-a-time (OFAT) approach [351]. All the parameters were fixed at a certain value, and only the value of the study was altered. For each parameter, the model was run 30 times, and boxplots were generated to delineate whether the parameter setting significantly influences the model's outcome. Appendix C presents the sensitivity analysis parameters and results.

## 4.5. MODEL CONCEPTUALISATION AND IMPLEMENTATION

This section describes the model conceptualisation and implementation using the ODD protocol [370].

### 4.5.1. MODELLING PURPOSE

The purpose of the model is to explore the energy security of CESs as collective distributed RETs. This is done by investigating the impact of various parameters (see Section 4.5.6) on the energy security of CESs based on solar photovoltaic (PV) and ground-source heat pumps.

### 4.5.2. ENTITIES AND STATE VARIABLES

Households are the only agents in the model. They use the national electricity grid and natural gas before joining a CES. We assume that these agents are in one neighbourhood and have already decided to join a CES at the start of the simulation. Being a member of a CES means the households have three energy choices, namely, (i) collective RETs, (ii) individual RETs, and (iii) national grid. Individual households select the latter two if the energy provided collectively does not meet their demands. The attributes of the households are energy demand, budget and internal motivations (that change during the simulation based on their network, see Section 4.5.3 and Section 4.5.4). Following [6], [58], the motivations taken into account are energy independence, trust, environmental concern and economic benefits, each having a value between 0 to 10 (0 weakest, 10 strongest).

### 4.5.3. INTERACTIONS, NETWORK AND ADAPTATION

The households are connected using a small-world network [332], commonly used in the context of CES (e.g. [97], [371], [272]). In each tick (representing a month), a random agent interacts with one of the other agents in its social network and is influenced by it. Suppose the agent's motivations (i.e. energy independence, trust, environmental concern and economic benefits) are between 2 and 8 (i.e., the values are not extreme and hard to change [30], [372]). In that case, they will be updated, leaning one value towards the interacting neighbour's opinion, for better or worse. This form of social interaction is used at the beginning of each simulation step to update the motivations for each agent. These connections eventually lead to the whole community making a decision about their CES.

### 4.5.4. MODEL INITIALISATION AND NARRATIVE

Before a CES initiation, the household agents used natural gas and the national electricity grid to cover their demand. To make the decision on different sources of energy (i.e. collective RETs, individual RETs, or continuing using a national grid) for the CES, the households first go through a period of information exchange, which means connected individual households learn more about their neighbours' motivations and possibly grow more towards each other. This is based on social interactions that are presented in Section 4.5.3 After the period of information exchange, households have three decisions to make, namely: (i) Selecting the percentage of renewable energy that they want to generate collectively together, (ii) Selecting an additional individual RETs in case the collective renewable generation does not fully cover the demand, and (iii) after the technology reaches its lifetime, involving new participants and deciding on continuing participating and new CES. The processes of these three decisions are as follows:

- First, the households decide how much collective renewable energy they want to generate together, which may not always collectively cover all the needed demand. Therefore, the households select a fraction between 0% – 100% of the whole community demand to be covered by collective renewable energy generation (for this study, solar photovoltaic (PV) and ground-source heat pump, see Section 4.5.5). More environmental-friendly households (i.e., more significant environmental concerns) select higher collective renewable energy generation. The constraint, however, is in the initial investment, as higher collective renewable energy generation needs higher investment. Each agent will make an individual decision about its preferred percentage of collective renewable energy. The percentage selected the most among the agents is for the whole community.

- When the selected collective renewable energy generation doesn't fully cover all the community demand, the households depending on their individual motivations, have three options: (i) import energy from the grid (i.e. continue to consume natural gas and the national electricity grid), (ii) selecting an individual RETs, and (iii) compensate their energy demand (i.e. lowering the demand and facing discomfort). The decision-making about this choice is as follows: If an agent's economic benefits value is greater than its environmental concerns, it selects to use the national grid for the remaining demand that the selected collective renewable energy generation does not cover. If an individual agent has more significant environmental concerns than economic benefits hence does not select the national grid, there are going to be two options:
    - If the agents have a sufficient budget, it selects individual renewable energy generation,

  - Suppose the budget is insufficient to select and invest in individual renewable energy generation at a particular tick. In that case, the agent selects to compensate for their energy demand and save-up money to invest in individual renewable energy generation in the future. This means that the individual household will face voluntary energy discomfort/ shortage due to unmet demand. In reality, this can be translated in different ways, such as: (i) turning off/ down the energy system inside the homes in the absents of individuals, (ii) shifting the demand from peak hours, (iii) reducing energy consumption, such as hot tap-water consumption.

- Lastly, every year (12 ticks in the simulation), the community checks (i) whether they have reached the end of their project time horizon and (ii) whether the technologies in place have reached their lifetime. If the technologies indeed reach their lifetime, the community will start another information exchange period including new members (i.e. new households who moved to the neighbourhood) and deciding on selecting a new energy configuration (i.e. 0% - 100% collective renewable energy generation). The new households have their own motivations, energy demands, and investments so the new collective renewable energy generation might differ. When the community selects the new percentage of collective renewable energy generation, the households who have a different preference over the new percentage leave the CES, which means they are disconnected from the CES (i.e. they connect fully to the national grid or get their energy demand elsewhere). Figure 4.1 presents the model conceptual flowchart.

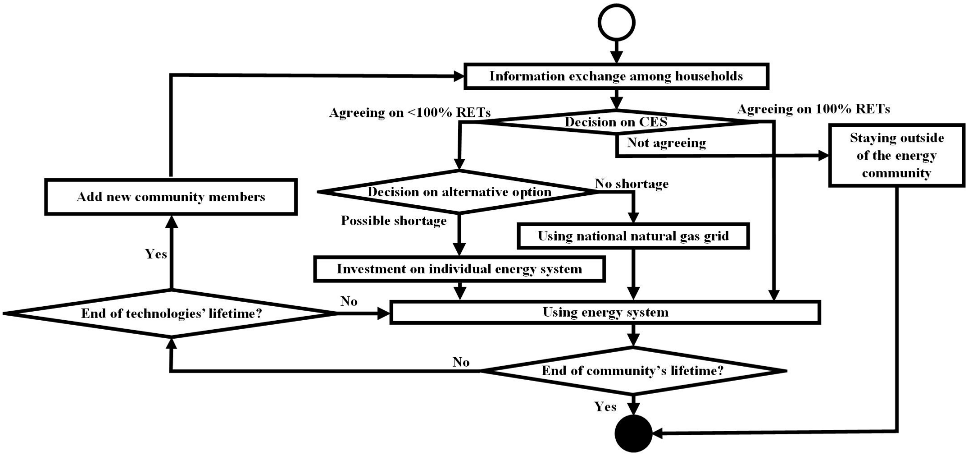


Figure 4.1.: Model conceptual flowchart

### 4.5.5. 4AS AS KEY PERFORMANCE INDICATORS (KPIS)

Using 4A's energy security concept, four key performance indicators (model's KPIs) are defined to measure energy communities' energy security. Detailed calculations related to these KPIs are presented in Appendix C.

#### AVAILABILITY: AVERAGE VOLUNTARY DISCOMFORT PERCENTAGE

To assess availability, a measure is used that indicates to what extent the energy is available to meet the demand of each agent [373]. Therefore, availability can be explored by calculating the average percentage of the energy demand per year which is not met. This can be translated as discomfort for households in the real world, as elaborated in Section 4.5.4.

#### AFFORDABILITY: AVERAGE COST

To assess affordability, a measure is used that calculates the total system costs per agent [373], based on three main sources of costs: collective renewable thermal energy system, individual renewable thermal energy system.

#### ACCESSIBILITY: DIVERSITY INDEX

Diversification is used to measure the accessibility of a CES [62]. In this modelling exercise, the diversity index is based on the Shannon index [373].

#### ACCEPTABILITY: $CO_2$ REDUCTION PER HOUSEHOLD

As acceptability is linked to environmental issues and reducing $CO_2$ emissions of the energy sector [64], the $CO_2$ reduction is measured in the model to assess acceptability.

### 4.5.6. TECHNICAL ASSUMPTIONS AND MODEL INPUTS

Households have three available energy options: (i) national grid, (ii) collective RETs (i.e. collective solar PV and heat pump), (iii) individual RETs (i.e. individual solar PV and heat pump). Two reasons account for the selection of such combination: (i) solar PV is a mature technology, and it is the main technology that the majority of current CESs are using [372]; (ii) heat pumps are selected for the reason that they are commonly connected to solar PV, to prepare for the transition towards electricity-based heating systems [374]. Appendix C presents the assumptions related to these technologies and the neighbourhood.

### 4.5.7. MODEL PARAMETERS AND EXPERIMENT SETTINGS

To explore the energy security of CESs, the following four parameters are selected from the literature that are potentially influential for energy security:

- **The demand of the households:** Since one of the primary motivations of CESs is to generate energy to meet the local demand [13], energy demand is essential for a CES. Following [76], [374], we hypothesise that lowering the energy demand helps enhance energy availability and, therefore, energy security.

- **Budget of households:** Investment size plays a significant role in CESs [6]. At the same time, higher investments can play a considerable role in increasing availability and affordability and, therefore, security of an energy system [62].

- **Energy prices:** Rising energy prices are argued as an effective strategy to lower energy consumption and an opportunity for the deployment of CESs in the literature [372]. The energy security literature argues that higher energy costs result in lower affordability and, therefore, lower energy security [76], [374].

- **Willingness to compensate for overuse of energy grid:** According to the participatory value evaluation theory, people are willing to accept changes in the provision of public goods [70]. The energy security literature has also explored willingness to compensate as important for the 4As' dimensions [70].

We use these four parameters as input to our modelling exercise. Using data from PBL, the average households demand and natural gas price were extracted. The experimentation includes 108 different combinations of settings for the four parameters (4*3*3*3=108), as shown in Table 4.1. Each combination was repeated 100 times; hence, the experimentation resulted in a total number of 10800 runs.

Table 4.1.: Experimental settings

| Model parameter (Unit) | Value |
|---|---|
| Each household demand (kWh/year) | 8185, 15161, 22622, 30084 |
| Natural gas price (€/kWh) | 0.09, 0.12, 0.15 |
| Willingness to compensate (%) | 10, 20, 30 |
| Budgets/ Investment-size (€) | 2500, 5000, 7500 |

## 4.6. RESULTS

In this section, we present the results of the simulation analysis. These results are discussed at three levels: (i) Overview of the KPIs, and (ii) most and least successful energy security performances.

### 4.6.1. OVERVIEW OF EACH KPI INDIVIDUALLY

In this stage, results for the final end-state of each run (i.e. at the end of the 55th year) for each KPI are presented separately. In Figure 4.2, the results are categorised into three categories:

- **Best results:** the best 10% of runs for each specific KPI (green colour);

- **Worst results:** the worst 10% of all runs for each particular KPI (red colour);

- **Others:** remaining 80% of the runs (grey colour).

#### KPI 1: AVERAGE VOLUNTARY DISCOMFORT PERCENTAGE

The simulation results for the average percentage of voluntary discomfort/ shortage are always less than 20%. As presented in Figure 4.2, only 10% of the runs have a discomfort percentage higher than 9%. These runs include communities with the most environmental-friendly behaviour (i.e. most significant environmental concern) but not financially strong enough to have a 100% collective energy system. Therefore, they voluntarily selected discomfort instead of the national grid for the demand that they do not meet. There is a prominent peak in the 0% discomfort, mostly for runs that selected a 100% collective energy system. These communities are also the most environmental-friendly but with substantial financial resources. However, the majority of the simulation runs are in the middle range of the discomfort percentage, between 4% and 9%. Lower demand, higher energy generation and higher energy import lead to the best performance of this KPI. While higher budgets showed positive influence, natural gas price and compensation were not impactful.

### KPI 2: AVERAGE COSTS

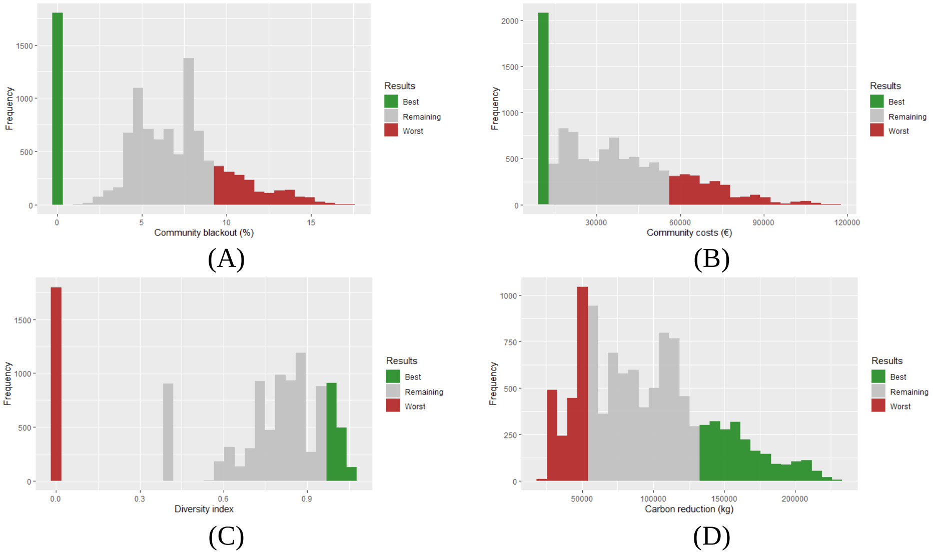
Average costs are calculated for each household based on the cost of the community in its lifetime (i.e. at the end of the 55th year) divided by the number of households. As Figure 4.2 illustrates, the majority of runs have low costs. Considering the assumptions related to current and future energy prices, 75% of all runs have better performance than using only the national grid. This means individual households who participate in a CES spend less money over 55 years on their energy bills. All the communities with the lowest costs are communities with the lowest demand. However, this does not necessarily mean higher investment as they have various investment sizes. Higher import independence (higher energy import from outside system boundaries) is usually more likely to lower costs. Natural gas price, willingness to compensate, and energy generation did not significantly influence KPI 2. Also, environmental-friendly agents are distributed within all communities; however, their population is more condensed within communities on average and lower costs.

### KPI 3: DIVERSITY INDEX

The diversity index is used as an indicator to measure the accessibility dimension in CESs. There is a peak at 0, which shows the dominance of a specific energy source, e.g. Solar PV, as presented in Figure 4.2. These communities select 100% collective renewable energy generation and have low energy demand and a large investment budget. However, the majority of the runs have a diversity index between 0.6 and 0.9, which means they have both collective and individual energy generation (with different generation capacity 10%-100%) and natural gas as their energy source. The runs with a diversity index higher than 0.9 have various parameters settings (see Section 4.5.5), but the high willingness to compensate is high among them.

### KPI 4: $CO_2$ REDUCTION INDEX

The carbon reduction index measures the average $CO_2$ reduction of each CES participant through its lifetime (i.e. the end of the 55th year); therefore, it represents the acceptability dimension. As the communities at least have to select 10% RE generation, the carbon reduction is always more than 0, see Figure 4.2. The best performance for this indicator is for communities with $CO_2$ reduction higher than 130.000 kg, which mostly have high budgets and environmental-friendly motivation. However, they have various demands, different natural gas prices and different “willingness to compensate” values. The communities with the lowest $CO_2$ reduction have the lowest budget.



(A) (B)

(C) (D)

Figure 4.2.: Overview of KPIs

## 4.6.2. MOST AND LEAST SUCCESSFUL ENERGY SECURITY PERFORMANCES BASED ON ALL 4 KPIS

CES (i.e. computer runs) with the overall most and least successful energy security performance are analysed in this part. The procedure to define these energy security performances is as follow:

- **Most successful performances:** From the 10800 model runs, for each KPI, the 50% of best performances are extracted separately. This gives us for each KPI 5400 runs that have performed the best. The overlapping runs are selected within these four sets of 5400 runs, with only 197 model runs in total. These 197 runs are the CESs with the most successful energy security performances for all the KPIs.

- **Least successful performances:** Through the same process, 50% of the worst performances are selected separately for each KPI, and then the overlaps are extracted, leading to 458 runs. These 458 runs are the CESs with the least successful energy security performances for all the KPIs.

Consequently, the values of the four parameters for the most and least successful were more closely studied. A clear division was identified between the most and least successful performances for the budget and willingness to compensate. The 197 most successful runs are dominated by the highest budget and average willingness to compensate. On the other hand, the least successful performances have the lowest budgets and lowest willingness to compensate. Natural gas price varies for both energy security performances. However, most successful performances do not have the highest natural gas price. Figure 4.3 illustrates these findings.

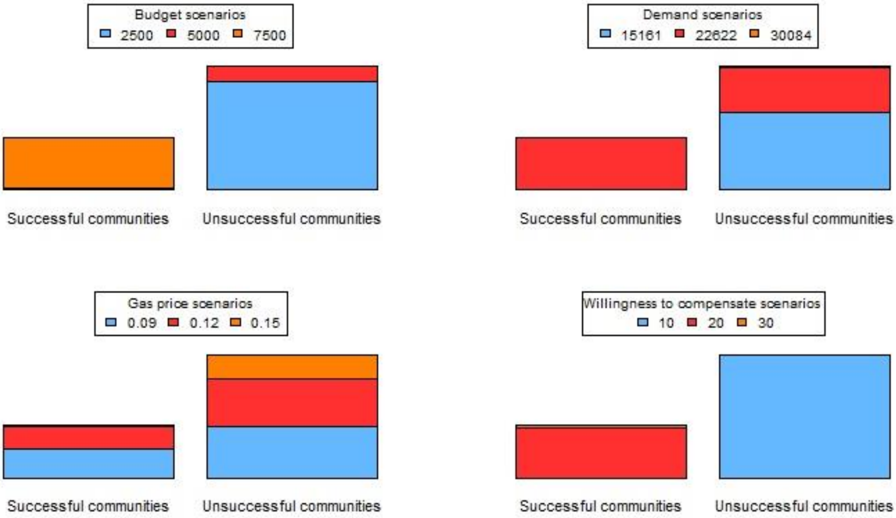


Figure 4.3.: Most and least successful energy security performances

## 4.7. DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

As key elements of the energy transition at the local level, community energy systems (CESs) are establishing swiftly as collective distributed renewable energy systems. Consequently, the body of literature on CESs is growing rapidly. Yet, little attention is given to the energy security of CESs, and the need to understand what energy security implies for them is becoming more vivid. Therefore, by using the 4A's energy security concept [66], this research aimed to study the energy security of CESs through an agent-based modelling approach for the first time.

Considering one KPI at a time, CESs are able to perform well for each one. Specifically, 10% of CESs had 0% voluntarily discomfort/ shortage (as an indicator for availability), and on average, all CESs reduced their $CO_2$ emission by 35% (as an indicator for acceptability). CESs also performed considerably well for the average cost of households (as an indicator for affordability). On average, the costs per household are around 45000€ over 55 years, which is less than current energy prices. Considering the technical and economic considerations of the technologies (see Section 4.5.5), this shows overall that CESs are economically feasible under the suggested parameter settings of this research.

There are still communities with an average cost of 70000 € per household, highlighting the economic challenges that studies such as [375] also mentioned.

Diversity (as an indicator for accessibility) showed various values between 0 to 1. The runs with 0 value in diversity are the communities with 100% collective renewable energy generation (and not 100% individual renewable energy generation or 100% national grid). The runs that used all three possible energy resources (i.e. the national grid, collective and individual renewable energy generation) have relatively higher performance in the diversity index. Considering the heterogeneous attributes of the agents (i.e. energy demand, budget and internal motivations), the results highlighted that agents intend to select diverse technological options to avoid shortage and reduce their $CO_2$ emissions.

However, energy security is a multi-dimensional concept, which means that all the dimensions should be considered and analysed simultaneously. To draw the whole picture and investigate four dimensions together, we analysed CESs with most and least successful energy security performances. Our analysis delineated that there are always trade-offs between the four dimensions, as, among 10800 runs, only 197 (less than 2% of all runs) have a performance that is considered successful in all four KPIs (i.e., >50%). Although it is rare to have a high performance for all four dimensions simultaneously, these successful performances showed that it is feasible to reduce $CO_2$ emission while not facing any discomfort and financial consequences. On the other hand, the portion of unsuccessful performances (i.e. <50% in all four KPIs) is two times higher (458 runs out of 10800 runs, 4.2% of total runs).

To analyse the four input parameters (i.e. demand, investment size, willingness to compensate and prices), a comparison between successful and unsuccessful energy security performances (i.e. four KPIs together) was performed. This comparison indicates which parameter leads to better performance. The only parameter which explicitly indicated an impact on successful vs unsuccessful performance is the budget. The successful performances have the highest budget (7500 €), and the unsuccessful ones are dominated by the lowest (2500 €). However, willingness to compensate and demand do not significantly impact success performance. For instance, the lowest demand (i.e. 15161 kWh) is the dominating demand parameter value among the unsuccessful performances. This is in contrast to the current body of literature which argues less demand leads to a better performance in energy security [76], [374]. Lastly, natural gas prices did not significantly influence the energy security of CESs as the unsuccessful performances have the full range of natural gas prices and the successful ones have 0.09 and 0.12 €/kWh.

Although the current study sheds light on the energy security of CESs, it has certain limitations, which highlight avenues for further research. First, it is still more of a conceptual model. Expanding and developing the model in more detail would be meaningful to have more realistic results and insights. For instance, adding other renewable energy technologies (e.g. geothermal wells and wind turbines), other actors (e.g. municipalities and community-boards), more detailed decision-making processes, and institution settings could potentially contribute to this end.

A second limitation is selecting the energy security concept for this modelling exercise. Although 4As' energy security concept and its representative indicators were useful for studying the energy security of CESs (as elaborated in Section 4.3), it is essential to keep in mind that there are other energy security concepts and indicators as discussed in [64], [76]). Lastly, using theories such as Ostrom's Collective Action theory [108], Social Value Orientation (SVO) theory [376] and Theory of Planned Behaviour [353] could have led to more realistic and detailed insights regarding the influence of households' motivations and decision-making processes on energy security.

The results can be translated into policy recommendations for further establishment of energy-secure CESs:

- CESs could substantially contribute to $CO_2$ emission reduction targets while not drastically negatively influencing cost or discomfort. Therefore, it is essential to support the CESs establishment.

- The budget is the most important consideration for establishing energy-secure CESs, as it can be a constrain for environmental-friendly households and a concern for economically driven households. Therefore, providing more support (e.g. subsidies and loans) is effective and essential.

- Energy demand is not the most influential consideration for the energy security of collective energy systems. Therefore, other policies and strategies such as RE subsidies could potentially impact collective energy security, then energy demand reduction policies. Nevertheless, households with relatively high energy demand need to reduce their demand to contribute to long-term security and environmental targets [19].

- The current PBL energy price scenario (0.12 €/kWh) is successful, as higher energy prices do not lead to successful performances, and no significant influence of energy prices was identified.

# 5

# ENERGY-SECURE THERMAL ENERGY COMMUNITIES

In community energy systems, the energy demand of a group of households is met by collectively generated electricity and heat from renewable energy sources. What makes these systems unique is their collective and collaborative form of organization and their distributed energy generation. While these features are crucial to the resilience of these systems and are beneficial for the sustainable energy transition in general, they may at the same time undermine the security of energy within these systems. This chapter takes a comprehensive view of the energy security of community energy systems by considering dimensions such as affordability, accessibility and availability, which are all impacted by decentralized and collective means of energy generation and distribution. The study analyses community energy systems' technical and institutional characteristics that influence their energy security. An agent-based modelling approach is used for the first time to study energy security, with a focus on thermal energy communities given the considerable share of thermal energy applications such as heating, cooling, and hot tap water. The simulation results articulate that energy communities are capable of contributing to the energy security of individual households. Results also demonstrated the substantial potential of energy communities in $CO_2$ emissions reduction (60% on average) while being affordable in 20 years. In addition, the results showed the importance of project leadership (particularly regarding the municipality) in relation to energy security performances. Finally, the results reveal that the amount of available subsidies and natural gas prices are relatively more effective for ensuring high energy security levels than $CO_2$ taxes. [1]

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[1] This chapter has been published as J. Fouladvand, A. Ghorbani, Y.Sarı, T. Hoppe, R. Kunneke, and P. Herder, "Energy security in community energy systems: An agent-based modelling approach," J. Clean. Pro, vol. 366, p. 132765, 2022. It has been slightly modified textually for alignment in this study. The first author has conceptualised and performed the research. The other authors have performed an advisory role.

## 5.1. INTRODUCTION

The energy sector has the most considerable potential to reduce greenhouse gasses (GHG) emissions [143], mainly by deploying renewable energy technologies (RETs) [318]. One of the possible approaches to enlarge the share of renewable energy in this sector are local community initiatives commonly referred to as community energy systems [4]. Community energy systems (CESs) promote local collective citizen action, which addresses various aspects of the sustainable energy transition to low carbon energy systems, including generation, distribution and consumption of energy for their community members [12].

CESs have received considerable attention in the academic literature over the past years. These systems have been studied from several disciplinary angles: technological (e.g. [52]), behavioural (e.g. [21]), organizational (e.g. [316]) and institutional(e.g. [59]), among others. In this relatively mature literature, however, little attention has been given to the energy security of CESs [41].

As one of the focal points in the energy-related literature, energy security is a complicated concept [64]. Traditionally energy security was defined in terms of security of supply [64]. However, in the academic literature, attention has shifted to a more comprehensive approach, with several other dimensions (e.g. affordability, environment and efficiency). Among many definitions (as presented by [64]), the Asia Pacific Energy Research Center (APERC) defines energy security as: “The ability of an economy to guarantee the availability of energy resource supply in a sustainable and timely manner with the energy price being at a level that will not adversely affect the economic performance of the economy” [63]. Along with this definition, APERC suggests the “4A’s concept” to measure energy security, i.e. in terms of availability, affordability, accessibility and acceptability.

Besides the diversity in definitions, the energy security literature mainly focuses on conventional energy systems, namely centralized, fossil-fuel-based and (inter)national energy systems [64]. There are only a limited number of papers addressing the security of decentralized energy systems. In contrast to the broader energy security literature, they mainly consider the narrower and traditional notion of security of supply of these energy systems. Given the collective and decentralized nature of CESs, other security dimensions also seem to play a crucial role. More specifically, energy may not be available at all times, especially when the system is not connected to the national grid [47], and energy may not be accessible at all times, given the distributed infrastructure and the intermittent nature of renewable energy sources [102]. Community energy may not be affordable for everyone given the upfront investment costs, among other factors [14]. Increasing energy efficiency levels and reducing environmental impacts of (local) energy systems such as CESs also offer significant challenges in this context [78]. Thus, considering the collective and decentralized nature of CES, various energy security concerns exist [41]. This knowledge gap, namely lack of attention to the multi-dimensional and distinguished nature of energy security in CESs, hampers the adoption of such collective energy systems to become mainstream at a larger scale. As CESs could drastically contribute to achieving sustainable energy transition goals, such as the GHG emissions reduction targets [272], there is a need for an improved conceptualization of security for these decentralized systems.

Therefore, the present study aims to contribute to a more comprehensive understanding of the energy security in CESs by looking at energy security in an integral fashion, going beyond mere security of supply in these systems. Given these systems' bottom-up, decentralized nature, we take a collective action perspective [82] that looks at CESs from behavioural and institutional perspectives and pays attention to how members arrange and manage such collective systems. To accommodate this, we use agent-based modelling and simulation (ABMS), adopting a bottom-up simulation approach [88], to measure and assess the energy security of CESs. ABMS allows to explore the complexities of decision-making processes in CESs and provides the opportunity to experiment with alternative strategies (e.g. policies) within a virtual simulation environment. Agent-based modelling is becoming a prominent tool to study energy systems and in particular CESs [368]; however, no research to date has used this approach to study the energy security of CESs.

To accurately explore energy security with a simulation approach, we focus on thermal applications of CESs, including heating, cooling, bathing, showering and cooking [27]. Thermal energy communities have received little attention in the literature despite the substantial share of thermal energy in energy systems [30]. Thermal energy applications in buildings and communities considerably impact $CO_2$ emissions; therefore, studying thermal energy would potentially bring further merit to sustainability discussions. Thus, the present study can also be seen as a further investigation into thermal energy communities with a particular focus on their energy security. To summarize, the scientific contributions of this research are as follows:

- To study and investigate different dimensions of energy security that could play a role in the security of CESs.
- To demonstrate the applicability and usefulness of computer simulations, namely ABMS, in the domain of energy security. It is the first to use ABMS to study the collective energy security of CESs.
- To focus on the characteristics of thermal community energy systems instead of the mainstream electricity-based communities.

The study also aims to provide concrete insights and recommendations to relevant stakeholders in decision-making processes along with these scientific contributions. In addition to local stakeholders (e.g. municipalities, local policy makers and community-boards), such insights and recommendations could also potentially contribute to energy, environmental and sustainability agendas at a higher level. More specifically, the study can be seen as a response to concerns in relation to the sustainability, societal impact and energy security of CESs.

The structure of the chapter is as follows: Section 5.2 elaborates the research approach and positions our research in the literature on community energy systems. Section 5.3 explains the theoretical background of this research. Section 5.4 describes the context of this research. Section 5.5 is dedicated to model conceptualization. Section 5.6 presents the model results. Finally, Section 5.7 concludes the main findings, presents an academic discussion, and provides recommendations and suggestions for further research.

## 5.2. USING ABMS TO STUDY ENERGY SYSTEMS AND CESS IN PARTICULAR

Community energy systems (CESs) can roughly be defined as a group of actors in a neighbourhood, who jointly invest in energy-saving measures [9], and renewable energy technologies and generate the electricity and heat they consume [13]. However, in the academic literature, other definitions are used as well (e.g. [5]).

Complementary to qualitative approaches, simulations can enhance our analytical power to study social systems such as CESs by relying on computational power to study multiple variables over time simultaneously. Like other modelling practices, ABMS represents a simplified version of reality [88]. In an agent-based model, agents are heterogeneous, autonomous and individual decision-making entities (such as households) that are able to learn and interact with each other and their environment [87]. In addition to capturing individuals' behavioural choices, using ABMS also allows for studying emerging system behaviour(s) [276]. ABMS provides the ability to add the time variable, which allows to examine different scenarios and understand inputs, variables, and outputs [88].

Given the bottom-up nature of CESs and the importance of individual characteristics, decision-making, and interactions for measuring energy security, we use ABMS instead of other simulation approaches such as System Dynamics [93] and discrete event simulations [94] that focus on system processes and outcomes.

The use of ABMS is becoming more prominent in the community energy literature. Among modelling research in this area, [95] study value conflict for accepting these decentralised energy systems. [97] also simulate behavioural attitudes and explore leadership in energy communities. [27] take a broader perspective and explore factors that influence the formation of thermal energy communities. [30] also study local heating systems. [272] also examined the role of institutional conditions on the formation and functioning of energy communities. Social acceptance of sustainable heating systems is explored in [289], and collective decision-making in local heat transition is investigated in [377]. Modelling and simulating zero energy communities, including the new and old buildings based on solar energy, is presented [102] and exploring the renewable energy technology adoption [104] are examples of studies using ABMS in community energy research. [361] also model developed that explores energy exchange between prosumers and consumers to observe how the presumption affects the self-consumption of a neighbourhood. [359] focuses on prosumers behaviour, including technological and spatial constraints for small-scale solar energy systems.

Besides models focusing specifically on CESs, ABMS is often used to study behaviour in energy systems. For example, the influence of regulatory framework on the adoption of renewable technology is explored in [104]. This study examines how additional rebates (i.e. partial refund of an item's cost) for low-income households and changes in the rebate amount affect the adoption of solar photovoltaic (solar PV) in Texas. [362] explores factors that are influencing solar PV adoption. [107] presents an ABMS to simulate and forecast wind power plants in Pakistan. [378] explores the influence of different energy policies such as natural gas subsidy on $CO_2$ emission reduction in Malaysia's energy sector. The impact of distribution tariff structures and peer effects on the adoption of distributed energy resources is presented [379]. Flexible market design and voluntarily bidding strategies for the electricity market are explored [380]. [381] presents an ABMS where the decision-making processes and characteristics of different stakeholders, particularly the farmers are modelled for bioenergy crop adoption.

Along with these modelling exercises, several review studies provide an overview of different topics, variables and applications of ABMS in the energy domain. For instance, [366] reviews ABMS with a focus on buildings demand and the indoor environment, while [365] analyses ABMS with a focus on climate-energy policy. [367] provides an overview of ABMS that modelled energy technology adoption, and ABMS with a focus on socio-technical sustainable energy transition is studied [368]. Nevertheless, none of these studies and models has explored the energy security of CESs.

## 5.3. THEORETICAL BACKGROUND

This section introduces the key concepts and theoretical approaches used as the backbone of our modelling exercise: energy security, the collective action perspective, and the social value orientation theory. We also use these theories to analyse our simulation results, as discussed in the coming sections.

### 5.3.1. CONCEPTUALIZING ENERGY SECURITY FOR COMMUNITY ENERGY SYSTEMS

Energy security is crucial for energy communities [357], [188], like any other energy system. As presented in [76], energy security consists of seven dimensions that contribute to its concept and measurement, including energy availability, infrastructure, energy price, environment, societal effects, governance, and energy efficiency. Table 5.1, gives an overview of these dimensions.

Table 5.1.: Dimensions and indicators of energy security, adapted from [76]

| Dimension | Short definition | Indicators |
|---|---|---|
| Energy availability | Availability of energy supply | Diversification, geopolitical factors influencing the supply of energy streams, supply disruptions |
| Infrastructure | Infrastructure is integral in providing a stable and uninterrupted energy supply, including all relevant energy technologies | Adequate and robust infrastructure with spare capacity, reliability |
| Energy prices | Energy prices determine the affordability of energy supplies | Absolute price level, price volatility, market competitions |
| Social effects | Social concerns and effects of the energy system | Societal welfare, energy poverty, social equity, distributional fairness |
| Environment | Sustainability and environmental issues | Environmental pollutions and risks |
| Governance | Sound government policies help to hedge against and mitigate short-term energy disruptions | Diplomacy, information gathering, policies (e.g. tax/ subsidies) |
| Energy efficiency | Developments in energy technologies, systems, and practices help to reduce energy needs and improve energy security | Technological developments, energy intensity and consumption |

Although the energy security concept presented in [76] (Table 5.1) is not explicitly developed for the energy security of energy communities, it is still the most suitable concept for measuring the energy security of CESs among other definitions (examples are presented in [64]) for the following reasons:

- This concept is one of the most recent concepts, which is well adapted to recent developments in the energy security literature;
- It is a multidisciplinary concept that addresses the multi-dimensional nature of energy security. Furthermore, Besides the environment, two other dimensions of societal effects and governance, which are influential to energy communities, are also present in this concept.

### 5.3.2. COMMUNITY ENERGY SYSTEMS AS A COLLECTIVE ACTION PROBLEM

Theoretically, CESs can be seen as a form of collective action where actors join efforts to achieve shared goals on a common-pool resource dilemma [160], namely renewable energy generation and consumption. In this regard, the Institutional Analysis and Development (IAD) framework of Ostrom [108] is specifically designed for analysing collective action problems from an institutional perspective. Institutions are political, social and legal rules, more loosely rules of the game, that form the basis of activities of actors [382]. The IAD framework enables the analysis of a collective system by breaking it into a number of building blocks [123]. Figure 5.1 presents the IAD framework.

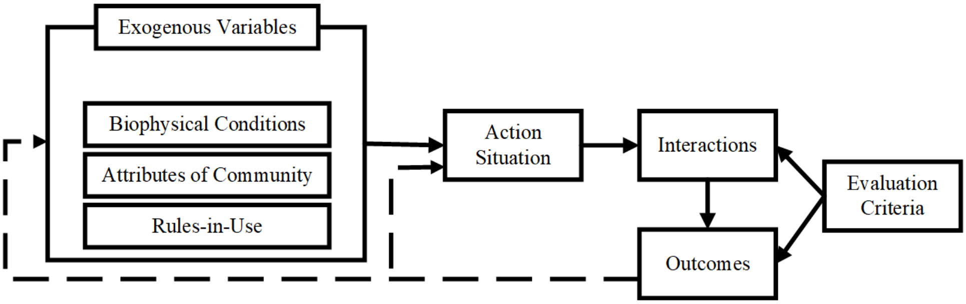

Figure 5.1.: IAD framework, adapted from [110]

The action situation is the main component of the IAD framework [322], which pertains to a conceptual space [108], where actors consider alternative courses of action, make decisions, take actions, and experience the consequences of their actions [163]. Exogenous variables, influence action situation:

- The biophysical conditions include the physical and material resources and capabilities available within the system's boundaries [123]. Resources include, for instance, available RETs and collective investment on them for collective energy generation [163].

- The attributes of the community include the cultural norms accepted by the community [123]. In other words, the shared values, beliefs and preferences about the potential outcomes of the action situation [127].

- Lastly, the rule-in-use component concerns the formal rules that govern the system [110]. Such formal rules include regulations and policies for the system's governance.

The interaction between exogenous variables and inter-actor agency in action situations results in patterns of interaction that generate certain outcomes [110]. Based on evaluation criteria, these outcomes can be objectively assessed[108]. In the end, there is a feedback loop that connects the outcome to the action situation and the exogenous variables [322].

Even though the IAD framework has conventionally been applied for the study of traditional common pool resource management, such as irrigation and fishery, it has recently also been extensively applied to energy systems (e.g. [125], [126]). The IAD framework has proven to be highly instrumental in the CESs domain as well [162], because it explicitly addresses the formal and informal institutional challenges for such collective initiatives [127]. Besides its analytical power for studying CESs from a collective action perspective, the IAD has proven useful for building agent-based models [129], [130]. Different studies in the energy-related literature used the IAD framework in developing ABMS [248] and [383]. In these studies, the IAD framework is used to conceptualize the model and analyse the simulation results. The IAD framework is used in a similar way in the present study.

### 5.3.3. MODELLING INDIVIDUAL BEHAVIOUR: SOCIAL VALUE ORIENTATION (SVO) THEORY

Fulfilling specific concerns (e.g. environmental and energy security concerns) and achieving certain goals (e.g. financial benefits) are the main motivations of individual people for joining CESs [10], [6]. In this regard, the Social Value Orientation (SVO) theory explains the motivations and concerns of people when they make decisions. In the SVO theory, it is assumed that people vary in their motivations or goals when evaluating different resource allocations between themselves and another person [384]. The SVO theory classifies individuals' personalities based on four groups considering pro-self-versus pro-social orientations [384]:

- Altruistic: these individuals are selfless, focusing on maximising joint benefits regardless of the impact on their own payoff; the opportunity of helping others is their motivation;

- Cooperative: these individuals aim to maximise others' outcomes in addition to their own;

- Individualistic: these individuals are mainly concerned with their own outcomes, focusing on their own payoff without having a specific need of minimising other's benefits;

- Competitive: these individuals aim for maximum results and strive to minimise other individuals' benefits.

The SVO theory helps capture and simulate real-life decision-making situations more closely by considering various decision-making motivations [376]. The SVO theory has been used across a range of interpersonal decision-making contexts, specifically in the domains of negotiation settings [385] and environmental attitudes [386] including resource dilemmas [387]. This theory has also been used in the energy domain [388].

To sum up, this section explained the theoretical underpinning for building an agent-based model to study the energy security of thermal energy communities. The energy community in this model is viewed as a collective action and therefore conceptualized using the IAD framework. To have a more concrete conceptualization of the institutional and technical structure of community energy systems, we focus on systems with thermal applications. In this setting, behaviour and decision-making are conceptualized using the SVO theory to categorize individuals based on their motivations. Finally, implementing energy security in the model builds on the concept defined by [76] and is summarized in Table 5.2.

Table 5.2.: Indicators of energy security in the model

| Dimension | Implemented indicators in the model |
|---|---|
| Energy availability | Average voluntary shortage per household |
| Infrastructure | Diversity of technologies (which have their own robustness) |
| Energy prices | Average renewable thermal heating costs of households |
| Social effects | Average community benefit per household |
| Environment | Average $CO_2$ emission per household |
| Governance | Duration of establishment for households |
| Energy efficiency | Average thermal insulation per household based on the housing energy label |

## 5.4. MODELLING CONTEXT

### 5.4.1. THERMAL APPLICATIONS IN CESS

Depending on the type of generation and its application, the CESs literature is divided into two mainstreams: either energy communities in the general sense of the concept (e.g. [8], [28]) or, more particularly, electrical energy communities (e.g. [53], [26]). However, thermal energy communities- focused on collective generation, distribution and consumption of thermal energy for applications such as heating, cooling, bathing, showering and cooking- have received little scholarly attention thus far [27]. The literature is mainly focused on top-down approaches as governments' solutions for providing heat (e.g. [282], [155]), rather than the collective action of individual households within CESs to generate and distribute some sort of heat together.

Thermal energy communities consist of three main components: (thermal) energy technology, affiliated institutions, and involved actors, including their behaviour [27].

Thermal energy technology consists of renewable heating generation technologies (such as biogas, geothermal valves and solar thermal collectors) [39], distribution system (mainly district heating) [38], and final consumption (e.g. space heating and showering) [280].

As rules of the game, the affiliated institutions are the second component of thermal energy communities, which refer to the human-constructed agreements and regulations for the generation, distribution and consumption of thermal energy within CESs [272]. In the literature on thermal applications in CES, formal rules such as regulation design (e.g. [308]), pricing strategies and market design (e.g. [116], [117]) have received considerable scholarly attention. Informal rules such as norms and values (e.g. [157], [247]) have also received attention.

Involved actors, their behaviour: roles and responsibilities represent the third component of thermal energy communities [27]. Topics such as actors involvement [305], financial responsibilities [11], and leadership [97] are related to this component.

### 5.4.2. THE NETHERLANDS AS A CASE STUDY

This research builds an agent-based model focusing on thermal applications in CESs and uses data from the Netherlands. The Netherlands was selected as the country to study CESs with thermal applications because of the following reasons:

- Presence of a high number of CESs as compared to other EU countries [11];
- Presence of well-developed energy and specifically heating infrastructure [132];
- Dutch national ambitious $CO_2$ reduction targets which influenced the heating sector [133];
- National norms for environmental concerns and sustainable development [134];
- The urge for the sustainable heat energy transition is due to a recently increasing number of gas-quakes [136].

Energy security is also important in the Dutch energy policy debates [24]. Historically, the Netherlands has a strong performance in the security of supply due to natural gas fields in the province of Groningen [70]. However, as energy security has been adopted more diverse dimensions, various studies have evaluated the energy security of the Netherlands in different ways (e.g. [24], [70]). Furthermore, particularly in the thermal energy context, topics such as gas-quakes [138], the geopolitics of natural gas imports/exports [139], and energy pricing [117] contribute to the importance of energy security within the Dutch thermal energy context.

The data used in the model include supportive policies (e.g. renewable energy subsidies) and punishing policies (e.g. taxes), from the "Stimuleringsregeling Duurzame Energie" (SDE++), Netherlands Environmental Assessment Agency (PBL), and built environment and energy efficiency regulations (e.g. retrofitting policies based on ‘Energiesprong’ and building energy labels).

## 5.5. MODEL CONCEPTUALIZATION

In this section, we explain the conceptual model using the IAD framework. First, the agents in the model and their motivations are introduced. Next, the exogenous variables, biophysical conditions, attributes of community and rules-in-use are elaborated. To explain the action situations and interactions, the decision-making processes of agents and the model narrative are presented. Lastly, evaluation criteria and outcomes are introduced as the model's key performance indicators (KPIs).

### 5.5.1. AGENTS IN THE MODEL

The model represents a city with multiple neighbourhoods, where each neighbourhood can only have one CES. The model has two types of agents: (i) individual households and (ii) the municipality.

- **Individual households** initially use natural gas to cover their thermal energy demand, and they also hold a specific set of internal motivations to participate in a thermal energy community. Following [6], [58], the primary motivations taken into account to conceptualise the motivations of the individual households in a CES are energy independence, sense of community, environmental concern and economic benefits. Independently from each other, the motivations have a value between 0 to 10 (i.e., 0 is the weakest and 10 is the strongest). Preferences of neighbours can influence the internal motivations of households (see Section 5.5.3). The community-board consists of the five most environmentally-friendly households in the neighbourhood. The other motivations of members in the community board (energy independence, sense of community and economic benefit) are also higher than the median value (>= 5) following [272]. The individual households make decisions based on their four internal motivations. The SVO theory is used to capture these internal motivations and categorize the decision-making processes based on the agents' personality type following [21], [58]. The SVO-type of the individual households is calculated as follows:

$$\begin{aligned}\text{Level of motivation} = {} & (\text{environmental concern} + \text{sens of community}) \\ & -(\text{financial concern} + \text{energy independence}) \qquad (5.1)\end{aligned}$$

  - If Level of motivation > 1: SVO-type 1,
  - If Level of motivation < -1: SVO-type 3,
  - If Level of motivation >= -1 and <= 1, and,
    sense of community < 5: SVO-type 4,
  - If Level of motivation >= -1 and <= 1, and,
    sense of community >= 5: SVO-type 2.

- **The municipality** represents the department(s) of the local government responsible for sustainable energy transition (particularly sustainable heat transition). The municipality is responsible for defining the formal institutions to support the neighbourhoods' transition off-gas, including the availability of subsidies, eligibility requirements of subsidies, and any other formal regulations and arrangements in the model. Following [297], [272], [172], municipalities have four strategies for supporting energy communities and specifically thermal energy communities, namely: environmentally driven (i.e. most $CO_2$ reduction option), economically driven (least economic burden for the municipality itself), socially driven (most involved participants in a neighbourhood) and a trade-off between the three. These strategies influence and determine the municipalities' decisions over their actions, such as subsidy allocation. Individual households are aware of the municipality's strategy from the beginning of the simulation.

### 5.5.2. BIOPHYSICAL CONDITIONS

#### TECHNOLOGICAL SCENARIOS

The agents can choose from several technological options (particularly for the Netherlands). Following [39], [297], technological options are presented in three categories:

- **Renewable thermal energy generation technology:** The collective renewable thermal energy generation technology options included in the model are biogas heaters, aquifer thermal energy systems (ATES), and electric boilers. The individual renewable thermal energy generation options are heat pumps, small bio-energy heaters (i.e. wood pallet based) and photovoltaic thermal hybrid solar collectors (i.e., Solar PVT).

- **Heat distribution:** The technological option for distribution is district heating. Although, in reality, the district heating infrastructure can be outfitted for low or medium-temperature heat, for simplification, it is assumed that only medium-temperature heat transportation is possible in this model.

- **Heat consumption:** The average households' heating demand and the housing insulation label are considered.

#### AVERAGE AMBIENT SURROUNDING TEMPERATURE

The ambient temperature is essential in determining (thermal) energy consumption. When the outdoor environment is colder, demand increases as the energy system generates more thermal energy. Therefore, the ambient temperature is modelled as a biophysical condition, influencing the agents' actions. Due to climate change, the ambient temperature changes over time in coming decades [143], [1], translating to changes in energy demand. The model's standard distribution of households' demand is based on the PBL data. To capture the impact of ambient temperature changes based on climate change scenarios, the model assumes that climate change leads to hotter outdoor temperatures and, therefore, reduces the households' energy demand in European countries, including the Netherlands.

### 5.5.3. ATTRIBUTES OF COMMUNITY

It is assumed that each neighbourhood has only one CES, implying that each individual household can only participate in one CES. The model assumes that households in one neighbourhood can interact with each other in monthly resident meetings (i.e. each tick in the model represents a month) but not with other neighbourhoods. In order to capture and simulate the interactions within each neighbourhood, the model uses a small-world network [332]. 'Small world' is a common approach for representing social networks of individuals within local renewable energy systems [27], [97]. The dynamics occur based on the following principle as argued in [97]: when two households interact, if the value of each motivation is between 2 and 8, the value will slightly lean towards the opinion of another agent attempting to simulate peer pressure. This means that the value will be updated by 1 towards the other agent's motivation value. It is also assumed that households with very extreme values (either higher than 8 or lower than 2) will not be peer pressured and hence will not be influenced by the interaction.

### 5.5.4. RELATED INSTITUTIONS

In our modelling exercise, two types of formal institutions are considered: (i) supportive policies (e.g. renewable energy subsidies) (ii) and punishing policies (e.g. $CO_2$ taxes). The data for these institutions are based on the SDE++ and built environment and energy efficiency regulations (e.g. retrofitting policies based on 'Energiesprong' and building energy labels). Furthermore, according to the PBL, the available subsidy is 2-5 million euros per municipality per year [272]. As the municipality's budget is limited, one of the crucial rules for decision-making is how the municipality should rank the communities and decide towards the allocation of the subsidy.

### 5.5.5. ACTION SITUATION AND INTERACTIONS

The processes during the lifetime of a CES can be modelled in four stages or action situations following [30], [233]:

#### INITIATION PHASE

The initiation phase aims to select the project leader (municipality or community-board) and the collective renewable heating technology source (biogas heaters, ATES or electric boilers) for the CESs.

**Decision on the project leader**

First, the households have a period to exchange information to know each others' motivations and align them. These interactions are based on the description in Section 5.5.3. The duration of the information exchange period is considered to be 7 months (see Table 5.4). After a period of information exchange among households, individual households decide on the type of project leadership, with two options: (i) community-board and (ii) municipality. The project leader is responsible for organizing and taking the initiative within a CES. In order to make such a decision, each household first checks the municipality's strategy. If the municipality's strategy is environmental, each household compares their own environmental friendliness value with the municipality's (which is assumed to be 6 or higher to favour the environment over other values). If the household also has a value greater than or equal to 6 and belongs to the first (i.e., altruistic) or second (i.e., cooperative) SVO types, it votes for the community-board. In case the household is SVO-3 (i.e., individualistic) or SVO-4 (i.e., competitive), it checks its "sense of community" value. If it's greater than or equal to 5, it goes for the community-board. If the municipality's strategy is societal capacity, the procedure works the same way as described above for the municipality with the environmental friendliness strategy. The only difference is that instead of environmental friendliness, agents compare their sense of community values with the value of the municipality in the first place.

When agents observe an alignment of high economic values with a municipality that prioritizes economic benefit as its strategy, they vote for the municipality, unlike in the two other cases. Finally, if the municipality's strategy is the trade-off between the three, the agents randomly go through one of the abovementioned processes with an equal chance.

**Decision on collective renewable heating technology source**

If the municipality takes the lead, specific collective heating technology is selected and communicated to individual households based on its strategy (environmental, economic, social and trade-off). To select the heating system, the municipality calculates three variables defined concerning each technology (i.e., $CO_2$ emission, costs, minimum needed participants).

$$\begin{aligned}\text{Total demand per year} = &\ \text{number of households}\\ &\times \text{average demand per household per year}\end{aligned} \tag{5.2}$$

$$\text{Annual } CO_2 \text{ emission} = \text{total demand per year} \times CO_2 \text{ intensity} \tag{5.3}$$

$$\begin{aligned}\text{Costs (investment)} = &\ \text{Technology capacity} \times \text{Capex}\\ + &\ \text{heat demand} \times \text{Operating costs} \times \text{lifetime}\end{aligned} \tag{5.4}$$

$$\text{Min needed participants} \leq \frac{\text{Costs}}{(\text{natural gas prices}) \times (\text{current consumption})} \tag{5.5}$$

These values are then normalized on a scale between 0 and 1, where 0 represents the worst-performing alternative (i.e., highest emission, highest costs, or least number of needed participants) and 1 stands for the best performing one. Then the municipality ranks the technologies according to their normalized values and strategy (lowest emission first for environmental, lowest cost first for the economic and lowest number of participants for social).

If the community-board takes the lead, the procedure of choosing a collective heating technology will be more participatory. The community-board goes through a multi-criteria decision-making process (MCDM) to select a collective thermal technology. The initial preference of the community-board over the type of collective technology is determined based on the majority vote of the individual preferences of the board members. The individual preference of a board-member is calculated as a weighted sum of each criterion where the weights are the set of motivations (i.e. environmental friendliness, financial drive, sense of community and energy independence). The board suggests the technology with the highest MCDM score as the thermal technology for the community as the alternative.

Once the community-board suggests a collective thermal technology, households within the neighbourhood (excluding the board members) calculate their score per collective thermal technology alternative in the way described above (i.e., MCDM). Based on this calculation, the following two conditions must hold at the same time for the technology to be accepted: i) the suggested technology by the community-board is not the technology that is rated as the lowest by more than one-third of the neighbourhood; ii) the suggested technology is the one that is rated as the highest by more than half of the neighbourhood. This step is necessary, as individuals might value motivations such as environmental concerns differently than the community-board. If the municipality is the project leader, this step is skipped.

Through both types of project leadership, the community as a whole reaches a consensus on collective renewable thermal energy technology. As part of this technology selection (i.e. investment), individual households commit to improving their home's energy efficiency level in this stage by 1 step (e.g., from energy label E to energy label D).

### TECHNICAL SETTINGS AND MEETING ENERGY DEMAND (I.E. FEASIBILITY PHASE)

Once the project leader and the collective renewable thermal energy technology are finalized, individual households have to decide how much of their individual energy demand would be covered by collective energy technology and how much would be covered by other sources (i.e. national-gas grid or individual renewable generation).

**Decision on the amount of collective generation**

Individual households decide how much energy they want to generate collectively through the selected collective thermal technology. Following [389], individual households select a fraction between 0 – 100% of the demand to be generated collectively. The capacity of collective thermal energy generation is calculated in terms of the percentage of total thermal demand of the members, and it is determined as the average percentage value favoured by individual households in a neighbourhood and applied to all the members. Therefore, a generation capacity is allocated to cover the corresponding percentage share of the thermal demand of each community member. A household's preference over how much collective thermal energy to generate is influenced by its budget and the SVO category it belongs to. The upper limit for this percentage is determined by the collective technology budget of the household, i.e., how much at most the household can afford with its budget. If the household belongs to the altruistic SVO-type, it prefers to meet all its demand (i.e. 100%) from the collective system. For the other SVO-types, the preferences to cover their energy demand collectively is as follows: Households with SVO-2 (i.e., cooperative) 90%, households with SVO-3 (i.e. individualistic) 80%, and households with SVO-4 (i.e. competitive) 70%. Suppose the collective energy system cannot fully cover all the community's energy demand. In that case, the individuals depending on their internal motivations, have to choose individual heating systems or use the national natural gas grid.

**Decision on individual heating technology source**

For individual heating systems, first, individual households decide on alternative energy scenarios based on their internal motivations: (i) if their financial concern is greater than environmental friendliness, they use natural gas as the energy source for the remaining demand that is not covered by the selected collective heating energy system, (ii) if an individual has higher environmental concerns than economic motivation hence does not choose natural-gas, there are going to be two options:

- If an environmental-friendly household's budget is allowed, it will further increase housing insulation and install an individual renewable thermal energy system.
- If the financial means of an environmentally friendly household is not sufficient for such an investment at a particular moment, it will choose to save up to install the technology in the future. This means that the individual household will use less heat and may voluntarily face thermal energy discomfort due to its unmet demand. In reality, this can be translated in different ways, such as: (i) turning off/ down the thermal energy system inside the homes in the absence of individuals, (ii) shifting the thermal demand from peak hours, (iii) reducing hot tap-water consumption. Members make this decision by comparing their budget with the needed investment for individual selected RETs. The money saved due to the voluntary discomfort will be accumulated over time and invested in individual renewable thermal energy systems when the financial situation allows.

When the household equally values environmental concerns and financial drives, the sense of community value serves as a tie-breaker. If its value is smaller than 5 (on a scale of 0 to 10), the household decides to leave the CES.

### FINANCIAL FEASIBILITY AND SUPPORTING PHASE

After choosing the technologies, there is a need to check the financial feasibility of the system for the second time, which entitles technical and financial calculations in order to apply for subsidies. The output of the financial feasibility and supporting phase is granting the subsidy and final checking the number of participants to distribute the costs.

The project leader (either the community-board or the municipality) considers the technical scenario with the most supporters and conducts a second technical and investment feasibility analysis for the collective and individual thermal energy systems of the selected scenario. This calculation is related to subsidy allocation processes. For the technical feasibility, renewable generation (including collective and individual technologies), $CO_2$ emission per kW heat generation (i.e. $CO_2$ intensity technology), and average heat generation capacity and load hours are used. For investment feasibility, criteria such as lifetime, investment costs, operation costs and availability of subsidies are used (to cover unreliable costs in business cases); see Appendix D.

Based on the total requested demand for energy as calculated in phase 2 (i.e. Technical settings and meeting energy demand), the project leader calculates how much subsidy they need to request in order to cover the entire investment. If this amount does not exceed the maximum amount, the government gives it to the neighbourhood. If the amount is more, the project leader requests the highest possible subsidy option the government is willing to give to one neighbourhood.

Once a year (every 12 ticks), the municipality considers all the CESs that have applied for the subsidy. The municipality ranks the requests based on its subsidy distribution strategy (i.e. environmental friendliness, financial drive, societal drive and trade-off) and provides the subsidy to those that meet their criteria until all the funding has been used. If a CES does not receive the subsidy (as it might not meet the municipality's criteria for receiving the subsidy or as it might be low in the ranking of the municipality), it waits for the next year and applies again.

### INSTALLATION, GENERATION AND EXPANSION PHASE

Once the technology investment has taken place and the community energy system is installed, energy is generated (thermal energy generation is calculated monthly). New participants can be potentially added to the community initiative over time, if they agree with the chosen arrangements (e.g. chosen technologies and monthly payments).

After receiving the subsidy and collective investment of individuals, the CES goes into a construction state for a year (i.e. twelve ticks in the simulation). Once the infrastructure is in place, the community is considered to be set up.

After setting up, every year (i.e. twelve ticks in the simulation), the individuals and community board check whether they have reached the end of their project time-horizon (i.e. 20 years in the simulation, 240 ticks). When the technologies reach their lifetime, meaning such technologies are needed to be renewed, the community will start another information exchange round, now including new community members, and choosing new technologies (i.e. starting from phase 1).

After the initial setup of the community, “non-members” can re-evaluate their participation, i.e., check if they are willing to participate. As “non-supporters” can interact with other agents in the neighbourhood (as presented in Section 5.3), their opinions might grow towards their neighbours' opinions who are members of CES. If these potential members agree with the installed energy technology, they will invest in thermal insulation as part of the agreement. Suppose their willingness to pay is equal or lower than the investment required per person in the neighbourhood. In that case, they will increase their energy efficiency (i.e. housing label insulation) and participate in the community system. When individuals disagree with the board decisions, they will no longer participate and will leave the energy community.

Figure 5.2 presents the four steps explained in Section 5.5.5 (i.e. (i) Initiation phase, (ii) Technical settings and meeting energy demand, (iii) Financial feasibility and supporting phase, and (iv) Installation, generation and expansion phase) as a conceptual model flowchart.

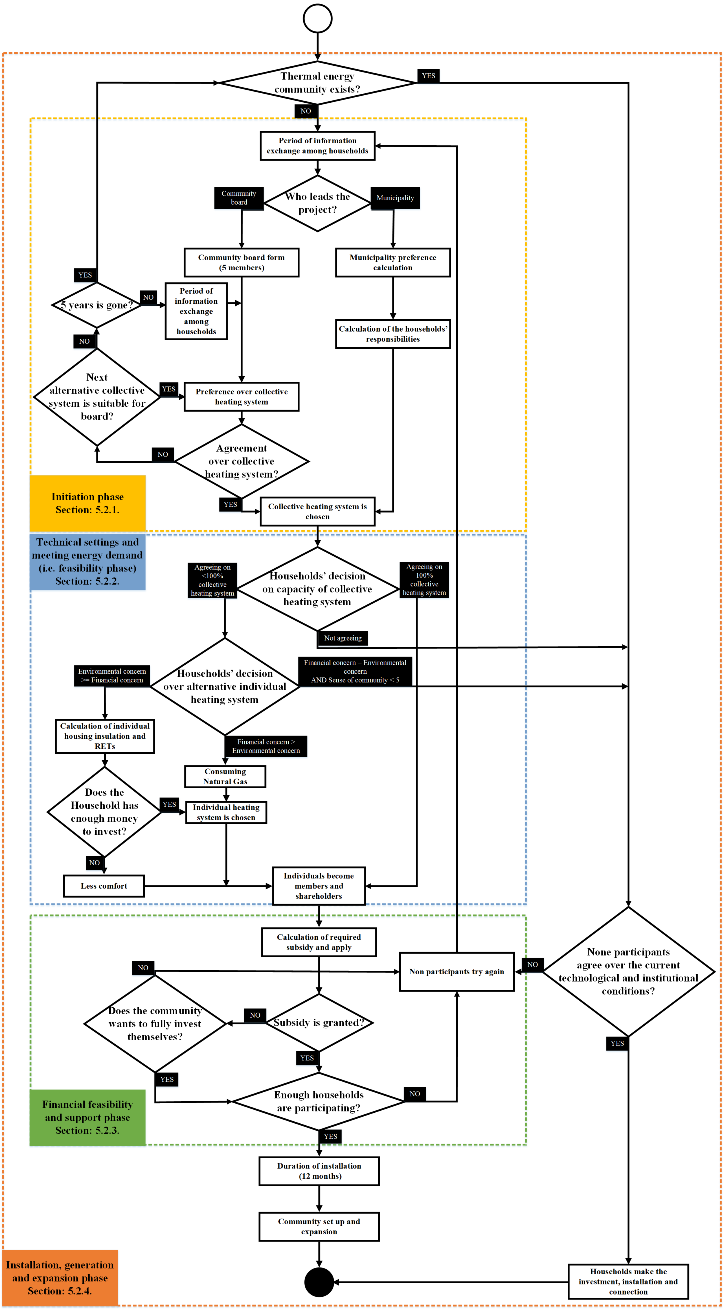

Figure 5.2.: Model conceptual flowchart

### **5.5.6.** EVALUATION CRITERIA AND OUTCOMES (MODEL'S KPIS)

By using seven energy security dimensions presented in [76], seven key performance indicators (model's KPIs) are defined for measuring the energy security of (thermal) energy communities. Calculations related to these KPIs are presented in Appendix D.

#### ENERGY AVAILABILITY: AVERAGE VOLUNTARILY DISCOMFORT PER HOUSEHOLD:

Energy availability can be measured by calculating the average percentage of the energy demand per year, which is not met. Not meeting the demand could be because of the behavioural attributes, technical and institutional choices of the individuals and the community as a whole. In the real world, this can be translated as discomfort for households which means the generation is not enough to provide enough thermal energy to heat the cold water and accommodations to the desired temperature.

#### ENERGY PRICES: AVERAGE COSTS PER HOUSEHOLD:

The average cost per year for each household that participates in a CES is calculated based on four primary sources of costs: collective renewable thermal energy system, individual renewable thermal energy system, natural-gas consumption and insulations.

#### ENVIRONMENTAL: AVERAGE $CO_2$ EMISSION PER HOUSEHOLD:

This indicator is about the average $CO_2$ emission per year of a household participating in CES. Although households reduce their $CO_2$ emission by adopting renewable thermal energy, still there is a possibility that they emit $CO_2$ as they might choose bioenergy and natural gas as their resources.

#### INFRASTRUCTURE: AVERAGE DIVERSITY OF INFRASTRUCTURE PER HOUSEHOLD:

Diversification of energy systems involves having a range of energy infrastructures (including generation and distribution) [76] that would provide various energy sources for involved stakeholders. In the community context, the diversity of infrastructure is reflected by the number of distinct energy sources households have access to. There are three main energy setups in the model, in which individuals choose from collective renewable thermal energy (including selection one of the following technologies: biogas heaters, ATES, and electric boilers), individual thermal energy (including a choice of one of the following technologies: heat pumps, wood pallet and Solar PVT), and natural gas. The modelling exercise uses the Shannon index [373] to calculate diversification.

#### ENERGY EFFICIENCY: AVERAGE THERMAL INSULATION PER HOUSEHOLD:

Individual households improve the efficiency of their accommodations represented by their home energy label is considered a KPI to measure the overall energy efficiency of households. There are two moments that individuals can improve their housing energy label. First, the moment they decide on collective renewable generation, they are required to improve their energy label by one step (e.g. from energy label D to energy label C). Second, suppose they want to choose an individual thermal energy system. In that case, they also have the opportunity to choose to invest in improving their housing energy label one step further (e.g. from energy label C to energy label B). These steps have different investment sizes and effects on energy consumption reduction. We used data from [390], [391], [392], for calculations related to insulation. At the end of the model, the average insulation of the whole community is calculated (see Appendix D).

#### GOVERNANCE: ESTABLISHMENT DURATION OF ENERGY COMMUNITIES:

The duration of the process in which the community goes through the establishment is used as an indicator for the governance dimension. This duration is influenced by various decisions, such as choosing the type of project leadership, technological choices, municipality subsidy allocation strategy and dynamics in individuals' motivations.

#### SOCIETAL EFFECTS: AVERAGE COMMUNITY BENEFIT PER HOUSEHOLD:

There are direct and indirect benefits for participating in a CES for a community. Direct benefits are the financial benefits related to energy savings over the years. Indirect benefits are a community's economic (and social) benefits associated with $CO_2$ emission reduction (e.g., fewer health issues).

In addition to these seven specific energy security KPIs, other criteria will be used to evaluate energy-secure TEC initiatives' establishment and functioning processes, presented in Table 5.3.

Table 5.3.: General KPIs

| Key performance indicator | Unit | Description |
|---|---|---|
| Final share of neighbourhood participation in CES | % | Percentage of the neighbourhood households that are connected to the district heating infrastructure after 20 years |
| Collective technology selection | - | The collective technology that the neighbourhood has selected and installed in the neighbourhood (biogas, ATES, electric boiler) |
| Individual technology selection | - | The individual technology that the neighbourhood has selected and installed in the neighbourhood (nothing, wood pallet, heat pump, solar thermal) |
| Percentage of collective renewable thermal energy generation | % | Percentage of collective renewable thermal energy generation based on the decision-making of individuals |
| Percentage of natural-gas consumption | % | Percentage of natural-gas consumption in a CES |
| Project leadership selection | - | The project leader that the neighbourhood has selected to lead the CES (either community-board or municipality) |

### 5.5.7. SENSITIVITY ANALYSIS AND EXPERIMENTATION ANALYSIS

A sensitivity analysis was conducted to explore the model's robustness, different experimental configurations for various model parameters following the one-factor-at-a-time (OFAT) approach [351]. For each parameter presented in Table 5.4, the model was run 30 times where all parameters were fixed at a certain value, and only the parameter under study was altered to test the model's sensitivity to that parameter [351]. The values for the parameters presented in Table 5.4 are set based on the sensitivity analysis. These values are also in line with the current body of literature, for instance, neighbourhood size [330], number of connections each household has and number of neighbourhoods in a municipality [272].

Table 5.4.: Sensitivity analysis results

| Parameter | Value | Unit |
|---|---|---|
| Duration of information exchange | 7 | Months |
| Neighbourhood size | 600 | households |
| Steps of percentage preference reduction per SVO type | 20 | % |
| Number of connections each household has | 3 | Number |
| Number of neighbourhoods in a municipality | 3 | Neighbourhood |
| Steps of yearly gas price increase | 0.01 | (€/kWh) |
| Steps of yearly $CO_2$ tax increase | 0.002 | (€/kg) |

### 5.5.8. PARAMETERS AND EXPERIMENTATION SETTINGS

To study the energy security of thermal energy communities, four parameters are selected from the literature that are potentially influential for the energy security of such systems:

- Natural-gas prices: the price of natural gas is influential for both (i) the deployment of renewable thermal energy technologies and district heating systems [133], [346], and (ii) energy security [133], [393].
- $CO_2$ tax: A policy that could significantly impact the RETs deployment and fossil fuel prices is the application of a $CO_2$ tax. $CO_2$ emission tax also influences energy security.
- Ambient temperature: Changes in ambient temperature has a considerable influence on energy security and RETs deployment, as it can potentially influence the (thermal) energy demand [394, 395].
- Amount of subsidy and municipality subsidy allocation strategy: The amount and allocation strategy of subsidy influences affordability of the energy system, and therefore it impacts the RETs deployment and energy security.

We use these four parameters as input in our modelling exercise. The experimentation included a total number of 108 different combinations of the four-parameter values in

Table 5.5. Each combination was repeated 50 times; hence, the experimentation resulted in a total number of 16200 runs. As the number of neighbourhoods (i.e. CESs) in each run is set at 3, the total number of CESs in this modelling exercise is 48600. The influence of these parameters on the modelling's KPIs is elaborated in Appendix D.

Table 5.5.: Experimentation settings

| Parameter | Value | Unit |
|---|---|---|
| Increasing rate of the natural gas price | 0.01, 0.02, 0.03 | (€/kWh) |
| $CO_2$ taxes | 0.002, 0.004, 0.006 | (€/kg) |
| Ambient temperature changes (Climate change) | Mild, High, Severe | - |
| Available subsidy | 2, 4, 6 | Million € |
| Municipality subsidy policy | Environment, social, economic, a trade-off | - |

## 5.6. RESULTS

In this section, we present the results of the experiments on two levels: (i) an overview of KPIs individually, which provides an overall view of energy security; and (ii) High and low energy security performances by combining the seven energy security KPIs.

### 5.6.1. GENERAL SECURITY PERFORMANCE OF CES

OVERVIEW OF TECHNICAL AND INSTITUTIONAL CONDITIONS

Among all the 48,600 simulated CESs (i.e. neighbourhoods in the model), around 60% of them chose aquifer thermal energy system (ATES) as their collective thermal energy system (see Figure 5.3). The explanation for this is (i) the relatively better environmentally performance (i.e. less $CO_2$ emission) of ATES systems in comparison with other technologies, (ii) the relatively long projects' time horizon (i.e. 20 years), which makes ATES more economically feasible. Furthermore, thermal energy communities also always include individual renewable energy sources, usually in the form of heat pumps (blue in Figure 5.3). Natural gas is the second choice for the individual systems (red in Figure 5.3). Less than 500 CESs chose wood pallets and solar PVT as their individual renewable thermal energy systems. These results confirm the relatively high willingness to adopt different RETs, particularly individual RETs (e.g. heat pump and Solar PVT), while the natural-gas option is available as an individual technology choice. Figure 5.3 presents the distribution of the technological choices among all 48,600 CESs.

The results show that thermal energy communities could dramatically reduce natural gas consumption and, therefore, contribute to the $CO_2$ emission reduction in the Netherlands. However, as presented in Figure 5.4, almost no community became completely natural-gas free. As illustrated in the model's narrative in Section 5.5.2, considering that individual households and communities as a whole could potentially not choose natural-gas consumption at all, this emphasizes the importance of natural gas for the (i)

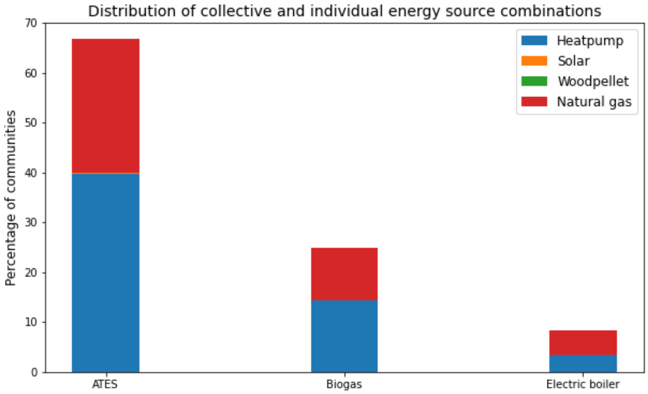

Figure 5.3.: Distribution of collective and individual energy sources combinations

Dutch heat energy transition; and (ii) the energy security of (thermal) energy communities.

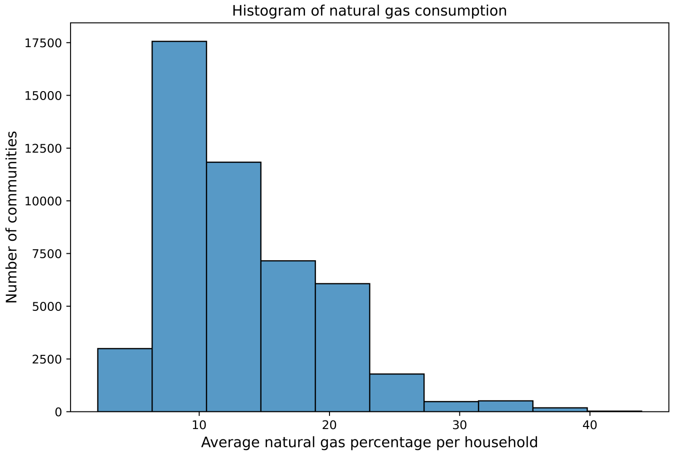

Figure 5.4.: Average natural gas consumption

The results show that community-boards took the leadership of 67% of CESs. Considering the Dutch context (i.e. attributes of community and rules-in-use particularly), this can be translated to communities being more likely to be led by their own community-boards. Such leadership does not necessarily lead to higher energy security performances, elaborated in Section 5.6.2 and Section 5.7.

### OVERVIEW OF ENERGY SECURITY KPIS

In order to compare the energy security KPIs with each other (see Table 5.2), the normalized distribution of each energy security KPI is presented. For instance, the modelling results for $CO_2$ emissions per household as one of the energy security KPIs are between 95 to 150 kg/month, which as a normalized distribution, is translated into values between 0 to 1. In Figure 5.5, the X-axis presents values between 0 to 1 as a normalized distribution of results for each energy security KPI in the model. The Y-axis presents the density of the number of runs.

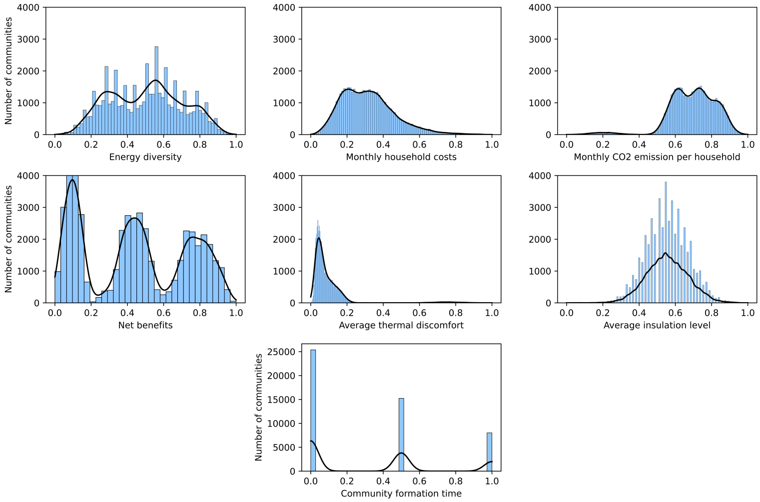

Figure 5.5.: Overview of normalized KPIs vs number of thermal energy communities overall runs

As Figure 5.5 shows, the results for thermal discomfort are mostly less than 0.2 on a normalized scale (9% discomfort), which shows the potential for high energy availability (i.e. security of supply) within CESs. Also, the results show that 53% of CESs' formation time is less than three years for formation time. KPIs such as energy costs, thermal insulation, and the energy diversity index are distributed among different normalized values depending on technical and institutional settings. There is no distinctive peak for these specific KPIs except for energy insulation. This can be translated into (i) depending on different parameter settings (e.g., $CO_2$ taxes and natural-gas prices) such KPIs can perform well, (ii) such KPIs do not have a significant influence on determining the energy security of thermal energy communities. Other KPIs, such as community benefit, community formation time and thermal discomfort, have distinctive peaks. The peak is nearly zero for discomfort KPI, which means the individual households face little thermal discomfort (less than 4% of their thermal demand every year). Particularly, there are three peaks for community benefit, with most performances lower than 0.5 in normalized presentation. Community formation time also has three discrete peaks due to decisions over subsidy allocation time at a certain time every year. The majority of the communities form relatively quickly (i.e. less than 3 years). This indicates that these KPIs could potentially play a significant role in determining the energy security of thermal energy communities as they show a lot of variability and sensitivity towards the parameter settings of the model. In the next section, we dive into the reasons behind these differences.

### 5.6.2. TECHNICAL AND INSTITUTIONAL CONDITIONS OF HIGH ENERGY SECURITY PERFORMANCE

This section analyses the technical and institutional factors for TEC initiatives with high and low energy security performances. To provide such analysis, first, we labelled the thermal energy communities as high or low energy security performance through the following procedure:

- High performance: For each KPI, the top 60% of all 48,600 communities across all runs are selected, leading to 29160 communities performing better than the rest. The communities that fall within the top-performing group of all KPIs are chosen as the highest performing ones in terms of security in general. This selection led to 472 communities in total.

- Low performance: The worst-performing communities are selected across all KPIs through the same process, leading to 587 thermal energy communities[2].

Table 5.6 shows the KPIs of communities that lie in the low and high-performance categories per KPI.

Table 5.6.: General conditions of high and low energy security performances

| | Low performances (587 CES) | High performances (472 CES) |
|---|---|---|
| The leadership of the Community-board | 89% | 15% |
| The leadership of the Municipality | 11% | 85% |
| Collective technology choice | 90% ATES, 10% Bioenergy | 15% ATES, 85% Bioenergy |
| Collective generation | 83% | 80% |
| Individual technology choices | 56% Heat pump, 43% natural-gas, 1% Solar PVT | 64% Heat pump, 35% natural-gas, 1% Solar PVT |
| Natural-gas consumption reduction | 56% | 64% |
| Participation of households | 91% | 84% |

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[2] This process was first conducted with 50% highest and lowest performance, however, the sample was very small (i.e. 47 and 132 communities respectively) therefore, the percentage was changed to 60%.

As Table 5.6 shows, there is a meaningful relationship between project leadership and energy security performances. 89% of CES with low energy security performances (523 runs out of 587) are led by the community-board. On the other hand, project leadership by the municipality can potentially lead to a higher energy security performance. ATES and bio-energy are the two collective technologies for both high and low performances. Although collective choices for technology differ substantially in high performing and low performing communities (ATES more popular in low performing communities and Bio-energy more popular in high performing ones), individual technology choices are quite similar.

To understand the influence of the five parameters, namely natural-gas prices, $CO_2$ taxes, ambient temperature (i.e. the influence of climate change), amount of subsidy and municipality subsidy allocation strategy Table 5.5 on high and low energy security performance, we studied them more closely. Among the five parameters, municipality strategy, amount of subsidy and ambient temperature (i.e. climate change influence) showed a clear and meaningful influence on energy security performances. The economic-drive strategy of the municipality is considered the dominating strategy for high energy security performance communities. The lowest subsidy amount dominates the low-performance communities. Natural-gas prices for low and high energy security performances are dominated by the median value (i.e. 0.002 €/kWh). The $CO_2$ taxes showed no meaningful division between the high and low energy security performances. Figure 5.6 illustrates the parameters for high and low energy security performance.

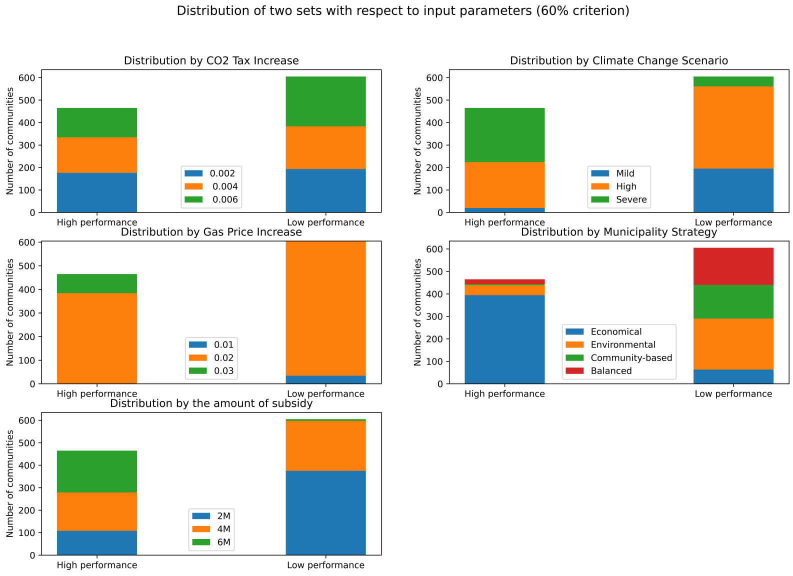


Figure 5.6.: Parameters for 60% high and low energy security performances

Furthermore, to bring more meaningful insights, the seven energy security indicators of the high energy secure communities are also analysed in relation to the two most essential characteristics, namely type of leadership and percentage of collective energy generated (see Figure 5.7).

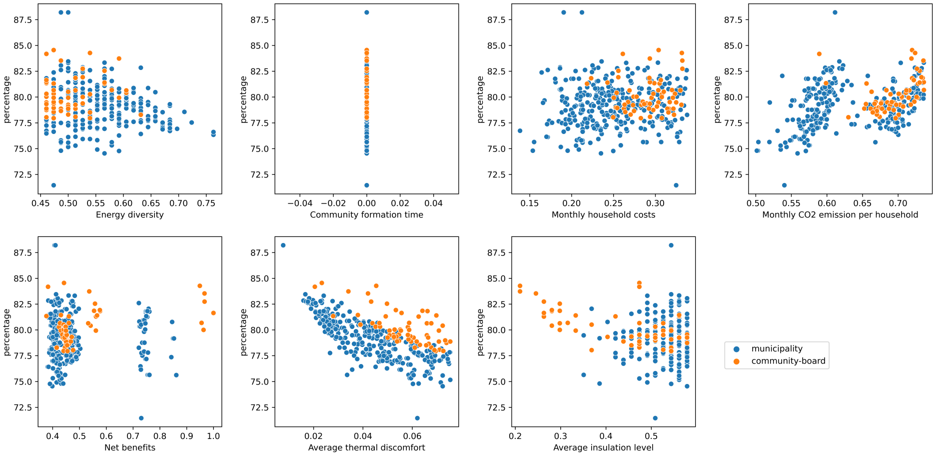


Figure 5.7.: Type of leadership and percentage of collective energy generation in the high energy secure communities

Considering that all the communities in Figure 5.7 are highly energy secure, 87.5% is the highest collective energy generation. The leadership type has considerably influenced the performance of these high energy secure communities. For instance, community board project leadership potentially leads to higher community benefit, while municipality project leadership leads to better performance of energy diversity and improves thermal insulation. As illustrated in Table 5.6, community-board leadership is more likely to lead to a lower energy security performance. All seven energy security KPIs show that community-board project leadership leads to higher collective generation in highly energy secure communities.

## 5.7. DISCUSSION AND CONCLUSIONS

### 5.7.1. ENERGY SECURITY OF ENERGY COMMUNITIES

The present study analysed the energy security of CESs, particularly CESs for thermal applications. It explored the technological and institutional factors that could potentially influence the energy security of such energy initiatives. By focusing on thermal energy communities, we also aimed to shed light on the unique characteristics and processes of these types of communities (e.g. thermal energy implementation and building insulation). An agent-based model (ABM) was built and parameterised using Dutch data. The developed model is the first ABM in the broader energy security literature, introducing the applicability and usefulness of this modelling approach to the field.

The energy security concept presented in [76], which goes beyond the security of supply by considering various dimensions (e.g. environment, governance and energy efficiency), was used to conceptualise energy security in our modelling exercise. The results demonstrated the substantial potential of CESs to reduce CO2 emissions while being affordable in a long-time horizon (i.e. 20 years in this modelling simulation). In detail, among all 48600 CESs in the modelling exercise, members of most CESs (i.e. around 28200, 58% in total) reduced their $CO_2$ emission by 60%, while their monthly payment was less than 80 Euros and only faced discomfort for 4% of their demand on a yearly basis. At the same time, 53% of all CESs were established within three years after the start of the simulation, demonstrating the relatively short duration of establishing such collective entities. With an increasing number of CESs in the future, these results highlight the importance of energy security dimensions other than only security of supply (i.e. availability). More specifically, in addition to availability, environment, governance and energy price dimensions need to be rigorously taken under consideration for a comprehensive energy security assessment with further uptake of these decentralised energy systems.

The study showed the importance of different technological configurations for the energy security of (thermal) energy communities. Although different energy source options were available for individual households in the model (e.g. fully collective renewable energy systems, individual renewable energy systems and fully natural-gas consumption (see Section 5.2), CESs have always decided to adopt natural gas as part of their energy mix. This highlights the importance of a connection to a natural gas grid (i.e. often a national grid) for maintaining (thermal) energy communities' energy security. However, it is important to note that our research only took the national gas grid into account, given its thermal application focus. To study whether the electricity grid plays an equally important role, the model needs to be further extended with other specific configurations (e.g. national electricity grid, micro grid and electric vehicle).

At the same time, the results also confirmed that collective energy generation could contribute to the energy security of individual households (e.g. see Figure 5.7). Among the RETs options, ATES and heat pumps, respectively, are the collective and individual renewable thermal energy technologies mostly used. The results showed that such a combination of technologies also reduces environmental impact, as highlighted in other studies (e.g., [396]). However, CESs with high energy security performances turn out to have mostly bio-energy as their collective energy source, mainly due to its lower price and faster establishment process than ATES.

Further analysis (Section 5.6.2) revealed that CES's leadership has also significantly impacted the CESs' energy security performances. In more detail, municipality leadership could potentially lead to a higher energy security performance of CESs. In contrast, community-board project leadership is advantageous for the communities themselves and the local government, resulting in a higher share of the collective heat generation and community economic benefit in the long run.

Finally, among the five input parameters (see Section 4.5.7), the present study found that available renewable energy subsidies are far more impactful on the energy security of (thermal) energy communities than natural-gas prices and $CO_2$ taxes. The ambient temperature (i.e. demand reduction) also showed a relatively positive influence on CESs' energy security performances but requires further investigation.

Considering all these points, we conclude that the following technical and institutional factors are critical for the energy security of (thermal) energy communities: (i) maintaining a connection to the national grid, (ii) enabling and promoting collective energy generation (e.g. in the form of ATES), (iii) municipality leadership, (iv) subsidy availability for community energy, and (v) more extended vision (e.g. 20 years) on return on investment.

### 5.7.2. LIMITATIONS AND FURTHER WORK

Although this study brought new insights into the energy security of (thermal) energy communities, it has certain limitations. A first limitation is the conceptualization of energy security using the concept developed in [76] (i.e. energy availability, infrastructure, energy price, environment, societal effects, governance, and energy efficiency). Despite the benefits this concept offers, it is crucial to keep in mind that other energy security concepts and indicators (such as 4As energy security concept and WEC indicators as presented in [64], [65]) could also be used in security-focused models.

A second limitation concerns the selection of theories used in the present study to structure our modelling exercise and approach the energy security of CES. The decision to use Ostrom's IAD framework and the SVO theory has provided a specific lens through which CES have been researched. Nevertheless, there are other frameworks and theories, such as Ostrom's Collective Action theory [108] and Theory of Planned Behaviour [353], that, when are applied to the same issue, systems and processes could provide potentially different insights. Using such frameworks and theories could complement current findings of the energy security of thermal energy communities.

A third limitation is regarding ABMS as a method to explore the energy security of CES. As argued in Section 5.4, ABM is considered a suitable approach for this study; however, it has limitations. ABMS presents a simplified version of real-world phenomena or systems like any other modelling approach. ABMS is mainly used to explore bottom-up approaches, decision-making processes, and system behaviour emergence. At the same time, the real world is somewhat more complicated, and top-down structures are also present. Therefore, other research methods, such as equilibrium modelling and serious gaming, could be beneficial in addition to the presented ABMS. More specifically, equilibrium modelling could address issues related to energy supply-demand, while serious gaming could provide insights into stakeholders' decision-making processes.

Finally, the case study selection (i.e., the Netherlands) is the fourth limitation. Although due to its unique characteristics, the Netherlands provides an opportunity to explore the energy security of CES (see Section 5.5.4), it is still a limitation, as it has its own energy system's specifications. The selected case influences data collection reflecting the national technical and institutional conditions, influencing the conceptualization of the model (e.g. input data on energy demand, building energy labels, heat pumps, solar thermal energy systems). Although technological choices, data, and the model's parameters are based on real-world realities, they still limit the study. For instance, other RETs such as deep geothermal energy systems and high-temperature district heating can be explored. An important consideration for further work is adding more details on thermal energy applications within buildings.The present study contributes to studies such as [397] and [398], where $CO_2$ emissions of buildings are explored. Another assumption of the model is that climate change impact is only limited to energy demand. Although the model provides meaningful results, it would be insightful to adapt the model's inputs in such a way that it can also fit the context of other countries such as Denmark, Belgium, Germany or the United Kingdom. Lastly, more reliable empirical data is needed in order to have more insightful outcomes. Conducting surveys and expert interviews would be helpful for this.

### 5.7.3. RECOMMENDATIONS

Considering the modelling simplifications and limitations of the present study, the overall results indicate that thermal energy communities can, on average, be established within three years if a high degree of support is experienced by households (e.g., approximately 50%). The modelling results and analysis show that scenarios combining a high degree of renewable energy generation (including both collective and individual technologies) with a connection to the national natural gas grid are preferred among households. Results also show that the majority of CESs considerably reduce their $CO_2$ emissions. Based on the present study, the following societal and policy recommendations are made:

- Policy-makers are suggested to consider the importance of maintaining natural gas as an option to sustain the energy security of thermal energy communities in the coming 20 years (as per the simulation timeline).
- Policy-makers are encouraged to focus more on developing supportive policies (e.g., renewable energy subsidies), which allocate the available resources based on economic considerations, rather than punishing policies (e.g. $CO_2$ taxes and increasing energy prices).
- Policy-makers are recommended to support community-boards leadership when possible. If a CES and its board are not in place, initiate the CESs through municipal leadership as it could lead to households' energy security.
- Policy-makers and households are recommended not to aim for completely independent energy systems. It appears that self-sufficient (i.e. off-grid) thermal energy communities could potentially not be established and face lower energy security if established.
- Regarding renewable energy technology, ATES (with a combination of heat pumps) appears to be the dominant technology that significantly contributes to thermal energy communities' energy security. Therefore, all stakeholders (particularly policy-makers) are encouraged to consider this technology in their decision-making.
- Households are recommended to overlook the size of investments and economic considerations in the initiation phase of CESs (and focus on the total cost of ownership) if possible, as in the long run, higher investment in (thermal) energy community systems leads to higher community benefits, less environmental impact and even more individual economic benefits.

# 6

# TOWARDS COLLECTIVE ENERGY SECURITY OF THERMAL ENERGY COMMUNITIES

This final chapter concludes the work described in this study by summarising its main results and insights, answering the research questions, and discussing its main contributions. The chapter ends with reflections on limitations and recommendations, both for practitioners and academics.

## 6.1. ANSWERS TO THE RESEARCH QUESTIONS

This study had the objective of *supporting the design and implementation of energy-secure thermal energy communities by investigating their technical, behavioural and institutional settings through a collective action perspective.* Therefore, this research investigated different characteristics of the TEC initiatives as a collective energy system and their surrounding (exogenous) conditions. For this research objective, a set of research questions are formulated. The following paragraphs summarise the main findings of these research questions.

*Research question 1: What technical, behavioural and institutional characteristics set thermal energy communities apart from electricity-driven communities?*

Research question 1 was posed to provide an overview of TEC initiatives' technical, behavioural, and institutional settings and the extent to which they can be considered distinctive collective energy systems. Although a TEC initiative is a type of energy community, the difference with other kinds of energy communities, particularly with electricity-driven communities (as a dominating type of energy community), was not clear. This research question was answered in Chapter 2 by conducting a literature review and applying a framework to analyse the literature structurally.

Among the identified technical, behavioural, and institutional settings, seven were particularly associated with TEC initiatives. From a technical point of view, these were thermal energy resources (e.g. geothermal) and associated technologies (e.g. district heating and thermal insulation). Ambient temperature and indoor air quality were also distinctive conditions considered when establishing TEC initiatives compared to electricity-driven energy communities. Typical behavioural and institutional characteristics were consumers' norms for final thermal application (e.g. heating and cooling), heat regulations and heat market analysis (e.g. natural gas price reforms, cost reduction by thermal insulation, and other thermal energy-related policies). Trade-offs between health issues and thermal applications (e.g. trade-off between indoor/outdoor air pollution and using bio-energy heaters) were identified as influential in decision-making processes for establishing and functioning of TEC initiatives. Finally, thermal performances and heat costs were the main criteria to evaluate the performance of TEC initiatives.

To further investigate the study's preliminary knowledge gap and to foster the establishment and sustained functioning of TEC initiatives, several areas for further research were also identified, in particular: (i) the roles and responsibilities of different actors: current literature on TEC initiatives is limited to either households or policy-makers, while the roles and responsibilities of other actors such as community-boards/ project leaders are understudied, (ii) institutions and interactions for collective thermal energy systems, both formal rules (e.g. available subsidies for renewable heat) and informal rules (e.g. actors' behavioural attributes in TEC initiatives), along with studying the social dynamics within such communities.

*Research question 2: How and to what extent do the identified technical, behavioural and institutional characteristics affect thermal energy communities' establishment and functioning processes?*

This investigation and analysis contributed to understanding the sensitivity of TEC initiatives' establishment and functioning processes to the identified settings from the previous research step. An agent-based model and simulation (ABMS) was developed, which allowed the exploration of TEC initiatives' establishment and functioning processes while considering technical, behavioural and institutional characteristics and their surrounding conditions. This model was populated with data from the Dutch context, including data related to individual households' thermal demand, natural-gas prices, motivations and concerns of individual households for joining TEC initiatives.

The results showed that among the identified characteristics and conditions, the behavioural and institutional characteristics had more influence on the establishment and functioning of TEC initiatives than technical settings such as available sources and technologies. Key pertained to providing training for TEC initiatives' leaders to empower them to become more skilled and allocating subsidies based on the projects' degree of environmental friendliness. The positive impact of a community-board as a project leader was considerable on TEC initiatives' establishment and functioning processes.

*Research question 3: How can energy security of a collective energy system be modelled?*

Given the distributed and collective action nature of energy communities, the energy security of these energy systems is more than just security of supply and is related to issues such as affordability and acceptability of energy to members of the community. Therefore, to investigate collective action decision-making processes, an ABMS was created that captures energy security in energy communities, considering the actors' decision-making process and the collective action nature of such entities. The energy security dimensions considered were availability, affordability, accessibility and acceptability, referred to as the 4As. The developed model approached collective energy security not only through supply security (i.e. availability), but also included other dimensions such as affordability, accessibility and acceptability. To explore the energy security of a collective energy system, four parameters were selected from the literature that are potentially influential for energy security: natural gas prices, energy demand, investment size, and willingness to compensate.

The model was a novel approach for studying energy security, as it simulates the collective decision-making of individuals and its influence on the energy security of an energy community. For the first time, ABMS is used to investigate and measure collective energy security by considering the heterogeneity of actors' motivations and the complexities of decision-making processes within a community energy system. The results articulated that collective energy systems such as energy communities contribute to the energy security of individual households. The energy communities demonstrated substantial potential to reduce $CO_2$ emissions while being affordable in a long-time horizon (i.e. 55 years the simulation time). The results also showed that energy communities are able to perform well for diversity (as an indicator of accessibility) and voluntarily shortage (as an indicator of availability). 10% of the simulations had 0% voluntarily shortage, reducing their $CO_2$ emissions dramatically and having maximum possible diversity. Results delineated that the investment size plays the most significant role among the investigated parameters.

*Research question 4: How do technical, behavioural and institutional settings affect the establishment and functioning of energy-secure thermal energy communities?*

Following research question 3, the modelling experience was applied to TEC initiatives to investigate the influence of technical, behavioural and institutional settings on their energy security. An agent-based model was built, which explored the energy security of TEC initiatives. This model was populated with data from the Dutch context, including data related to available subsidies, distribution of individual households' thermal demand, motivations and concerns of individual households for joining TEC initiatives.

Simulation results showed that among the technological options (i.e., collective energy generation, individual energy generation and connection to the natural gas grid), collective energy generation and connection to the natural gas grid have a substantial positive influence on the energy security performances of TEC initiatives. Although TEC initiatives based on 100% renewable thermal energy technologies could be an option, they were hardly ever selected by the agents in the simulation. Therefore, off-grid TEC initiatives are not recommended from an energy security point of view. Type of project leadership was also found to be influential for energy security performance, as municipality project leadership led to higher energy security performance compared to other leadership types. The results revealed that supportive policies (e.g. amount of available subsidy) are relatively more positively influential for the energy security of TEC initiatives than prohibiting ones (e.g. $CO_2$ emissions taxes). Increasing natural gas prices as an energy policy did not show a significant influence on establishing and functioning energy-secure TEC initiatives.

### REFLECTION ON THE RESEARCH OBJECTIVE

Considering the insights from four research questions, it is concluded that energy-secure TEC initiatives are collective energy systems with particular characteristics and surrounding conditions. The results demonstrated that behavioural and institutional settings (e.g. role of the community-boards, environmentally friendly behaviour and subsidy allocation strategies) are relatively more influential than technical settings (e.g. available renewable thermal technologies and resources) for establishing and sustained functioning of energy-secure collective energy systems. The most critical technical setting for the energy security of TEC initiatives was the connection to the natural gas grid. Reducing the individual households' thermal demand was also found to influence energy-secure TEC initiatives positively.

From a behavioural and institutional analysis point of view, the municipality's leadership with economic consideration for allocating subsidies, collective action of individual households who have a long-term vision/ commitment to their TEC initiative, and having access to the financial resources (e.g. their own budget and/or investments) are necessary for establishing and sustaining functioning of energy-secure TEC initiatives. The results also delineated that supportive policies (e.g. available subsidy) had a more considerable positive impact than prohibiting policies (e.g. $CO_2$ emissions tax). Lastly, the study concluded that energy-secure TEC initiatives have a significant potential to contribute to enlarging local renewable energy generation and, therefore, the energy transition as a whole while being energy secure and economically feasible in the long term.

### REFLECTION FROM THE THEORETICAL ANGLE

By approaching TEC initiatives from an institutional analysis angle (as elaborated in Chapter 1 and Section 1.5.2), the study particularly provided insights into the institution and behavioural settings that influence the establishment and functioning of energy-secure TEC initiatives.

#### The four-layer model of Williamson

Different actors and their institutional and behaviour conditions, which are located on different layers of the four-layer model of Williamson, are analysed in this study. Among the four layers (i.e. social embeddedness, institutional environment, governance and individual analysis), the study showed that layer 3, governance, particularly has considerable influence on establishing and functioning energy-secure TEC initiatives. The existence and knowledge of such a stakeholder (e.g. community leaders) could drastically fasten such processes. Furthermore, a specific type of leadership, municipality leadership (a distinct governance type), could potentially lead to a higher energy security performance within TEC initiatives. Further elaboration on these layers and their presentative actors are presented in Chapter 3 and Chapter 5.

#### The institutional and analysis developemnt (IAD) framework

This study used the IAD framework to understand and analyse the decision-making processes and collective action dynamics within TEC initiatives while systematically structuring technical, institutional and behavioural settings. All these settings are structured within three types of exogenous variables in the IAD framework (i.e. biophysical conditions, attributes of community and rules-in-use). Attributes of community (e.g. environmentally friendly behaviour) were found to be the most crucial exogenous variable. Furthermore, supportive policies (as a particular type of rules-in-use) and connected to the grid energy communities (as a specific type of biophysical condition) were found to be essential for establishing and functioning energy-secure TEC initiatives.

These insights from the theoretical angle are presented in detail in each chapter and translated into recommendations for different actors. These are concluded as research contributions Section 6.2.

## 6.2. RESEARCH CONTRIBUTIONS

### 6.2.1. SCIENTIFIC CONTRIBUTION

This study bridged two domains: (thermal) energy communities and energy security. The scientific contributions of this study are as follows:

#### LOCAL (THERMAL) ENERGY TRANSITION

- The study contributed to the academic literature by identifying, structuring and studying characteristics of TEC initiatives. The study formulated the TEC initiatives as particular collective energy systems and identified their technical, behavioural and institutional characteristics and surrounding conditions. Therefore, the study developed and tailored a concept of TEC initiatives. The study provided a research agenda for studying local thermal energy transition, particularly TEC initiatives.

- The study contributed to studying various local actors of (energy-secure) TEC initiatives for the first time. The presented ABMS captured and explored the roles and responsibilities of actors and provided concrete recommendations and insights, examples being policy interventions (e.g. empowering community boards, influence and amount of subsidy) and households' behavioural (e.g. long-term vision/ commitment).

- By approaching (energy-secure) TEC initiatives from the collective action and institutional analysis perspectives for the first time, this research contributed to the literature by demonstrating an application of collective action as a possible solution for the local energy transition. The presented models used frameworks such as the four-layer model of Williamson and the institutional analysis and development (IAD) framework for the first time together to model and investigate such collective energy systems.

- Furthermore, the study contributed to the following topics related to TEC initiatives:
  - Energy policy: The study showed that supportive policies (e.g. available subsidies) have a more considerable positive influence on the establishment and functioning process of (energy-secure) TEC initiatives than prohibiting policies (e.g. $CO_2$ emissions tax). The study illustrated that increasing taxes on

natural gas prices as planned by the Dutch government does not influence the energy security of TEC initiatives.

- Leadership: The study demonstrated that the leadership of TEC initiatives has a significant influence on the energy security performance of such collective energy systems. Notably, it showed the strong positive impact of community-board leadership on collective generation, $CO_2$ emissions reduction and energy security performances.
- Behaviour: The study confirmed that for the establishment and sustained functioning of TEC initiatives, all decision-making criteria and motivations (i.e. energy independence, trust, environmental concern and economic benefits) are influential. Therefore, balancing all relevant decision-making criteria is crucial. The results also demonstrated that environmentally friendly and collective behaviour potentially leads to higher energy security performances within TEC initiatives.
- Economic conditions: The study showed that TEC initiatives' are economically feasible with a payback time of a minimum of 10 years. Economic conditions (e.g. the size of investment by households and the amount of available subsidy) have a considerable positive influence on the performance of energy-secure TEC initiatives. Individuals' long-term vision (e.g. 10 years) and larger initial investments, along with larger supportive policies (e.g. 2 million euros), are effective and essential for the performance of such collective systems.
- Technical configurations: The study revealed that higher collective renewable energy generation (in contrast to individual renewable energy generation) has a more positive impact on establishing and functioning of energy-secure TEC initiatives. Therefore, larger thermal technologies (e.g. geothermal wells) contribute much further to such collective energy systems compared to smaller thermal technologies (e.g. individual wood pallets and heat pumps). Connection to the natural gas grid has a strong positive influence on the energy security of TEC initiatives. Furthermore, the size of the community and the number of participants/members were not influential, as long as they were not undermining the economy of scale.

### ENERGY SECURITY

This study is one of the first studies to approach and investigate energy security through the collective action lens. Using ABMS as the modelling tool, this research bridged two branches of literature (i.e. energy security and (thermal) energy communities) to understand the relationship between collective action and energy security. Therefore, it contributed to a more inclusive energy security concept (rather than only security of supply). The study demonstrated concrete examples of such approaches and simulations for studying collective energy security. The study also contributed to the energy security of the renewable energy systems by facilitating the establishment and functioning of energy-secure TEC initiatives.

### 6.2.2. SOCIETAL CONTRIBUTION

This study provided two main societal contributions. First, by providing insights into the design, establishment, and functioning of energy-secure TEC initiatives, it contributed to facilitating enlarging the share of local renewable energy generation and the energy transition. This study responds to the increasing concerns of actors regarding neglecting households' thermal energy consumption in the local energy transition discussions. Second, the research contributed to responding to one of the focal concerning points for different actors within energy communities, collective energy security, with a new approach. Such an approach contributed to helping energy security analysts to develop more rigorous and applicable policies while taking different actors' perspectives into account and exploring trade-offs and scenarios for achieving higher collective energy security. These societal contributions are translated to recommendations for two main actors of energy-secure TEC initiatives, who are also among the audiences of this study:

#### POLICY-MAKERS: POLICIES FOR THE THERMAL ENERGY TRANSITION

This study supports practitioners in the energy transition, particularly policy-makers, in developing rigorous energy policies.

The study sheds light on the importance of the project leadership role, where two specific types of leadership (i.e. municipality leadership and community-board leadership) were explored. Based on the results, policy-makers are recommended to empower and provide substantial support to community boards, as their leadership leads to the faster establishment of TEC initiatives with higher collective thermal energy generation and $CO_2$ emission reduction (which could also potentially lead to higher energy security performances). Providing such support could be done in different ways, such as developing programmes that improve the capabilities of community boards to increase households' knowledge about the heating transition and their participation in TEC initiatives.

Furthermore, the results demonstrated the significant positive influence of supportive policies such as available subsidies on establishing and functioning energy-secure TEC initiatives (in comparison with prohibiting policies (e.g. $CO_2$ emissions taxes)). The policy-makers are encouraged to focus more on developing rigorous, supportive policies. In addition to providing subsidies and loans for individual households and TEC initiatives, such support also includes providing relevant detailed information for individual households with the purpose of empowering them (along with offering training to community boards).

In the next related step, strategies for subsidies allocation were also found to be influential in establishing and functioning energy-secure TEC initiatives. In particular, allocating subsidies based on the projects' environmental friendliness is the best strategy for establishing TEC initiatives, while allocating subsidies only based on the projects' costs and economic feasibility resulted in slightly better energy security performances. Policy-makers are recommended to prioritise TEC initiatives with higher environmental friendliness performances to be granted the subsidy while also considering the economic constraints.

As thermal energy demand reduction and collective renewable heat generation positively impact establishing and functioning of energy-secure TEC initiatives, policy-makers are encouraged to develop supportive policies to underpin and reinforce these two conditions in the long term. Such supportive policies could include encouraging individuals (and community-bards) to act collectively to select thermal energy technologies with higher collective thermal energy generation, incentivising collective retrofitting and possibly aggregated energy flexibility.

The study brought insights into current ongoing fossil-fuel-based energy policies (e.g. natural gas price reforms). The study showed that increasing taxes on natural gas prices as planned by the Dutch government is suitable for achieving energy security within TEC initiatives. Therefore, the Dutch government is recommended to continue its natural gas price strategy. These results are based on the stable and steady trends in the natural gas market and do not reflect the current crises in eastern Europe and its impact on natural gas prices.

#### INDIVIDUAL HOUSEHOLDS: ATTRIBUTES FOR THE THERMAL ENERGY TRANSITION

The study also sheds light on the attributes of communities (e.g. participating motivations, size of the community and time-frame visions) within the context of energy-secure TEC initiatives. Although the results showed more environmental-friendly behaviours lead to higher $CO_2$ emissions reduction and more economic considerations lead to a better energy security performance, balancing all the decision-making criteria (i.e. energy independence, trust, environmental concern and economic benefits) is key to success.

The study demonstrated that by considering current trends in energy policy (e.g. natural gas prices and $CO_2$ taxes), in a long-term investment (i.e. longer than ten years), TEC initiatives are financially more attractive than using fossil fuels (i.e. natural gas), while their contribution to the $CO_2$ emission reduction is considerable. Furthermore, higher collective thermal energy generation could potentially lead to lower costs, which can potentially be more attractive for individuals to coordinate themselves for achieving an agreement for higher collective energy generation within their TEC initiatives. Individual households are encouraged to take the initiative to establish their own TEC initiatives and facilitate the process of implementation of renewable thermal energy technologies in their neighbourhoods, as it could bring them and society economic and environmental benefits. Policy-makers are recommended to support such initiatives, as they contribute considerably to the local energy transition. In this line, the community board is an essential actor, which by being empowered (e.g. through receiving information and training), could substantially facilitate the establishment and functioning of energy-secure TEC initiatives.

### 6.2.3. LIMITATIONS AND DIRECTIONS FOR FURTHER RESEARCH

This study demonstrated an approach to understanding, investigating, and measuring energy-secure TEC initiatives' establishment and functioning processes through institutional and behavioural lenses. The research objectives were approached through analytical desk research and agent-based modelling and simulation (ABMS). This section discusses the implications of research choices and approaches for answering research questions. The limitations and potential avenues for further research are also elaborated on in detail.

### ENERGY SECURITY OF COLLECTIVE ENERGY SYSTEMS

The research proposed a new approach to investigate and measure the energy security of collective energy systems and brought both scientific and societal insights (see Section 6.2), but it also has limitations.

The current study is a starting point for studying the energy security of collective energy systems. In this research, we used two energy security concepts, (i) 4As' energy security concept: availability, affordability, accessibility and acceptability; and (ii) Ang et al. energy security concept: availability, energy prices, environment, infrastructure, governance, energy efficiency and social effects for evaluating establishment and functioning processes of TEC initiatives. First, it is crucial to keep in mind that other energy security concepts (e.g. as elaborated in Chapter 5 and [64]) and their representing dimensions (e.g., energy flexibility and energy independence) could also be used to study and model collective energy security. The study is limited to approaching energy security through particular lenses using mentioned energy security concepts. Using other energy security concepts and their representative dimensions could potentially have derived different insights regarding the energy security of TEC initiatives. Therefore, it could add value to understanding collective energy security more in-depth. Using other available energy security concepts and comparing such studies could potentially validate the current study.

The second limitation and avenue for further research is that a limited number of energy security indicators for measuring energy security dimensions were considered in this study. For instance, indicators such as payback-time, initial investment, and average cost are used in the literature for the affordability dimension of energy security but are not considered in the models of the current study. Other energy security indicators could potentially be used in the modelling exercises, as elaborated extensively in Chapter 4 and Chapter 5, examples being domestic energy generation per capita of a collective energy system (as an indicator for availability dimension) and investments for switching away from fossil fuels (as an indicator for acceptability). Considering other energy security indicators could potentially influence the trade-offs of the actors and, therefore, could have derived different insights. For instance, in Chapter 5, instead of having one energy security indicator for each energy security dimension (seven indicators in total), the modelling exercise could include two indicators per dimension and fourteen energy security indicators. Using several indicators for the same energy security dimension can be translated to approaching that dimension from different angles, potentially leading to a more comprehensive and extensive understanding of individuals' energy security trade-offs and decision-making processes. Therefore, it could capture more realistic trade-offs within collective energy systems and further develop a collective energy security concept.

### BEHAVIOURAL AND INSTITUTIONAL ASPECTS OF ENERGY-SECURE TEC INITIATIVES

To study and model energy-secure TEC initiatives, they have been approached through institutional and behavioural lenses. As discussed in Chapters 2 and 3, renewable thermal energy technologies are mature. A key challenge for establishing and functioning (energy-secure) TEC initiatives is related to the institutional design of such a collective energy system. In this research, the four-layer model of Williamson to study different actors, the Institutional Analysis and Development (IAD) framework and the Social Value Orientation (SVO) theory to capture their decision-making processes and behaviour were particularly used. However, looking at energy-secure TEC initiatives through such lenses has several challenges and limitations.

The first limitation is the lack of real-world data on behavioural and institutional conditions for such systems' establishment and functioning processes (also for simulation purposes). Such limitation is particularly challenging as the number of real-world established and functioning (energy-secure) TEC initiatives are low, and the established ones are still young. There is also a real-world data limitation on the established young TEC initiatives that could not show the step-by-step establishment and functioning processes. Therefore, collecting empirical data, specifically additional qualitative and quantitative data about motivations, interactions, and decision-making processes of energy-secure (thermal) energy communities, would be beneficial. This data could be collected through interviews, questionnaires and focus groups, which could contribute to a more realistic decision-making process in the models and, therefore, more useful and realistic results and recommendations related to the collective decision-making of local actors on the establishment and functioning of energy-secure thermal energy communities.

Along with the need to further study local actors (i.e., individual households and community boards), it is also meaningful to research and explore other actors' roles, responsibilities, and interactions. Examples of such actors are waste companies and farmers (for providing bio-based energy), insulation companies (for providing collective retrofitting solutions) and urban planners (for providing insights on spatial planning). Investigating such actors could bring further insights on topics such as technological options and needed space for implementing a thermal energy system.

### AGENT-BASED MODELLING AND SIMULATION

For this study, agent-based modelling and simulation (ABMS) was used as the computer simulation approach. An advantage of using ABMS is that we could explore the complex establishment and functioning processes of energy-secure TEC initiatives while considering various technical, behavioural and institutional characteristics and embedded heterogeneously of such collective energy systems during the long-term planning horizon. Although the developed ABMS provided meaningful insights (as elaborated in Chapter 3, Chapter 4, Chapter 5 and Section 6.2.), they have certain limitations.

The first limitation is in the context of conceptualising and capturing the responsibilities and decision-making processes of involved actors within the developed ABMS. In addition to the lack of real-world data, the roles and responsibilities of actors within TEC initiatives, specifically the community-boards and project leaders, were also missing, which was another challenge and limitation for this study. To overcome such difficulties, and to structure our ABMS and the decision-making processes, we used particular frameworks and theories from institutional economics, such as the Institutional Analysis and Development (IAD) framework and the four layers of Williamson. Nevertheless, there are other frameworks and theories, such as the Socio-Ecological System framework by Ostrom [120] (to explore the collective action and institutional settings further) and the Theory of Planned Behaviour (to explore the actors' behavioural attitudes and decision-making processes further) [353]. Using such frameworks and theories could complement current findings and enrich the understanding regarding the conditions, interactions and decision-making processes for energy-secure TEC initiatives. More detailed real-world data and data-driven models based on empirical research as input to the modelling exercise could also potentially bring more realistic insights. For instance, modelling a specific case study about an ongoing TEC initiative in a (Dutch) city can be beneficial.

Finally, by definition, models cannot include all the details of the objects they represent and have their own specific limitations. The model's assumptions and structure in this study can be improved. In particular, the biophysical conditions (e.g. technological details and ambient temperature) are simplified in this study's modelling exercises. The reason for this was to focus on behavioural attributes and institutional design insights rather than to explore the technical design and techno-economic feasibility of energy-secure TEC initiatives. Such simplifications and limitations are considered in the analysis and do not jeopardise the results and recommendations. To overcome these limitations, the model could be coupled with a technical optimisation model for the technical outcome and an equilibrium model to capture the energy supply-demand relationships to be complete and more conclusive. Therefore, a promising future research direction would be to enhance the computational models built in this study by integrating them with other modelling approaches. Also, the modelling exercises have extensively studied the role of the policy-makers and municipalities as resource providers, while in reality, their function is much more complex than this.

### 6.2.4. FINAL REMARKS

This study studied and investigated conditions that affect the establishment and functioning of energy-secure thermal energy communities as collective distributed renewable energy systems. Energy communities, particularly thermal energy communities (TEC initiatives), are relatively new energy systems. Consequently, topics related to these collective systems, such as their energy security as a concern for all actors, are very active research fields. This thesis presented a set of agent-based models to investigate technical, behavioural and institutional conditions of energy-secure thermal energy communities. The study targets three types of audiences: academics (by delineating new approaches and applications for studying collective energy systems and their collective energy security), practitioners in thermal energy transition (by outlining policy-oriented recommendations), and individual households (by delineating behavioural attribute-oriented recommendations). This study contributes to the urgent national and international collective challenge to ensure everyone's energy security through collective distributed renewable energy technologies.

# BIBLIOGRAPHY

[1] M. Pacesila, S. G. Burcea, and S. E. Colesca. “Analysis of renewable energies in European Union”. In: *Renewable and Sustainable Energy Reviews* (2016). ISSN: 18790690. DOI: `10.1016/j.rser.2015.10.152`.

[2]

bibinitperiod L. D. Verbong G. *Governing the Energy Transition: Reality, Illusion or Necessity*. Routledge, Taylor & Francis Group, 2012.

[3] “TRENDS IN GLOBAL CO 2 EMISSIONS Trends in global CO 2 emissions: 2015 Report”. In: ().

[4] M. Oteman, M. Wiering, and J. K. Helderman. “The institutional space of community initiatives for renewable energy: a comparative case study of the Netherlands, Germany and Denmark”. In: *Energy, Sustainability and Society* 4.1 (2014), pp. 1–17. ISSN: 21920567. DOI: `10.1186/2192-0567-4-11`.

[5] D. Magnusson and J. Palm. “Come together-the development of Swedish energy communities”. In: *Sustainability (Switzerland)* 11.4 (2019), pp. 1–19. ISSN: 20711050. DOI: `10.3390/su11041056`.

[6] G. Dóci and E. Vasileiadou. “"Let’s do it ourselves" Individual motivations for investing in renewables at community level”. In: *Renewable and Sustainable Energy Reviews* 49 (2015), pp. 41–50. ISSN: 18790690. DOI: `10.1016/j.rser.2015.04.051`. URL: `http://dx.doi.org/10.1016/j.rser.2015.04.051`.

[7] J. Rogers, E. Simmons, I. Convery, and A. Weatherall. “Public perceptions of opportunities for community-based renewable energy projects”. In: *Energy Policy* 36.11 (Nov. 2008), pp. 4217–4226. ISSN: 0301-4215. DOI: `10.1016/J.ENPOL.2008.07.028`. URL: `https://www.sciencedirect.com/science/article/pii/S0301421508003662`.

[8] G. Walker. “What are the barriers and incentives for community-owned means of energy production and use?” In: *Energy Policy* 36.12 (2008), pp. 4401–4405. ISSN: 03014215. DOI: `10.1016/j.enpol.2008.09.032`.

[9] W. Schram, A. Louwen, I. Lampropoulos, and W. Van Sark. “Comparison of the greenhouse gas emission reduction potential of energy communities”. In: *Energies* 12.23 (2019), pp. 1–23. ISSN: 19961073. DOI: `10.3390/en12234440`.

[10] T. Bauwens. “Explaining the diversity of motivations behind community renewable energy”. In: *Energy Policy* 93 (2016), pp. 278–290. ISSN: 03014215. DOI: `10.1016/j.enpol.2016.03.017`. URL: `http://dx.doi.org/10.1016/j.enpol.2016.03.017`.

[11] T. Bauwens, B. Gotchev, and L. Holstenkamp. “What drives the development of community energy in Europe? the case of wind power cooperatives”. In: *Energy Research and Social Science* (2016). ISSN: 22146296. DOI: `10.1016/j.erss.2015.12.016`.

[12] J. S. Gregg, S. Nyborg, M. Hansen, V. J. Schwanitz, A. Wierling, J. P. Zeiss, S. Delvaux, V. Saenz, L. Polo-Alvarez, C. Candelise, W. Gilcrease, O. Arrobbio, A. Sciullo, and D. Padovan. “Collective action and social innovation in the energy sector: A mobilization model perspective”. In: *Energies* 13.3 (2020). ISSN: 19961073. DOI: `10.3390/en13030651`.

[13] G. Dóci, E. Vasileiadou, and A. C. Petersen. “Exploring the transition potential of renewable energy communities”. In: *Futures* 66 (2015), pp. 85–95. ISSN: 00163287. DOI: `10.1016/j.futures.2015.01.002`.

[14] T. Bauwens. “Analyzing the determinants of the size of investments by community renewable energy members: Findings and policy implications from Flanders”. In: *Energy Policy* 129.March (2019), pp. 841–852. ISSN: 03014215. DOI: `10.1016/j.enpol.2019.02.067`. URL: `https://doi.org/10.1016/j.enpol.2019.02.067`.

[15] F. Fuentes, E. Sauma, and A. V. D. Weijde. “The Scottish experience in community energy development : A starting point for Chile”. In: *Renewable and Sustainable Energy Reviews* 113.June 2018 (2019), p. 109239. ISSN: 1364-0321. DOI: `10.1016/j.rser.2019.06.046`. URL: `https://doi.org/10.1016/j.rser.2019.06.046`.

[16] C. Rae and F. Bradley. “Energy autonomy in sustainable communities—A review of key issues”. In: *Renewable and Sustainable Energy Reviews* 16.9 (2012), pp. 6497–6506.

[17] “Energy Policies of IEA Countries - The European Union 2014 Review”. In: ().

[18] M. Wolsink. “The research agenda on social acceptance of distributed generation in smart grids: Renewable as common pool resources”. In: *Renewable and Sustainable Energy Reviews* (2012). ISSN: 13640321. DOI: `10.1016/j.rser.2011.09.006`.

[19] M. Olonscheck, C. Walther, M. Lüdeke, and J. P. Kropp. “Feasibility of energy reduction targets under climate change: The case of the residential heating energy sector of the Netherlands”. In: *Energy* (2015). ISSN: 03605442. DOI: `10.1016/j.energy.2015.07.080`.

[20] Z. Huang and H. Yu. “Approach for integrated optimization of community heating system at urban detailed planning stage”. In: *Energy and Buildings* 77 (2014), pp. 103–111. ISSN: 03787788. DOI: `10.1016/j.enbuild.2014.03.045`. URL: `http://dx.doi.org/10.1016/j.enbuild.2014.03.045`.

[21] T. Von Wirth, L. Gislason, and R. Seidl. “Distributed energy systems on a neighborhood scale: Reviewing drivers of and barriers to social acceptance”. In: (2017). DOI: `10.1016/j.rser.2017.09.086`.

[22] K. Vringer, M. van Middelkoop, and N. Hoogervorst. “Saving energy is not easy: An impact assessment of Dutch policy to reduce the energy requirements of buildings”. In: *Energy Policy* (2016). ISSN: 03014215. DOI: `10.1016/j.enpol.2016.02.047`.

[23] C. Nolden. “Governing community energy-Feed-in tariffs and the development of community wind energy schemes in the United Kingdom and Germany”. In: *Energy Policy* (2013). ISSN: 03014215. DOI: `10.1016/j.enpol.2013.08.050`.

[24] K. Matsumoto, M. Doumpos, and K. Andriosopoulos. “Historical energy security performance in EU countries”. In: *Renewable and Sustainable Energy Reviews* 82.December 2016 (2018), pp. 1737–1748. ISSN: 18790690. DOI: `10.1016/j.rser.2017.06.058`. URL: `http://dx.doi.org/10.1016/j.rser.2017.06.058`.

[25] G. St. Denis and P. Parker. “Community energy planning in Canada: The role of renewable energy”. In: *Renewable and Sustainable Energy Reviews* 13.8 (2009), pp. 2088–2095. ISSN: 13640321. DOI: `10.1016/j.rser.2008.09.030`.

[26] P. Vuichard, A. Stauch, and N. Dällenbach. “Individual or collective? Community investment, local taxes, and the social acceptance of wind energy in Switzerland”. In: *Energy Research and Social Science* 58.January (2019), p. 101275. ISSN: 22146296. DOI: `10.1016/j.erss.2019.101275`. URL: `https://doi.org/10.1016/j.erss.2019.101275`.

[27] J. Fouladvand, N. Mouter, A. Ghorbani, and P. Herder. “Community Systems : An Explorative Agent-Based”. In: (2020).

[28] B. P. Koirala, E. Koliou, J. Friege, R. A. Hakvoort, and P. M. Herder. *Energetic communities for community energy: A review of key issues and trends shaping integrated community energy systems.* 2016. DOI: `10.1016/j.rser.2015.11.080`.

[29] S. Ruggiero, T. Onkila, and V. Kuittinen. “Realizing the social acceptance of community renewable energy: A process-outcome analysis of stakeholder influence”. In: *Energy Research and Social Science* (2014). ISSN: 22146296. DOI: `10.1016/j.erss.2014.09.001`.

[30] J. Busch, K. Roelich, C. S. Bale, and C. Knoeri. “Scaling up local energy infrastructure; An agent-based model of the emergence of district heating networks”. In: *Energy Policy* 100.October 2016 (2017), pp. 170–180. ISSN: 03014215. DOI: `10.1016/j.enpol.2016.10.011`. URL: `http://dx.doi.org/10.1016/j.enpol.2016.10.011`.

[31] R. van Leeuwen, J. de Wit, and G. Smit. “Review of urban energy transition in the Netherlands and the role of smart energy management”. In: *Energy Conversion and Management* (2017). ISSN: 01968904. DOI: `10.1016/j.enconman.2017.05.081`.

[32] K. N. Finney, J. Zhou, Q. Chen, X. Zhang, C. Chan, V. N. Sharifi, J. Swithenbank, A. Nolan, S. White, S. Ogden, and R. Bradford. “Modelling and mapping sustainable heating for cities”. In: *Applied Thermal Engineering* (2013). ISSN: 13594311. DOI: `10.1016/j.applthermaleng.2012.04.009`.

[33] U. Persson, B. Möller, and S. Werner. "Heat Roadmap Europe: Identifying strategic heat synergy regions". In: *Energy Policy* (2014). ISSN: 03014215. DOI: `10.1016/j.enpol.2014.07.015`.

[34] A. Itten, F. Sherry-brennan, T. Hoppe, A. Sundaram, and P. Devine-wright. "Energy Research & Social Science Co-creation as a social process for unlocking sustainable heating transitions in Europe". In: *Energy Research & Social Science* 74.August 2020 (2021), p. 101956. ISSN: 2214-6296. DOI: `10.1016/j.erss.2021.101956`. URL: `https://doi.org/10.1016/j.erss.2021.101956`.

[35] C. C. Michelsen and R. Madlener. "Homeowners' preferences for adopting innovative residential heating systems: A discrete choice analysis for Germany". In: *Energy Economics* (2012). ISSN: 01409883. DOI: `10.1016/j.eneco.2012.06.009`.

[36] C. C. Michelsen and R. Madlener. "Motivational factors influencing the homeowners' decisions between residential heating systems: An empirical analysis for Germany". In: *Energy Policy* (2013). ISSN: 03014215. DOI: `10.1016/j.enpol.2013.01.045`.

[37] A. Lyden, R. Pepper, and P. G. Tuohy. "A modelling tool selection process for planning of community scale energy systems including storage and demand side management". In: *Sustainable Cities and Society* 39.August 2017 (2018), pp. 674–688. ISSN: 22106707. DOI: `10.1016/j.scs.2018.02.003`. URL: `https://doi.org/10.1016/j.scs.2018.02.003`.

[38] B. Rezaie and M. A. Rosen. "District heating and cooling: Review of technology and potential enhancements". In: *Applied Energy* 93 (2012), pp. 2–10. ISSN: 03062619. DOI: `10.1016/j.apenergy.2011.04.020`. URL: `http://dx.doi.org/10.1016/j.apenergy.2011.04.020`.

[39] G. Mavromatidis, K. Orehounig, and J. Carmeliet. "A review of uncertainty characterisation approaches for the optimal design of distributed energy systems". In: *Renewable and Sustainable Energy Reviews* 88.February (2018), pp. 258–277. ISSN: 18790690. DOI: `10.1016/j.rser.2018.02.021`. URL: `https://doi.org/10.1016/j.rser.2018.02.021`.

[40] E. Viardot. "The role of cooperatives in overcoming the barriers to adoption of renewable energy". In: *Energy Policy* 63 (2013), pp. 756–764. ISSN: 03014215. DOI: `10.1016/j.enpol.2013.08.034`. URL: `http://dx.doi.org/10.1016/j.enpol.2013.08.034`.

[41] R. Ilieva and A. Hernandez. "Scaling-Up Sustainable Development Initiatives: A Comparative Case Study of Agri-Food System Innovations in Brazil, New York, and Senegal". en. In: *Sustainability* 10.11 (Nov. 2018), p. 4057. ISSN: 2071-1050. DOI: `10.3390/su10114057`.

[42] J. De Boer and C. Zuidema. "Towards an integrated energy landscape". In: *Proceedings of the Institution of Civil Engineers: Urban Design and Planning* 168.5 (2015), pp. 231–240. ISSN: 17550807. DOI: `10.1680/udap.14.00041`.

[43] S. V. Valentine. “Emerging symbiosis: Renewable energy and energy security”. In: *Renewable and Sustainable Energy Reviews* 15.9 (2011), pp. 4572–4578. ISSN: 13640321. DOI: `10.1016/j.rser.2011.07.095`. URL: `http://dx.doi.org/10.1016/j.rser.2011.07.095`.

[44] E. Hache. “Do renewable energies improve energy security in the long run?” In: *International Economics* 156.November 2017 (2018), pp. 127–135. ISSN: 21107017. DOI: `10.1016/j.inteco.2018.01.005`. URL: `https://doi.org/10.1016/j.inteco.2018.01.005`.

[45] P. Connor, V. Bürger, L. Beurskens, K. Ericsson, and C. Egger. “Devising renewable heat policy: Overview of support options”. In: *Energy Policy* (2013). ISSN: 03014215. DOI: `10.1016/j.enpol.2012.09.052`.

[46] D. F. von Hippel, T. Suzuki, J. H. Williams, T. Savage, and P. Hayes. “Evaluating the energy security impacts of energy policies”. In: *The Routledge handbook of energy security*. Routledge, 2010, pp. 92–113.

[47] F. Poggi, A. Firmino, and M. Amado. “Shaping energy transition at municipal scale: A net-zero energy scenario-based approach”. In: *Land Use Policy* 99.April 2019 (2020), p. 104955. ISSN: 02648377. DOI: `10.1016/j.landusepol.2020.104955`. URL: `https://doi.org/10.1016/j.landusepol.2020.104955`.

[48] H. Chen, R. Ooka, K. Iwamura, H. Huang, N. Yoshizawa, K. Miisho, S. Yoshida, S. Namatame, A. Sakakura, and S. Tanaka. “Study on sustainable redevelopment of a densely built-up area in Tokyo by introducing a distributed local energy supply system”. In: *Energy and Buildings* 40.5 (2008), pp. 782–792. ISSN: 03787788. DOI: `10.1016/j.enbuild.2007.05.012`.

[49] E. Transitions. “Technologies of Engagement : How Battery Storage”. In: (2019), pp. 1–15.

[50] D. Schmidt. *Low Temperature District Heating for Future Energy Systems*. Vol. 149. 2018, pp. 595–604. ISBN: 3899990706. DOI: `10.1016/j.egypro.2018.08.224`.

[51] A. Arteconi, N. J. Hewitt, and F. Polonara. “Domestic demand-side management (DSM): Role of heat pumps and thermal energy storage (TES) systems”. In: *Applied Thermal Engineering* 51.1-2 (2013), pp. 155–165. ISSN: 13594311. DOI: `10.1016/j.applthermaleng.2012.09.023`. URL: `http://dx.doi.org/10.1016/j.applthermaleng.2012.09.023`.

[52] Y. Li, M. Jin, and Y. Li. “Community energy system planning: A case study on technology selection and operation optimization”. In: *Procedia Engineering* 205 (2017), pp. 2076–2083. ISSN: 18777058. DOI: `10.1016/j.proeng.2017.10.100`. URL: `https://doi.org/10.1016/j.proeng.2017.10.100`.

[53] M. T. Rees, J. Wu, B. Awad, J. Ekanayake, and N. Jenkins. “A total energy approach to integrated community infrastructure design”. In: *IEEE Power and Energy Society General Meeting* (2011). ISSN: 19449925. DOI: `10.1109/PES.2011.6038976`.

[54] L. Tronchin, M. Manfren, and B. Nastasi. “Energy efficiency, demand side management and energy storage technologies – A critical analysis of possible paths of integration in the built environment”. In: *Renewable and Sustainable Energy Reviews* 95.June (2018), pp. 341–353. ISSN: 18790690. DOI: `10.1016/j.rser.2018.06.060`. URL: `https://doi.org/10.1016/j.rser.2018.06.060`.

[55] E. K. Stigka, J. A. Paravantis, and G. K. Mihalakakou. “Social acceptance of renewable energy sources: A review of contingent valuation applications”. In: *Renewable and Sustainable Energy Reviews* (2014). ISSN: 13640321. DOI: `10.1016/j.rser.2013.12.026`.

[56] J. R. Woo, S. Chung, C. Y. Lee, and S. Y. Huh. “Willingness to participate in community-based renewable energy projects: A contingent valuation study in South Korea”. In: *Renewable and Sustainable Energy Reviews* 112.May 2018 (2019), pp. 643–652. ISSN: 18790690. DOI: `10.1016/j.rser.2019.06.010`. URL: `https://doi.org/10.1016/j.rser.2019.06.010`.

[57] B. J. Kalkbrenner and J. Roosen. “Citizens’ willingness to participate in local renewable energy projects: The role of community and trust in Germany”. In: *Energy Research and Social Science* (2016). ISSN: 22146296. DOI: `10.1016/j.erss.2015.12.006`.

[58] B. P. Koirala, Y. Araghi, M. Kroesen, A. Ghorbani, R. A. Hakvoort, and P. M. Herder. “Trust, awareness, and independence: Insights from a socio-psychological factor analysis of citizen knowledge and participation in community energy systems”. In: *Energy Research and Social Science* 38.February (2018), pp. 33–40. ISSN: 22146296. DOI: `10.1016/j.erss.2018.01.009`. URL: `https://doi.org/10.1016/j.erss.2018.01.009`.

[59] M. A. Heldeweg and Séverine Saintier. “Renewable energy communities as ‘socio-legal institutions’: A normative frame for energy decentralization?” In: *Renewable and Sustainable Energy Reviews* 119.November 2019 (2020). ISSN: 18790690. DOI: `10.1016/j.rser.2019.109518`.

[60] B. K. Sovacool and T. W. Lim. “Exploring the contested and convergent nature of energy security”. In: *The Routledge handbook of energy security [Internet]. Taylor & Francis* (2010), pp. 414–427.

[61] A. Månsson, B. Johansson, and L. J. Nilsson. “Assessing energy security: An overview of commonly used methodologies”. In: *Energy* 73 (2014), pp. 1–14. ISSN: 03605442. DOI: `10.1016/j.energy.2014.06.073`.

[62] B. Kruyt, D. P. van Vuuren, H. J. de Vries, and H. Groenenberg. “Indicators for energy security”. In: *Energy Policy* (2009). ISSN: 03014215. DOI: `10.1016/j.enpol.2009.02.006`.

[63] E. Security. “The Transformation of ASEAN”. In: 2.April (2017).

[64] B. K. Sovacool. “Introduction: Defining, measuring, and exploring energy security”. In: *The Routledge handbook of energy security*. Routledge, 2010, pp. 19–60.

[65] J. Bartos and A. Robertson. "Energy Supply Security: Emergency Response of IEA Countries". In: *International Energy Agency* (2014), p. 606. ISSN: 1464-3553. URL: `https://www.iea.org/publications/freepublications/publication/energy-supply-security-the-emergency-response-of-iea-countries-2014.html%5Cnhttps://www.iea.org/publications/freepublications/publication/ENERGYSUPPLYSECURITY2014.pdf`.

[66] S. Tongsopit, N. Kittner, Y. Chang, A. Aksornkij, and W. Wangjiraniran. "Energy security in ASEAN: A quantitative approach for sustainable energy policy". In: *Energy Policy* (2016). ISSN: 03014215. DOI: `10.1016/j.enpol.2015.11.019`.

[67] WEC. "World Energy Trilemma Index | 2017". In: (2017), p. 145. URL: `https://www.worldenergy.org/wp-content/uploads/2017/11/Energy-Trilemma-Index-2017_Executive-Summary_WEB.pdf%0Ahttps://www.worldenergy.org/wp-content/uploads/2017/11/Energy-Trilemma-Index-2017-Report.pdf`.

[68] B. K. Sovacool and I. Mukherjee. "Conceptualizing and measuring energy security: A synthesized approach". In: *Energy* 36.8 (2011), pp. 5343–5355. ISSN: 03605442. DOI: `10.1016/j.energy.2011.06.043`. URL: `http://dx.doi.org/10.1016/j.energy.2011.06.043`.

[69] A. Cherp and J. Jewell. "The concept of energy security: Beyond the four as". In: *Energy Policy* (2014). ISSN: 03014215. DOI: `10.1016/j.enpol.2014.09.005`.

[70] M. Radovanović, S. Filipović, and D. Pavlović. "Energy security measurement – A sustainable approach". In: *Renewable and Sustainable Energy Reviews* 68 (2017), pp. 1020–1032. ISSN: 13640321. DOI: `10.1016/j.rser.2016.02.010`.

[71] Z. Wang, G. Xu, H. Wang, and J. Ren. "Distributed energy system for sustainability transition: A comprehensive assessment under uncertainties based on interval multi-criteria decision making method by coupling interval DEMATEL and interval VIKOR". In: *Energy* 169 (2019), pp. 750–761. ISSN: 03605442. DOI: `10.1016/j.energy.2018.12.105`. URL: `https://doi.org/10.1016/j.energy.2018.12.105`.

[72] G. Mutani, V. Todeschi, A. Tartaglia, and G. Nuvoli. "Energy communities in piedmont region (IT). the case study in pinerolo territory". In: *INTELEC, International Telecommunications Energy Conference (Proceedings)* 2018-Octob (2019), pp. 1–8. ISSN: 02750473. DOI: `10.1109/INTLEC.2018.8612427`.

[73] O. Samuel, A. Almogren, A. Javaid, M. Zuair, I. Ullah, and N. Javaid. "Leveraging blockchain technology for secure energy trading and least-cost evaluation of decentralized contributions to electrification in sub-Saharan Africa". In: *Entropy* 22.2 (2020). ISSN: 10994300. DOI: `10.3390/e22020226`.

[74] S. Rinaldi, M. Pasetti, A. Flammini, P. Ferrari, E. Sisinni, and F. Simoncini. "A Testing Framework for the Monitoring and Performance Analysis of Distributed Energy Systems". In: *IEEE Transactions on Instrumentation and Measurement* 68.10 (2019), pp. 3831–3840. ISSN: 15579662. DOI: `10.1109/TIM.2019.2911733`.

[75] Z. Wang and A. T. Perera. “Robust optimization of power grid with distributed generation and improved reliability”. In: *Energy Procedia* 159 (2019), pp. 400–405. ISSN: 18766102. DOI: `10.1016/j.egypro.2018.12.069`. URL: `https://doi.org/10.1016/j.egypro.2018.12.069`.

[76] B. W. Ang, W. L. Choong, and T. S. Ng. “Energy security: Definitions, dimensions and indexes”. In: *Renewable and Sustainable Energy Reviews* (2015). ISSN: 13640321. DOI: `10.1016/j.rser.2014.10.064`.

[77] J. Ren and B. K. Sovacool. “Quantifying, measuring, and strategizing energy security: Determining the most meaningful dimensions and metrics”. In: *Energy* (2014). ISSN: 03605442. DOI: `10.1016/j.energy.2014.08.083`.

[78] J. Morris. “The Evolving Localism (and Neoliberalism) of Urban Renewable Energy Projects”. In: *Culture, Agriculture, Food and Environment* 35.1 (2013), pp. 16–29. ISSN: 21539553. DOI: `10.1111/cuag.12002`.

[79] C. D. D. D. “Incorporating community governance: Planning sustainable energy security”. eng. In: *International Journal of Environmental, Cultural, Economic and Social Sustainability* 7.4 (2011), pp. 349–365. ISSN: 18322077.

[80] C. Erickson. “Rural milk preservation with the ISAAC solar icemaker”. In: *Energy for Sustainable Development* 13.4 (2009), pp. 287–291. ISSN: 09730826. DOI: `10.1016/j.esd.2009.10.007`. URL: `http://dx.doi.org/10.1016/j.esd.2009.10.007`.

[81] A. Ehrensperger, J. R. Randriamalala, L. I. Raoliarivelo, and J. M. Husi. “Jatropha mahafalensis for rural energy supply in south-western Madagascar?” In: *Energy for Sustainable Development* 28 (2015), pp. 60–67. ISSN: 23524669. DOI: `10.1016/j.esd.2015.07.006`. URL: `http://dx.doi.org/10.1016/j.esd.2015.07.006`.

[82] O. E. E. E. “Collective action and the evolution of social norms”. eng. In: *Journal of Natural Resources Policy Research* 6.4 (2014), pp. 235–252. ISSN: 19390459.

[83] D. F. F. F. *Intentional agents and goal formation.* eng. 1998. ISBN: 03029743.

[84] C. R. R. R. “Computational social and behavioral science”. eng. In: *New Frontiers in the Study of Social Phenomena: Cognition, Complexity, Adaptation* (2016), pp. 1–7.

[85] A. Ghorbani and G. Bravo. “Managing the commons: A simple model of the emergence of institutions through collective action”. In: *International Journal of the Commons* 10.1 (2016), pp. 200–219. ISSN: 18750281. DOI: `10.18352/ijc.606`.

[86] 2. Bruce. “No Title No Title”. In: *Journal of Chemical Information and Modeling* 53.9 (2013), pp. 1689–1699. ISSN: 1098-6596. DOI: `10.1017/CBO9781107415324.004`.

[87] S. F. Railsback and V. Grimm. *Agent-Based and Individual-Based Modeling: A Practical Introduction.* Princeton: Princeton University Press, 2012.

[88] U. Wilensky and W. Rand. *An Introduction to Agent-Based Modeling.* The MIT Press, Sept. 2015. ISBN: 9780262731898. DOI: `10.2307/j.ctt17kk851`. URL: `http://www.jstor.org/stable/j.ctt17kk851`.

[89] V. D. K. H. K. K.H. "Agent-based Modelling of socio-technical systems". eng. In: *Agent-Based Modelling of Socio-Technical Systems* (2013).

[90] D. L. DeAngelis and V. Grimm. "Individual-based models in ecology after four decades". In: *F1000Prime Reports* 6.June (2014). ISSN: 20517599. DOI: 10.12703/P6-39.

[91] E. Bonabeau. "Agent-based modeling: Methods and techniques for simulating human systems". In: *Proceedings of the National Academy of Sciences of the United States of America* 99.Suppl 3 (2002), p. 7280.

[92] *Handbook of Computable General Equilibrium Modeling.* Vol. 1. 2013. ISBN: 9780444595683.

[93] M. Ouyang. "Review on modeling and simulation of interdependent critical infrastructure systems". In: *Reliability Engineering and System Safety* 121 (2014), pp. 43–60. ISSN: 0951-8320. DOI: 10.1016/j.ress.2013.06.040. URL: http://dx.doi.org/10.1016/j.ress.2013.06.040.

[94] S. Edition. "Introduction to Discrete Event Systems Introduction to Discrete Event Systems". In: ().

[95] T. E. D. Wildt, E. J. L. Chappin, G. V. D. Kaa, P. M. Herder, and I. R. V. D. Poel. "Energy Research & Social Science Conflicted by decarbonisation : Five types of conflict at the nexus of capabilities and decentralised energy systems identified with an agent-based model". In: *Energy Research & Social Science* 64.January (2020), p. 101451. ISSN: 2214-6296. DOI: 10.1016/j.erss.2020.101451. URL: https://doi.org/10.1016/j.erss.2020.101451.

[96] T. Yue, R. Long, H. Chen, J. Liu, H. Liu, and Y. Gu. "Energy-saving behavior of urban residents in China: A multi-agent simulation". In: *Journal of Cleaner Production* 252 (2020). ISSN: 09596526. DOI: 10.1016/j.jclepro.2019.119623.

[97] A. Ghorbani, L. Nascimento, and T. Filatova. "Growing community energy initiatives from the bottom up: Simulating the role of behavioural attitudes and leadership in the Netherlands". In: *Energy Research and Social Science* 70.March (2020), p. 101782. ISSN: 22146296. DOI: 10.1016/j.erss.2020.101782. URL: https://doi.org/10.1016/j.erss.2020.101782.

[98] C. Nava, G. Korevaar, and H. H. Hansen. "Agent-Based Modeling of a Thermal Energy Transition in the Built Environment". In: (2019). DOI: 10.3390/en12050856.

[99] W. Devia, K. Agbossou, and A. Cardenas. "An evolutionary approach to modeling and control of space heating and thermal storage systems". In: *Energy and Buildings* 234 (2021), p. 110674. ISSN: 03787788. DOI: 10.1016/j.enbuild.2020.110674. URL: https://doi.org/10.1016/j.enbuild.2020.110674.

[100] S. Norouziasl, A. Jafari, and C. Wang. "An agent-based simulation of occupancy schedule in office buildings". In: *Building and Environment* 186.September (2020), p. 107352. ISSN: 03601323. DOI: 10.1016/j.buildenv.2020.107352. URL: https://doi.org/10.1016/j.buildenv.2020.107352.

[101] J. W. Dziedzic, D. Yan, H. Sun, and V. Novakovic. “Building occupant transient agent-based model – Movement module”. In: *Applied Energy* 261.7491 (2020), p. 114417. ISSN: 03062619. DOI: `10.1016/j.apenergy.2019.114417`. URL: `https://doi.org/10.1016/j.apenergy.2019.114417`.

[102] A. Mittal, C. C. Krejci, M. C. Dorneich, and D. Fickes. “An agent-based approach to modeling zero energy communities”. In: *Solar Energy* 191.December 2018 (2019), pp. 193–204. ISSN: 0038092X. DOI: `10.1016/j.solener.2019.08.040`. URL: `https://doi.org/10.1016/j.solener.2019.08.040`.

[103] N. A. Mohammed and A. Al-Bazi. “Management of renewable energy production and distribution planning using agent-based modelling”. In: *Renewable Energy* 164 (2021), pp. 509–520. ISSN: 18790682. DOI: `10.1016/j.renene.2020.08.159`. URL: `https://doi.org/10.1016/j.renene.2020.08.159`.

[104] V. Rai and S. A. Robinson. “Agent-based modeling of energy technology adoption: Empirical integration of social, behavioral, economic, and environmental factors”. In: *Environmental Modelling and Software* 70 (2015), pp. 163–177. ISSN: 13648152. DOI: `10.1016/j.envsoft.2015.04.014`. URL: `http://dx.doi.org/10.1016/j.envsoft.2015.04.014`.

[105] V. Burg, K. G. Troitzsch, D. Akyol, U. Baier, S. Hellweg, and O. Thees. “Farmer’s willingness to adopt private and collective biogas facilities: An agent-based modeling approach”. In: *Resources, Conservation and Recycling* 167.December 2020 (2021). ISSN: 18790658. DOI: `10.1016/j.resconrec.2021.105400`.

[106] C. Fraunholz, E. Kraft, D. Keles, and W. Fichtner. “Advanced price forecasting in agent-based electricity market simulation”. In: *Applied Energy* 290.November 2020 (2021), p. 116688. ISSN: 03062619. DOI: `10.1016/j.apenergy.2021.116688`. URL: `https://doi.org/10.1016/j.apenergy.2021.116688`.

[107] I. Mahmood, M. Mobeen, A. U. Rahman, S. Younis, A. W. Malik, M. M. Fraz, and K. Ullah. “Modeling, simulation and forecasting of wind power plants using agent-based approach”. In: *Journal of Cleaner Production* 276 (2020), p. 124172. ISSN: 09596526. DOI: `10.1016/j.jclepro.2020.124172`. URL: `https://doi.org/10.1016/j.jclepro.2020.124172`.

[108] E. Ostrom. “Do institutions for collective action evolve?” In: *Journal of Bioeconomics* 16.1 (Apr. 2014), pp. 3–30. ISSN: 1387-6996. DOI: `10.1007/s10818-013-9154-8`. URL: `http://link.springer.com/10.1007/s10818-013-9154-8`.

[109] J. M. Anderies, M. A. Janssen, and E. Schlager. “Institutions and the performance of coupled infrastructure systems”. In: *International Journal of the Commons* 10.2 (2016), pp. 495–516. ISSN: 18750281. DOI: `10.18352/ijc.651`.

[110] E. Ostrom. “Background on the Institutional Analysis and Development Framework”. In: *Policy Studies Journal* 39.1 (2011), pp. 7–27. ISSN: 0190292X. DOI: `10.1111/j.1541-0072.2010.00394.x`.

[111] U. I. Diversity. *No Title.* ISBN: 9780691122076.

[112] A. Armstrong and H. Bulkeley. "Micro-hydro politics: Producing and contesting community energy in the North of England". In: *Geoforum* 56 (2014), pp. 66–76. ISSN: 00167185. DOI: `10.1016/j.geoforum.2014.06.015`. URL: `http://dx.doi.org/10.1016/j.geoforum.2014.06.015`.

[113] A. Mahzouni. "The role of institutional entrepreneurship in emerging energy communities: The town of St. Peter in Germany". In: *Renewable and Sustainable Energy Reviews* 107.January 2018 (2019), pp. 297–308. ISSN: 18790690. DOI: `10.1016/j.rser.2019.03.011`. URL: `https://doi.org/10.1016/j.rser.2019.03.011`.

[114] C. Walker and J. Baxter. "Procedural justice in Canadian wind energy development: A comparison of community-based and technocratic siting processes". In: *Energy Research and Social Science* (2017). ISSN: 22146296. DOI: `10.1016/j.erss.2017.05.016`.

[115] M. Filippini, L. C. Hunt, and J. Zorić. "Impact of energy policy instruments on the estimated level of underlying energy efficiency in the EU residential sector". In: *Energy Policy* (2014). ISSN: 03014215. DOI: `10.1016/j.enpol.2014.01.047`.

[116] N. Hoekstra, M. Pellegrini, M. Bloemendal, G. Spaak, A. Andreu Gallego, J. Rodriguez Comins, T. Grotenhuis, S. Picone, A. J. Murrell, H. J. Steeman, A. Verrone, P. Doornenbal, M. Christophersen, L. Bennedsen, M. Henssen, S. Moinier, and C. Saccani. "Increasing market opportunities for renewable energy technologies with innovations in aquifer thermal energy storage". In: *Science of the Total Environment* 709.December 2019 (2020), p. 136142. ISSN: 18791026. DOI: `10.1016/j.scitotenv.2019.136142`. URL: `https://doi.org/10.1016/j.scitotenv.2019.136142`.

[117] W. Liu, D. Klip, W. Zappa, S. Jelles, G. J. Kramer, and M. van den Broek. "The marginal-cost pricing for a competitive wholesale district heating market: A case study in the Netherlands". In: *Energy* 189 (2019), p. 116367. ISSN: 03605442. DOI: `10.1016/j.energy.2019.116367`. URL: `https://doi.org/10.1016/j.energy.2019.116367`.

[118] C. Friedl and J. Reichl. "Realizing energy infrastructure projects - A qualitative empirical analysis of local practices to address social acceptance". In: *Energy Policy* (2016). ISSN: 03014215. DOI: `10.1016/j.enpol.2015.11.027`.

[119] F. Goedkoop and P. Devine-Wright. "Partnership or placation? the role of trust and justice in the shared ownership of renewable energy projects". In: *Energy Research and Social Science* (2016). ISSN: 22146296. DOI: `10.1016/j.erss.2016.04.021`.

[120] M. D. McGinnis and E. Ostrom. "Social-ecological system framework: Initial changes and continuing challenges". In: *Ecology and Society* 19.2 (2014). ISSN: 17083087. DOI: `10.5751/ES-06387-190230`.

[121] D. C. North. "The New Institutional Economics". In: *Journal of Institutional and Theoretical Economics (JITE) / Zeitschrift für die gesamte Staatswissenschaft* 142.1 (Mar. 1986), pp. 230–237. ISSN: 09324569. URL: `http://www.jstor.org/stable/40726723`.

[122] G. W. Scully. “The Institutional Framework and Economic Development”. In: *Journal of Political Economy* 96.3 (1988), pp. 652–662. ISSN: 00223808, 1537534X. URL: `http://www.jstor.org/stable/1830363`.

[123] M. D. McGinnis. “An Introduction to IAD and the Language of the Ostrom Workshop: A Simple Guide to a Complex Framework”. In: *Policy Studies Journal* (2011). ISSN: 0190292X. DOI: `10.1111/j.1541-0072.2010.00401.x`.

[124] R. Kunneke and M. Finger. “The governance of infrastructures as common pool resources”. In: *Elinor Ostrom and the Blomington School of Political Economy*. Ed. by D. Cole and M. D. McGinnis. Vol. 4. Lexington Books, 2018, p. 233. ISBN: 978-0-7391-9113-2.

[125] I. Lammers and M. A. Heldeweg. “An empirico-legal analytical and design model for local microgrids: Applying the ‘iltiad’ model, combining the iad-framework with institutional legal theory”. In: *International Journal of the Commons* 13.1 (2019), pp. 479–506. ISSN: 18750281. DOI: `10.18352/ijc.885`.

[126] I. Lammers and T. Hoppe. “Watt rules? Assessing decision-making practices on smart energy systems in Dutch city districts”. In: *Energy Research and Social Science* 47.October 2018 (2019), pp. 233–246. ISSN: 22146296. DOI: `10.1016/j.erss.2018.10.003`. URL: `https://doi.org/10.1016/j.erss.2018.10.003`.

[127] C. Milchram, C. Märker, and J. F. Hake. “The role of values in analyzing energy systems: Insights from moral philosophy, institutional economics, and sociology”. In: *Energy Procedia* 158 (2019), pp. 3741–3747. ISSN: 18766102. DOI: `10.1016/j.egypro.2019.01.882`. URL: `https://doi.org/10.1016/j.egypro.2019.01.882`.

[128] H. Lestari, M. Arentsen, H. Bressers, B. Gunawan, J. Iskandar, and Parikesit. “Sustainability of renewable off-grid technology for rural electrification: A comparative study using the IAD framework”. In: *Sustainability (Switzerland)* 10.12 (2018). ISSN: 20711050. DOI: `10.3390/su10124512`.

[129] S. Simulation, A. Ghorbani, P. Bots, and V. Dignum. “MAIA : A Framework for Developing Agent-based Social Simulations Amineh Ghorbani , Pieter Bots , Virginia Dignum and Gerard Dijkema ( 2013 ) MAIA : a Framework for Developing Agent-Based Social Simulations”. In: August 2014 (2013). DOI: `10.18564/jasss.2166`.

[130] I. Nikolic and A. Ghorbani. “A method for developing agent-based models of socio-technical systems A Method for Developing Agent-based Models of Socio-technical”. In: May 2014 (2011). DOI: `10.1109/ICNSC.2011.5874914`.

[131] I. Nikolic and A. Ghorbani. “A method for developing agent-based models of socio-technical systems”. In: *2011 International Conference on Networking, Sensing and Control, ICNSC 2011* April (2011), pp. 44–49. DOI: `10.1109/ICNSC.2011.5874914`.

[132] F. Hooimeijer and L. Tummers. “Integrating subsurface management into spatial planning in the Netherlands, Sweden and Flanders”. In: *Proceedings of the Institution of Civil Engineers: Urban Design and Planning* 170.4 (2017), pp. 161–172. ISSN: 17550807. DOI: `10.1680/jurdp.16.00033`.

[133] M. Van den Broek, P. Veenendaal, P. Koutstaal, W. Turkenburg, and A. Faaij. "Impact of international climate policies on CO2 capture and storage deployment. Illustrated in the Dutch energy system". In: *Energy Policy* (2011). ISSN: 03014215. DOI: `10.1016/j.enpol.2011.01.036`.

[134] A. Ligtvoet, E. Cuppen, O. Di Ruggero, K. Hemmes, U. Pesch, J. Quist, and D. Mehos. "New future perspectives through constructive conflict: Exploring the future of gas in the Netherlands". In: *Futures* (2016). ISSN: 00163287. DOI: `10.1016/j.futures.2016.03.008`.

[135] H. W. Van Os, R. Herber, and B. Scholtens. "Not under Our Back Yards? A case study of social acceptance of the Northern Netherlands CCS initiative". In: *Renewable and Sustainable Energy Reviews* (2014). ISSN: 13640321. DOI: `10.1016/j.rser.2013.11.037`.

[136] G. Perlaviciute, L. Steg, E. J. Hoekstra, and L. Vrieling. "Perceived risks, emotions, and policy preferences: A longitudinal survey among the local population on gas quakes in the Netherlands". In: *Energy Research and Social Science* (2017). ISSN: 22146296. DOI: `10.1016/j.erss.2017.04.012`.

[137] F. deLlano-Paz, P. Martínez Fernandez, and I. Soares. "Addressing 2030 EU policy framework for energy and climate: Cost, risk and energy security issues". In: *Energy* (2016). ISSN: 03605442. DOI: `10.1016/j.energy.2016.01.068`.

[138] J. Kester. "Energy security and human security in a Dutch gasquake context: A case of localized performative politics". In: *Energy Research and Social Science* (2017). ISSN: 22146296. DOI: `10.1016/j.erss.2016.12.019`.

[139] A. Correljé and C. van der Linde. "Energy supply security and geopolitics: A European perspective". In: *Energy Policy* 34.5 (2006), pp. 532–543. ISSN: 03014215. DOI: `10.1016/j.enpol.2005.11.008`.

[140] U. Persson and S. Werner. "Heat distribution and the future competitiveness of district heating". In: *Applied Energy* 88.3 (2011), pp. 568–576. ISSN: 03062619. DOI: `10.1016/j.apenergy.2010.09.020`. URL: `http://dx.doi.org/10.1016/j.apenergy.2010.09.020`.

[141] R. Niessink and H. Rösler. "Developments of Heat Distribution Networks in the Netherlands". In: June (2015). URL: `ftp://ftp.ecn.nl/pub/www/library/report/2015/e15069.pdf`.

[142] W. Lise and J. van der Laan. "Investment needs for climate change adaptation measures of electricity power plants in the EU". In: *Energy for Sustainable Development* 28.April 2014 (2015), pp. 10–20. ISSN: 23524669. DOI: `10.1016/j.esd.2015.06.003`. URL: `http://dx.doi.org/10.1016/j.esd.2015.06.003`.

[143] V. Masson-Delmotte, H. O. Portner, and D. Roberts. *IPCC Global warming of 1.5 C*. 9. 2018, p. 32. ISBN: 9788578110796. DOI: `10.1017/CBO9781107415324.004`. URL: `https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_SPM_version_report_LR.pdf`.

[144] T. Van Der Schoor and B. Scholtens. *Power to the people: Local community initiatives and the transition to sustainable energy*. 2015. DOI: `10.1016/j.rser.2014.10.089`.

[145] “Commission for Environmental Cooperation Guide to Developing a Community Renewable Energy Project”. In: ().

[146] B. Warbroek, T. Hoppe, H. Bressers, and F. Coenen. “Energy Research & Social Science Testing the social , organizational , and governance factors for success in local low carbon energy initiatives”. In: *Energy Research & Social Science* 58.August (2019), p. 101269. ISSN: 2214-6296. DOI: `10.1016/j.erss.2019.101269`. URL: `https://doi.org/10.1016/j.erss.2019.101269`.

[147] V. I. I. I. “Sustainable Communities”. eng. In: *Green Energy and Technology* (2020), pp. 341–384. ISSN: 18653529.

[148] G. Walker and P. Devine-Wright. “Community renewable energy: What should it mean?” In: *Energy Policy* 36.2 (2008), pp. 497–500. ISSN: 03014215. DOI: `10.1016/j.enpol.2007.10.019`.

[149] V. Z. Gjorgievski, S. Cundeva, and G. E. Georghiou. “Social arrangements , technical designs and impacts of energy communities : A review”. In: *Renewable Energy* 169 (2021), pp. 1138–1156. ISSN: 0960-1481. DOI: `10.1016/j.renene.2021.01.078`. URL: `https://doi.org/10.1016/j.renene.2021.01.078`.

[150] C. Hachem-Vermette, F. Guarino, V. La Rocca, and M. Cellura. “Towards achieving net-zero energy communities: Investigation of design strategies and seasonal solar collection and storage net-zero”. In: *Solar Energy* 192.July 2018 (2019), pp. 169–185. ISSN: 0038092X. DOI: `10.1016/j.solener.2018.07.024`. URL: `https://doi.org/10.1016/j.solener.2018.07.024`.

[151] K. Gaiser and P. Stroeve. “The impact of scheduling appliances and rate structure on bill savings for net-zero energy communities: Application to West Village”. In: *Applied Energy* 113 (2014), pp. 1586–1595. ISSN: 03062619. DOI: `10.1016/j.apenergy.2013.08.075`. URL: `http://dx.doi.org/10.1016/j.apenergy.2013.08.075`.

[152] J. Burch, J. Woods, E. Kozubal, and A. Boranian. “Zero energy communities with central solar plants using liquid desiccants and local storage”. In: *Energy Procedia* 30 (2012), pp. 55–64. ISSN: 18766102. DOI: `10.1016/j.egypro.2012.11.008`. URL: `http://dx.doi.org/10.1016/j.egypro.2012.11.008`.

[153] T. van der Schoor and B. Scholtens. “The power of friends and neighbors: a review of community energy research”. In: *Current Opinion in Environmental Sustainability* 39 (2019), pp. 71–80. ISSN: 18773435. DOI: `10.1016/j.cosust.2019.08.004`. URL: `https://doi.org/10.1016/j.cosust.2019.08.004`.

[154] J. Song, H. Li, and F. Wallin. “Cost comparison between district heating and alternatives during the price model restructuring process”. In: *Energy Procedia* 105 (2017), pp. 3922–3927. ISSN: 1876-6102. DOI: `10.1016/j.egypro.2017.03.813`. URL: `http://dx.doi.org/10.1016/j.egypro.2017.03.813`.

[155] I. G. Jensen, F. Wiese, R. Bramstoft, and M. Münster. “Potential role of renewable gas in the transition of electricity and district heating systems”. In: *Energy Strategy Reviews* 27.November 2019 (2020), p. 100446. ISSN: 2211-467X. DOI: `10.1016/j.esr.2019.100446`. URL: `https://doi.org/10.1016/j.esr.2019.100446`.

[156] M. Engelken, B. Römer, M. Drescher, I. M. Welpe, and A. Picot. “Comparing drivers , barriers , and opportunities of business models for renewable energies : A review”. In: *Renewable and Sustainable Energy Reviews* 60 (2016), pp. 795–809. ISSN: 1364-0321. DOI: `10.1016/j.rser.2015.12.163`. URL: `http://dx.doi.org/10.1016/j.rser.2015.12.163`.

[157] R. Reyes, H. Nelson, F. Navarro, and C. Retes. “The firewood dilemma: Human health in a broader context of well-being in Chile”. In: *Energy for Sustainable Development* 28 (2015), pp. 75–87. ISSN: 23524669. DOI: `10.1016/j.esd.2015.07.005`. URL: `http://dx.doi.org/10.1016/j.esd.2015.07.005`.

[158] D. X. Zhao, B. J. He, C. Johnson, and B. Mou. “Social problems of green buildings: From the humanistic needs to social acceptance”. In: *Renewable and Sustainable Energy Reviews* (2015). ISSN: 18790690. DOI: `10.1016/j.rser.2015.07.072`.

[159] X. Cipriano, A. Vellido, J. Cipriano, J. Martí-Herrero, and S. Danov. “Influencing factors in energy use of housing blocks: a new methodology, based on clustering and energy simulations, for decision making in energy refurbishment projects”. In: *Energy Efficiency* 10.2 (2017), pp. 359–382. ISSN: 15706478. DOI: `10.1007/s12053-016-9460-9`.

[160] O. E. E. E. “Institutions and common-pool resources”. eng. In: *Journal of Theoretical Politics* 4.3 (1992), pp. 243–245. ISSN: 09516298.

[161] C. Milchram, C. Märker, H. Schlör, R. Künneke, and G. Van De Kaa. “Understanding the role of values in institutional change: The case of the energy transition”. In: *Energy, Sustainability and Society* 9.1 (2019). ISSN: 21920567. DOI: `10.1186/s13705-019-0235-y`.

[162] I. Lammers and T. Hoppe. “Analysing the institutional setting of local renewable energy planning and implementation in the EU: A systematic literature review”. In: *Sustainability (Switzerland)* 10.9 (2018). ISSN: 20711050. DOI: `10.3390/su10093212`.

[163] A. I. Framework and P. Analysis. “Polski Ostrom 2011 IAD-for-policy-applications”. In: (), pp. 13–47.

[164] C. Märker, S. Venghaus, and J. F. Hake. “Integrated governance for the food–energy–water nexus – The scope of action for institutional change”. In: *Renewable and Sustainable Energy Reviews* 97.July (2018), pp. 290–300. ISSN: 18790690. DOI: `10.1016/j.rser.2018.08.020`. URL: `https://doi.org/10.1016/j.rser.2018.08.020`.

[165] S. Thomas, M. Richter, W. Lestari, S. Prabawaningtyas, and Y. Anggoro. “Energy Research & Social Science Transdisciplinary research methods in community energy development and governance in Indonesia : Insights for sustainability science”. In: *Energy Research & Social Science* 45.November 2017 (2018), pp. 184–194. ISSN: 2214-6296. DOI: `10.1016/j.erss.2018.06.021`. URL: `https://doi.org/10.1016/j.erss.2018.06.021`.

[166] M. A. A. A. “Energy security through membershipin nato and the eu: Interests andachievements of Lithuania”. eng. In: *Lithuanian Foreign Policy Review* 32 (2014), pp. 13–32. ISSN: 13925504.

[167] M. Owen, R. v. der Plas, and S. Sepp. “Can there be energy policy in Sub-Saharan Africa without biomass?” In: *Energy for Sustainable Development* 17.2 (2013), pp. 146–152. ISSN: 09730826. DOI: `10.1016/j.esd.2012.10.005`. URL: `http://dx.doi.org/10.1016/j.esd.2012.10.005`.

[168] A. Ahmad. “Economic risks of Jordan’s nuclear program”. In: *Energy for Sustainable Development* 29 (2015), pp. 32–37. ISSN: 23524669. DOI: `10.1016/j.esd.2015.09.001`. URL: `http://dx.doi.org/10.1016/j.esd.2015.09.001`.

[169] N. J. van Eck and L. Waltman. “{VOSviewer} manual”. In: *Leiden: Univeristeit Leiden* January (2013). URL: `http://www.vosviewer.com/documentation/Manual_VOSviewer_1.6.1.pdf`.

[170] P. J. Nel, M. J. Booysen, and B. van der Merwe. “Energy perceptions in South Africa: An analysis of behaviour and understanding of electric water heaters”. In: *Energy for Sustainable Development* 32 (2016), pp. 62–70. ISSN: 23524669. DOI: `10.1016/j.esd.2016.03.006`. URL: `http://dx.doi.org/10.1016/j.esd.2016.03.006`.

[171] D. A. Katsaprakakis, S. Kalligeros, N. Pasadakis, M. Moniakis, and I. Skias. “The feasibility of the introduction of natural gas into the electricity production system in the island of Crete (Greece)”. In: *Energy for Sustainable Development* 27 (2015), pp. 155–167. ISSN: 23524669. DOI: `10.1016/j.esd.2015.04.009`. URL: `http://dx.doi.org/10.1016/j.esd.2015.04.009`.

[172] F. Ceglia, P. Esposito, E. Marrasso, and M. Sasso. “From smart energy community to smart energy municipalities: Literature review, agendas and pathways”. In: *Journal of Cleaner Production* 254 (2020), p. 120118. ISSN: 09596526. DOI: `10.1016/j.jclepro.2020.120118`. URL: `https://doi.org/10.1016/j.jclepro.2020.120118`.

[173] F. Liberati, A. D. Giorgio, A. Giuseppi, A. Pietrabissa, E. Habib, and L. Martirano. “Joint Model Predictive Control of Electric and Heating Resources in a Smart Building”. In: *IEEE Transactions on Industry Applications* 55.6 (2019), pp. 7015–7027. ISSN: 19399367. DOI: `10.1109/TIA.2019.2932954`.

[174] H. Gong, V. Rallabandi, M. L. McIntyre, and D. M. Ionel. “On the Optimal Energy Controls for Large Scale Residential Communities including Smart Homes”. In: *2019 IEEE Energy Conversion Congress and Exposition, ECCE 2019* (2019), pp. 503–507. DOI: `10.1109/ECCE.2019.8912490`.

[175] F. P. P. P. “Sustainable Energy Campus: A Challenge on Smart Facilities and Operations”. eng. In: *World Sustainability Series* (2017), pp. 241–255. ISSN: 21997373.

[176] W. J. J. J. “Energy Value Based Efficiency Index of Energy Utilization for Multi-energy Cooperative Park”. eng. In: *Dianli Xitong Zidonghua/Automation of Electric Power Systems* 43.21 (2019), pp. 54–62. ISSN: 10001026.

[177] B. Coyne, S. Lyons, and D. McCoy. “The effects of home energy efficiency upgrades on social housing tenants: evidence from Ireland”. In: *Energy Efficiency* 11.8 (2018), pp. 2077–2100. ISSN: 15706478. DOI: `10.1007/s12053-018-9688-7`.

[178] H. Batista da Silva, W. Uturbey, and B. M. Lopes. “Market diffusion of household PV systems: Insights using the Bass model and solar water heaters market data”. In: *Energy for Sustainable Development* 55 (2020), pp. 210–220. ISSN: 23524669. DOI: `10.1016/j.esd.2020.02.004`. URL: `https://doi.org/10.1016/j.esd.2020.02.004`.

[179] G. Methenitis, M. Kaisers, and H. L. Poutre. “A multi-scale energy demand model suggests sharing market risks with intelligent energy cooperatives”. In: *Proceedings of the 2015 IEEE Innovative Smart Grid Technologies - Asia, ISGT ASIA 2015* (2016), pp. 1–6. DOI: `10.1109/ISGT-Asia.2015.7386995`.

[180] A. Menéndez and M. D. Curt. “Energy and socio-economic profile of a small rural community in the highlands of central Tanzania: A case study”. In: *Energy for Sustainable Development* 17.3 (2013), pp. 201–209. ISSN: 09730826. DOI: `10.1016/j.esd.2012.12.002`. URL: `http://dx.doi.org/10.1016/j.esd.2012.12.002`.

[181] G. N. Gugul, M. Aydinalp Koksal, and V. I. Ugursal. “Techno-economical analysis of building envelope and renewable energy technology retrofits to single family homes”. In: *Energy for Sustainable Development* 45 (2018), pp. 159–170. ISSN: 23524669. DOI: `10.1016/j.esd.2018.06.006`. URL: `https://doi.org/10.1016/j.esd.2018.06.006`.

[182] E. Fabrizio. “Feasibility of polygeneration in energy supply systems for healthcare facilities under the Italian climate and boundary conditions”. In: *Energy for Sustainable Development* 15.1 (2011), pp. 92–103. ISSN: 09730826. DOI: `10.1016/j.esd.2011.01.003`. URL: `http://dx.doi.org/10.1016/j.esd.2011.01.003`.

[183] M. Cellura, F. Guarino, S. Longo, and G. Tumminia. “Climate change and the building sector: Modelling and energy implications to an office building in southern Europe”. In: *Energy for Sustainable Development* 45.2018 (2018), pp. 46–65. ISSN: 23524669. DOI: `10.1016/j.esd.2018.05.001`. URL: `https://doi.org/10.1016/j.esd.2018.05.001`.

[184] F. Foiadelli, S. Nocerino, M. Di Somma, and G. Graditi. “Optimal Design of der for Economic/Environmental Sustainability of Local Energy Communities”. In: *Proceedings - 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2018* (2018), pp. 1–7. DOI: `10.1109/EEEIC.2018.8493898`.

[185] S. Helynen. “Bioenergy policy in Finland”. In: *Energy for Sustainable Development* 8.1 (2004), pp. 36–46. ISSN: 09730826. DOI: `10.1016/S0973-0826(08)60389-0`. URL: `http://dx.doi.org/10.1016/S0973-0826(08)60389-0`.

[186] P. Silva, I. Klytchnikova, and D. Radevic. “Poverty and environmental impacts of electricity price reforms in Montenegro”. In: *Utilities Policy* 17.1 (2009), pp. 102–113. ISSN: 09571787. DOI: `10.1016/j.jup.2008.02.008`. URL: `http://dx.doi.org/10.1016/j.jup.2008.02.008`.

[187] A. Schueftan, J. Sommerhoff, and A. D. González. “Firewood demand and energy policy in south-central Chile”. In: *Energy for Sustainable Development* 33 (2016), pp. 26–35. ISSN: 23524669. DOI: `10.1016/j.esd.2016.04.004`. URL: `http://dx.doi.org/10.1016/j.esd.2016.04.004`.

[188] P. Sokolnikova, P. Lombardi, B. Arendarski, K. Suslov, A. M. Pantaleo, M. Kranhold, and P. Komarnicki. “Net-zero multi-energy systems for Siberian rural communities: A methodology to size thermal and electric storage units”. In: *Renewable Energy* 155 (2020), pp. 979–989. ISSN: 18790682. DOI: `10.1016/j.renene.2020.03.011`. URL: `https://doi.org/10.1016/j.renene.2020.03.011`.

[189] B. Koirala and R. Hakvoort. *Integrated Community-Based Energy Systems: Aligning Technology, Incentives, and Regulations.* Vol. 1. Elsevier Inc., 2017, pp. 363–363. ISBN: 9780128117637. DOI: `10.1016/B978-0-12-811758-3.00018-8`. URL: `http://dx.doi.org/10.1016/B978-0-12-811758-3/00018-8`.

[190] L. F. M. V. Summeren, A. J. Wieczorek, and G. P. J. Verbong. “Energy Research & Social Science The merits of becoming smart : How Flemish and Dutch energy communities mobilise digital technology to enhance their agency in the energy transition”. In: *Energy Research & Social Science* 79 (2021), p. 102160. ISSN: 2214-6296. DOI: `10.1016/j.erss.2021.102160`. URL: `https://doi.org/10.1016/j.erss.2021.102160`.

[191] Q. Xu and S. Dubljevic. “Model predictive control of solar thermal system with borehole seasonal storage”. In: *Computers and Chemical Engineering* 101 (2017), pp. 59–72. ISSN: 00981354. DOI: `10.1016/j.compchemeng.2017.02.023`. URL: `http://dx.doi.org/10.1016/j.compchemeng.2017.02.023`.

[192] Y. Lin and W. Yang. “Solar energy model and thermal performance of an electrochromic dome-covered house”. In: *Energy for Sustainable Development* 39 (2017), pp. 82–90. ISSN: 23524669. DOI: `10.1016/j.esd.2017.05.001`. URL: `http://dx.doi.org/10.1016/j.esd.2017.05.001`.

[193] T. Rogers. “Development of innovation systems for small island states: A functional analysis of the Barbados solar water heater industry”. In: *Energy for Sustainable Development* 31 (2016), pp. 143–151. ISSN: 23524669. DOI: `10.1016/j.esd.2016.01.002`. URL: `http://dx.doi.org/10.1016/j.esd.2016.01.002`.

[194] E. Azad. “Design, installation and operation of a solar thermal public bath in eastern Iran”. In: *Energy for Sustainable Development* 16.1 (2012), pp. 68–73. ISSN: 09730826. DOI: `10.1016/j.esd.2011.10.006`. URL: `http://dx.doi.org/10.1016/j.esd.2011.10.006`.

[195] A. Der Minassians and S. R. Sanders. “Stirling engines for distributed low-cost solar-thermal-electric power generation”. In: *Journal of Solar Energy Engineering, Transactions of the ASME* 133.1 (2011), pp. 1–10. ISSN: 01996231. DOI: `10.1115/1.4003144`.

[196] M. H. Kim, D. Kim, J. Heo, and D. W. Lee. “Techno-economic analysis of hybrid renewable energy system with solar district heating for net zero energy community”. In: *Energy* 187 (2019), p. 115916. ISSN: 03605442. DOI: `10.1016/j.energy.2019.115916`. URL: `https://doi.org/10.1016/j.energy.2019.115916`.

[197] C. R. R. R. *Evaluating the energy savings from community scale solar water heating in Los Angeles County: Residential case studies.* eng. 2019.

[198] O. Asa’d, V. I. Ugursal, and N. Ben-Abdallah. “Investigation of the energetic performance of an attached solar greenhouse through monitoring and simulation”. In: *Energy for Sustainable Development* 53 (2019), pp. 15–29. ISSN: 23524669. DOI: `10.1016/j.esd.2019.09.001`. URL: `https://doi.org/10.1016/j.esd.2019.09.001`.

[199] A. Boretti and S. Al-Zubaidy. “A case study on combined cycle power plant integrated with solar energy in Trinidad and Tobago”. In: *Sustainable Energy Technologies and Assessments* 32.July 2018 (2019), pp. 100–110. ISSN: 22131388. DOI: `10.1016/j.seta.2019.02.006`. URL: `https://doi.org/10.1016/j.seta.2019.02.006`.

[200] U. Kingsley, A. C. Eloka-Eboka, and F. L. Inambao. “Review of solar energy inclusion in Africa: Case study of Nigeria”. In: *ISES Solar World Congress 2017 - IEA SHC International Conference on Solar Heating and Cooling for Buildings and Industry 2017, Proceedings* (2017), pp. 962–973. DOI: `10.18086/swc.2017.16.05`.

[201] A. Mawire and S. H. Taole. “Experimental energy and exergy performance of a solar receiver for a domestic parabolic dish concentrator for teaching purposes”. In: *Energy for Sustainable Development* 19.1 (2014), pp. 162–169. ISSN: 09730826. DOI: `10.1016/j.esd.2014.01.004`. URL: `http://dx.doi.org/10.1016/j.esd.2014.01.004`.

[202] F. Spertino, S. Fichera, A. Ciocia, G. Malgaroli, P. Di Leo, and A. Ratclif. “Toward the complete self-sufficiency of an NZEBS microgrid by photovoltaic generators and heat pumps: Methods and applications”. In: *IEEE Transactions on Industry Applications* 55.6 (2019), pp. 7028–7040. ISSN: 19399367. DOI: `10.1109/TIA.2019.2914418`.

[203] E. Svetec, L. Nad, R. Pasicko, and B. Pavlin. “Blockchain application in renewable energy microgrids: An overview of existing technology towards creating climate-resilient and energy independent communities”. In: *International Conference on the European Energy Market, EEM* 2019-Septe (2019), pp. 0–6. ISSN: 21654093. DOI: `10.1109/EEM.2019.8916292`.

[204] F. Lwiza, J. Mugisha, P. N. Walekhwa, J. Smith, and B. Balana. “Dis-adoption of Household Biogas technologies in Central Uganda”. In: *Energy for Sustainable Development* 37 (2017), pp. 124–132. ISSN: 23524669. DOI: `10.1016/j.esd.2017.01.006`. URL: `http://dx.doi.org/10.1016/j.esd.2017.01.006`.

[205] Z. Shareefdeen, A. Elkamel, L. Perera, K. Vaideswaran, and J. Z. Jinxu Zhang. “Design and analysis of a biogas digester for a net-zero energy community in southwestern Ontario”. In: *IEOM 2015 - 5th International Conference on Industrial Engineering and Operations Management, Proceeding* (2015), pp. 1–7. DOI: `10.1109/IEOM.2015.7093887`.

[206] N. A. MacCarty and K. M. Bryden. “Modeling of household biomass cookstoves: A review”. In: *Energy for Sustainable Development* 26 (2015), pp. 1–13. ISSN: 23524669. DOI: `10.1016/j.esd.2015.02.001`. URL: `http://dx.doi.org/10.1016/j.esd.2015.02.001`.

[207] B. D. D. D. “Modelling of a CHP SOFC system fed with biogas from anaerobic digestion of municipal waste integrated with solar collectors and storage unit”. eng. In: *International Journal of Thermodynamics* 16.1 (2013), pp. 28–35. ISSN: 13019724.

[208] O. Jimenez, A. Curbelo, and Y. Suarez. “Biomass based gasifier for providing electricity and thermal energy to off-grid locations in Cuba. Conceptual design”. In: *Energy for Sustainable Development* 16.1 (2012), pp. 98–102. ISSN: 09730826. DOI: `10.1016/j.esd.2011.12.003`. URL: `http://dx.doi.org/10.1016/j.esd.2011.12.003`.

[209] B. D. D. D. *Modelling of a CHP SOFC power system fed with biogas from anaerobic digestion of municipal wastes integrated with a solar collector and storage units.* eng. 2012.

[210] J. Martí-Herrero, M. Ceron, R. Garcia, L. Pracejus, R. Alvarez, and X. Cipriano. “The influence of users’ behavior on biogas production from low cost tubular digesters: A technical and socio-cultural field analysis”. In: *Energy for Sustainable Development* 27 (2015), pp. 73–83. ISSN: 23524669. DOI: `10.1016/j.esd.2015.05.003`. URL: `http://dx.doi.org/10.1016/j.esd.2015.05.003`.

[211] M. E. Niklitschek, R. Labbé, and J. Guerrero. “Heating and hot water with wood chips. Is it convenient to replace firewood boilers in southern Chile?” In: *Energy for Sustainable Development* 55 (2020), pp. 24–31. ISSN: 23524669. DOI: `10.1016/j.esd.2019.12.001`.

[212] O. Lehtonen and L. Okkonen. “Energy cost reduction creates additional socioeconomic benefits– The case of Eno Energy Cooperative, Finland”. In: *Energy Policy* 129.December 2018 (2019), pp. 352–359. ISSN: 03014215. DOI: `10.1016/j.enpol.2019.02.018`. URL: `https://doi.org/10.1016/j.enpol.2019.02.018`.

[213] A. Albatayneh, D. Alterman, A. Page, and B. Moghtaderi. “Development of a new metric to characterise the buildings thermal performance in a temperate climate”. In: *Energy for Sustainable Development* 51 (2019), pp. 1–12. ISSN: 23524669. DOI: `10.1016/j.esd.2019.04.002`. URL: `https://doi.org/10.1016/j.esd.2019.04.002`.

[214] Y. Puentes-Rodriguez, P. Torssonen, S. Ramcilovik-Suominen, and S. Pitkänen. “Fuelwood value chain analysis in Cassou and Ouagadougou, Burkina Faso: From production to consumption”. In: *Energy for Sustainable Development* 41 (2017), pp. 14–23. ISSN: 09730826. DOI: `10.1016/j.esd.2017.07.008`. URL: `http://dx.doi.org/10.1016/j.esd.2017.07.008`.

[215] D. Grosspietsch, M. Saenger, and B. Girod. “Matching decentralized energy production and local consumption : A review of renewable energy systems with conversion and storage technologies”. In: 2016.July 2018 (2019), pp. 1–18. DOI: `10.1002/wene.336`.

[216] E. R. A. R. R.A. *A novel multigeneration energy system for a sustainable community*. eng. 2020. ISBN: 18653529.

[217] I. Acheilas, F. Hooimeijer, and A. Ersoy. “A Decision Support Tool for Implementing District”. In: (2020).

[218] H. S. Suh and D. D. Kim. “Energy performance assessment towards nearly zero energy community buildings in South Korea”. In: *Sustainable Cities and Society* 44.August 2018 (2019), pp. 488–498. ISSN: 22106707. DOI: `10.1016/j.scs.2018.10.036`. URL: `https://doi.org/10.1016/j.scs.2018.10.036`.

[219] I. Ruble and P. El Khoury. “Lebanon’s market for domestic solar water heaters: Achievements and barriers”. In: *Energy for Sustainable Development* 17.1 (2013), pp. 54–61. ISSN: 09730826. DOI: `10.1016/j.esd.2012.11.004`. URL: `http://dx.doi.org/10.1016/j.esd.2012.11.004`.

[220] R. Lybæk. “Discovering market opportunities for future CDM projects in Asia based on biomass combined heat and power production and supply of district heating”. In: *Energy for Sustainable Development* 12.2 (2008), pp. 34–48. ISSN: 09730826. DOI: `10.1016/S0973-0826(08)60427-5`. URL: `http://dx.doi.org/10.1016/S0973-0826(08)60427-5`.

[221] Z. Li, L. Ma, Z. Li, and W. Ni. “Multi-energy cooperative utilization business models : A case study of the solar-heat pump water heater”. In: *Renewable and Sustainable Energy Reviews* 108.April (2019), pp. 392–397. ISSN: 1364-0321. DOI: `10.1016/j.rser.2019.04.015`. URL: `https://doi.org/10.1016/j.rser.2019.04.015`.

[222] I. Baniasad Askari, M. Oukati Sadegh, and M. Ameri. “Energy management and economics of a trigeneration system Considering the effect of solar PV, solar collector and fuel price”. In: *Energy for Sustainable Development* 26 (2015), pp. 43–55. ISSN: 23524669. DOI: `10.1016/j.esd.2015.03.002`. URL: `http://dx.doi.org/10.1016/j.esd.2015.03.002`.

[223] S. S. S. S. *Financial measures Serbia should offer for solar hot water systems*. eng. 2011.

[224] D. Kimemia and H. Annegarn. “An urban biomass energy economy in Johannesburg, South Africa”. In: *Energy for Sustainable Development* 15.4 (2011), pp. 382–387. ISSN: 09730826. DOI: `10.1016/j.esd.2011.10.002`. URL: `http://dx.doi.org/10.1016/j.esd.2011.10.002`.

[225] S. L. Fischer, C. P. Koshland, and J. A. Young. "Social, economic, and environmental impacts assessment of a village-scale modern biomass energy project in Jilin province, China: local outcomes and lessons learned". In: *Energy for Sustainable Development* 9.4 (2005), pp. 50–59. ISSN: 09730826. DOI: `10.1016/S0973-0826(08)60499-8`. URL: `http://dx.doi.org/10.1016/S0973-0826(08)60499-8`.

[226] J. Liu, K. Yuan, Y. Xu, Y. Song, C. Sun, X. Jin, and D. Hu. "Research on Comprehensive Assessment System of Park Integrated Energy System". In: *2019 IEEE PES Innovative Smart Grid Technologies Asia, ISGT 2019* 1 (2019), pp. 1503–1508. DOI: `10.1109/ISGT-Asia.2019.8881399`.

[227] K. M. Zhang, R. J. Thomas, M. Bohm, and M. Miller. "An integrated design approach for sustainable community development". In: *Proceedings of the 42nd Annual Hawaii International Conference on System Sciences, HICSS* (2009), pp. 1–10. DOI: `10.1109/HICSS.2009.67`.

[228] B. Yan, M. Di Somma, P. B. Luh, and G. Graditi. "Operation Optimization of Multiple Distributed Energy Systems in an Energy Community". In: *Proceedings - 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2018* (2018), pp. 1–6. DOI: `10.1109/EEEIC.2018.8494476`.

6

[229] G. Comodi, A. Bartolini, F. Carducci, B. Nagaranjan, and A. Romagnoli. "Achieving low carbon local energy communities in hot climates by exploiting networks synergies in multi energy systems". In: *Applied Energy* 256.June (2019), p. 113901. ISSN: 03062619. DOI: `10.1016/j.apenergy.2019.113901`. URL: `https://doi.org/10.1016/j.apenergy.2019.113901`.

[230] H. A. Melo and C. Heinrich. "Analysis of household heating systems in a renewable energy community". In: *2012 11th International Conference on Environment and Electrical Engineering, EEEIC 2012 - Conference Proceedings* (2012), pp. 64–68. DOI: `10.1109/EEEIC.2012.6221530`.

[231] D. Plaza, J. Artigas, J. Ábrego, A. Gonzalo, J. L. Sánchez, A. D. Dro, and Y. Richardson. "Design and operation of a small-scale carbonization kiln for cashew nutshell valorization in Burkina Faso". In: *Energy for Sustainable Development* 53 (2019), pp. 71–80. ISSN: 23524669. DOI: `10.1016/j.esd.2019.10.005`.

[232] J. Gu, D. Han, Y. Liu, Y. Li, C. Jin, and W. Yu. "Performance analysis of a thermoelectric generator with closed and flooded passive cooling in small-scale space". In: *Energy for Sustainable Development* 51 (2019), pp. 21–31. ISSN: 23524669. DOI: `10.1016/j.esd.2019.05.002`. URL: `https://doi.org/10.1016/j.esd.2019.05.002`.

[233] F. L. Hooimeijer, H. Puts, and T. Geerdink. "Successful Development of Decentralised District Heating Application of a Theoretical Framework Successful Development of Decentralised District Heating : Application of a Theoretical Framework". In: (2016). DOI: `10.19188/03JSSPSI052016`.

[234] F. S. S. S. *Low energy communities with district heating and cooling*. eng. 2008.

[235] X. Liu, Z. Yan, and J. Wu. “Optimal coordinated operation of a multi-energy community considering interactions between energy storage and conversion devices”. In: *Applied Energy* 248.March (2019), pp. 256–273. ISSN: 03062619. DOI: `10.1016/j.apenergy.2019.04.106`. URL: `https://doi.org/10.1016/j.apenergy.2019.04.106`.

[236] N. Good and P. Mancarella. “Flexibility in Multi-Energy Communities with Electrical and Thermal Storage: A Stochastic, Robust Approach for Multi-Service Demand Response”. In: *IEEE Transactions on Smart Grid* 10.1 (2019), pp. 503–513. ISSN: 19493053. DOI: `10.1109/TSG.2017.2745559`.

[237] H. Branco, R. Castro, and A. Setas Lopes. “Battery energy storage systems as a way to integrate renewable energy in small isolated power systems”. In: *Energy for Sustainable Development* 43 (2018), pp. 90–99. ISSN: 09730826. DOI: `10.1016/j.esd.2018.01.003`. URL: `https://doi.org/10.1016/j.esd.2018.01.003`.

[238] F. Mancini. “How Climate Change A ff ects the Building Energy Consumptions Due to Cooling , Heating , and”. In: (2020).

[239] T. Makonese, H. J. Annegarn, and J. Meyer. “Performance evaluation of three methanol stoves using a contextual testing approach”. In: *Energy for Sustainable Development* 55 (2020), pp. 13–23. ISSN: 23524669. DOI: `10.1016/j.esd.2019.12.002`. URL: `https://doi.org/10.1016/j.esd.2019.12.002`.

[240] F. Hernandez-Roman, C. Sheinbaum-Pardo, and A. Calderon-Irazoque. ““Socially neglected effect” in the implementation of energy technologies to mitigate climate change: Sustainable building program in social housing”. In: *Energy for Sustainable Development* 41 (2017), pp. 149–156. ISSN: 09730826. DOI: `10.1016/j.esd.2017.09.005`. URL: `https://doi.org/10.1016/j.esd.2017.09.005`.

[241] S. J. Jalal and R. K. Bani. “Impact of orientation of residential neighborhoods on optimizing sustainable and equitable exposure of insolation-Case study of Sulaimani, Iraq”. In: *Energy for Sustainable Development* 31 (2016), pp. 170–177. ISSN: 23524669. DOI: `10.1016/j.esd.2015.12.004`. URL: `http://dx.doi.org/10.1016/j.esd.2015.12.004`.

[242] K. R. R. R. *Premier Gardens Cresleigh Rosewood: A Zero Energy community case study*. eng. 2007.

[243] E. Rodrigues, N. Soares, M. S. Fernandes, A. R. Gaspar, Á. Gomes, and J. J. Costa. “An integrated energy performance-driven generative design methodology to foster modular lightweight steel framed dwellings in hot climates”. In: *Energy for Sustainable Development* 44 (2018), pp. 21–36. ISSN: 09730826. DOI: `10.1016/j.esd.2018.02.006`. URL: `https://doi.org/10.1016/j.esd.2018.02.006`.

[244] C. A. Correa-Florez, A. Michiorri, and G. Kariniotakis. “Optimal Participation of Residential Aggregators in Energy and Local Flexibility Markets”. In: *IEEE Transactions on Smart Grid* 11.2 (2020), pp. 1644–1656. ISSN: 19493061. DOI: `10.1109/TSG.2019.2941687`.

[245] J. Whitton, I. M. Parry, M. Akiyoshi, and W. Lawless. “Conceptualizing a social sustainability framework for energy infrastructure decisions”. In: *Energy Research and Social Science* (2015). ISSN: 22146296. DOI: `10.1016/j.erss.2015.05.010`.

[246] B. C. McLellan, A. J. Chapman, and K. Aoki. “Geography, urbanization and lock-in – considerations for sustainable transitions to decentralized energy systems”. In: *Journal of Cleaner Production* 128 (2016), pp. 77–96. ISSN: 09596526. DOI: `10.1016/j.jclepro.2015.12.092`. URL: `http://dx.doi.org/10.1016/j.jclepro.2015.12.092`.

[247] M. Mujuru, T. Dube, H. Mabizela, and N. Ntuli. “Evaluating greenhouse gas emission reductions by using solar water heaters: A case of low income households in Ekurhuleni, South Africa”. In: *Physics and Chemistry of the Earth* March 2019 (2020), p. 102843. ISSN: 14747065. DOI: `10.1016/j.pce.2020.102843`. URL: `https://doi.org/10.1016/j.pce.2020.102843`.

[248] R. Verhoog, A. Ghorbani, and G. P. Dijkema. “Modelling socio-ecological systems with MAIA: A biogas infrastructure simulation”. In: *Environmental Modelling and Software* 81 (2016), pp. 72–85. ISSN: 13648152. DOI: `10.1016/j.envsoft.2016.03.011`. URL: `http://dx.doi.org/10.1016/j.envsoft.2016.03.011`.

[249] S. Outcault, A. Sanguinetti, and M. Pritoni. “Using social dynamics to explain uptake in energy saving measures: Lessons from space conditioning interventions in Japan and California”. In: *Energy Research and Social Science* 45.August (2018), pp. 276–286. ISSN: 22146296. DOI: `10.1016/j.erss.2018.07.017`. URL: `https://doi.org/10.1016/j.erss.2018.07.017`.

6

[250] M. C. Claudy, M. Peterson, and A. O. Driscoll. “Understanding the Attitude-Behavior Gap for Renewable Energy Systems Using Behavioral Reasoning Theory”. In: 33.4 (2013), pp. 273–287. DOI: `10.1177/0276146713481605`.

[251] L. Steg, J. W. Bolderdijk, K. Keizer, and G. Perlaviciute. *An Integrated Framework for Encouraging Pro-environmental Behaviour: The role of values, situational factors and goals.* 2014. DOI: `10.1016/j.jenvp.2014.01.002`.

[252] H. Hasselqvist, C. Bogdan, M. Romero, and O. Shafqat. “Supporting energy management as a cooperative amateur activity”. In: *Conference on Human Factors in Computing Systems - Proceedings* 18 (2015), pp. 1483–1488. DOI: `10.1145/2702613.2732724`.

[253] M. Irfan, Z.-y. Zhao, H. Li, and A. Rehman. “The influence of consumers ’ intention factors on willingness to pay for renewable energy : a structural equation modeling approach”. In: (2020), pp. 21747–21761.

[254] P. Yadav, P. J. Davies, and S. Khan. “Breaking into the photovoltaic energy transition for rural and remote communities : challenging the impact of awareness norms and subsidy schemes”. In: *Clean Technologies and Environmental Policy* 22.4 (2020), pp. 817–834. ISSN: 1618-9558. DOI: `10.1007/s10098-020-01823-0`. URL: `https://doi.org/10.1007/s10098-020-01823-0`.

[255] G. Walker, P. Devine-Wright, S. Hunter, H. High, and B. Evans. “Trust and community: Exploring the meanings, contexts and dynamics of community renewable energy”. In: *Energy Policy* (2010). ISSN: 03014215. DOI: `10.1016/j.enpol.2009.05.055`.

[256] P. D. Conradie, O. D. Ruyck, J. Saldien, and K. Ponnet. “Who wants to join a renewable energy community in Flanders ? Applying an extended model of Theory of Planned Behaviour to understand intent to participate”. In: *Energy Policy* 151.June 2020 (2021), p. 112121. ISSN: 0301-4215. DOI: `10.1016/j.enpol.2020.112121`. URL: `https://doi.org/10.1016/j.enpol.2020.112121`.

[257] H. F. L. F. F.L. “Successful development of decentralised district heating: Application of a theoretical framework”. eng. In: *Journal of Settlements and Spatial Planning* 2016 (2016), pp. 19–30. ISSN: 20693419.

[258] N. M. Alavijeh, C. Alemany Benayas, D. Steen, and A. T. Le. “Impact of Internal Energy Exchange Cost on Integrated Community Energy Systems”. In: *iSPEC 2019 - 2019 IEEE Sustainable Power and Energy Conference: Grid Modernization for Energy Revolution, Proceedings* (2019), pp. 2138–2143. DOI: `10.1109/iSPEC48194.2019.8975145`.

[259] B. P. Koirala, R. A. Hakvoort, and E. C. V. Oost. *Community Energy Storage : Governance and Business Models*. Elsevier Inc., 2019, pp. 209–234. ISBN: 9780128168356. DOI: `10.1016/B978-0-12-816835-6.00010-3`. URL: `https://doi.org/10.1016/B978-0-12-816835-6.00010-3`.

[260] L. Gorroño-albizu, K. Sperling, and S. Djørup. “Energy Research & Social Science The past , present and uncertain future of community energy in Denmark : Critically reviewing and conceptualising citizen ownership”. In: *Energy Research & Social Science* 57.June (2019), p. 101231. ISSN: 2214-6296. DOI: `10.1016/j.erss.2019.101231`. URL: `https://doi.org/10.1016/j.erss.2019.101231`.

[261] F. Zhang, Y. Zhang, X. Zhan, J. Luo, H. Miao, and Y. Gui. “Research on System Dynamics and Agent Hybrid Modeling Method for Multi-Energy Collaborative Control under Ubiquitous Power Internet”. In: *2019 3rd IEEE Conference on Energy Internet and Energy System Integration: Ubiquitous Energy Network Connecting Everything, EI2 2019* (2019), pp. 1856–1860. DOI: `10.1109/EI247390.2019.9062129`.

[262] I. O. Ogundari and F. A. Otuyemi. “Project planning and monitoring analysis for sustainable environment and power infrastructure project development in Lagos State, Nigeria”. In: *International Journal of Critical Infrastructures* 15.1 (2019), pp. 24–45. ISSN: 14753219. DOI: `10.1504/IJCIS.2019.096566`.

[263] G. Bravo, R. Kozulj, and R. Landaveri. “Energy access in urban and peri-urban Buenos Aires”. In: *Energy for Sustainable Development* 12.4 (2008), pp. 56–72. ISSN: 09730826. DOI: `10.1016/S0973-0826(09)60008-9`. URL: `http://dx.doi.org/10.1016/S0973-0826(09)60008-9`.

[264] D. Brown, P. Kivimaa, and S. Sorrell. “An energy leap? Business model innovation and intermediation in the ‘Energiesprong’ retrofit initiative”. In: *Energy Research and Social Science* 58 (Dec. 2019), p. 101253. ISSN: 22146296. DOI: `10.1016/j.erss.2019.101253`.

[265] T. Shimizu, Y. Kikuchi, H. Sugiyama, and M. Hirao. “Design method for a local energy cooperative network using distributed energy technologies”. In: *Applied Energy* 154 (2015), pp. 781–793. ISSN: 03062619. DOI: `10.1016/j.apenergy.2015.05.032`. URL: `http://dx.doi.org/10.1016/j.apenergy.2015.05.032`.

[266] T. Hoppe, A. Graf, B. Warbroek, I. Lammers, and I. Lepping. “Local governments supporting local energy initiatives: Lessons from the best practices of Saerbeck (Germany) and Lochem (The Netherlands)”. In: *Sustainability (Switzerland)* 7.2 (2015), pp. 1900–1931. ISSN: 20711050. DOI: `10.3390/su7021900`.

[267] B. Shaffer, R. Flores, S. Samuelsen, M. Anderson, R. Mizzi, and E. Kuitunen. “Urban Energy Systems and the Transition to Zero Carbon - Research and Case Studies from the USA and Europe”. In: *Energy Procedia* 149 (2018), pp. 25–38. ISSN: 18766102. DOI: `10.1016/j.egypro.2018.08.166`. URL: `https://doi.org/10.1016/j.egypro.2018.08.166`.

[268] S. G. G. G. *Toward an interactive visualization environment for architecting microgrids in ultra low energy communities.* eng. 2012.

[269] J. T. Van Lew, A. Ying, and M. Abdou. “A discrete element method study on the evolution of thermomechanics of a pebble bed experiencing pebble failure”. In: *Fusion Engineering and Design* 89.7-8 (2014), pp. 1151–1157. ISSN: 09203796. DOI: `10.1016/j.fusengdes.2014.04.066`. URL: `http://dx.doi.org/10.1016/j.fusengdes.2014.04.066`.

[270] N. Good, P. Mancarella, and K. Lintern. “Techno-economic assessment of community energy solutions to network capacity issues”. In: *2017 IEEE Manchester PowerTech, Powertech 2017* (2017), pp. 1–6. DOI: `10.1109/PTC.2017.7980906`.

[271] A. Kerimray, L. Rojas-Solórzano, M. Amouei Torkmahalleh, P. K. Hopke, and B. P. Ó Gallachóir. “Coal use for residential heating: Patterns, health implications and lessons learned”. In: *Energy for Sustainable Development* 40 (2017), pp. 19–30. ISSN: 23524669. DOI: `10.1016/j.esd.2017.05.005`.

[272] J. Fouladvand, M. Aranguren, T. Hoppe, and A. Ghorbani. “Simulating thermal energy community formation : Institutional enablers outplaying technological choice”. In: *Applied Energy* xxxx (2021), p. 117897. ISSN: 0306-2619. DOI: `10.1016/j.apenergy.2021.117897`. URL: `https://doi.org/10.1016/j.apenergy.2021.117897`.

[273] X. Zhang, M. Zhang, H. Zhang, Z. Jiang, and C. Liu. “A review on energy , environment and economic assessment in remanufacturing based on life cycle assessment method”. In: *Journal of Cleaner Production* 255 (2020), p. 120160. ISSN: 0959-6526. DOI: `10.1016/j.jclepro.2020.120160`. URL: `https://doi.org/10.1016/j.jclepro.2020.120160`.

[274] X. J. J. J. *Research on carbon emissions measurement of coal-energy chain based on life-cycle assessment method.* eng. 2013. ISBN: 16609336.

[275] S. Harris, M. Martin, and D. Diener. “Circularity for circularity ’ s sake ? Scoping review of assessment methods for environmental performance in the circular economy .” In: 26 (2021), pp. 172–186. DOI: `10.1016/j.spc.2020.09.018`.

[276] E. Bonabeau. “Agent-based modeling: Methods and techniques for simulating human systems”. In: *Proceedings of the National Academy of Sciences of the United States of America* 99.SUPPL. 3 (2002), pp. 7280–7287. ISSN: 00278424. DOI: `10.1073/pnas.082080899`.

[277] S. Watts and P. Stenner. “Doing Q methodology : theory , method and interpretation Doing Q methodology : theory , method and interpretation”. In: 0887 (2008). DOI: `10.1191/1478088705qp022oa`.

[278] *Serious Games, Debriefing, and Simulation_Gaming as a Discipline _ Enhanced Reader.pdf*.

[279] D. Brounen, N. Kok, and J. M. Quigley. “Energy literacy , awareness , and conservation behavior of residential households”. In: *Energy Economics* 38 (2013), pp. 42–50. ISSN: 0140-9883. DOI: `10.1016/j.eneco.2013.02.008`. URL: `http://dx.doi.org/10.1016/j.eneco.2013.02.008`.

[280] D. Majcen, L. C. M. Itard, and H. Visscher. “Theoretical vs . actual energy consumption of labelled dwellings in the Netherlands : Discrepancies and policy implications”. In: *Energy Policy* 54 (2013), pp. 125–136. ISSN: 0301-4215. DOI: `10.1016/j.enpol.2012.11.008`. URL: `http://dx.doi.org/10.1016/j.enpol.2012.11.008`.

[281] T. Bauwens. “What Roles for Energy Cooperatives in the Diffusion of Distributed Generation Technologies?” In: *SSRN Electronic Journal* 7.0 (2014), pp. 1–29. DOI: `10.2139/ssrn.2382596`.

[282] M. H. Abokersh, M. Vallès, L. F. Cabeza, and D. Boer. “A framework for the optimal integration of solar assisted district heating in different urban sized communities: A robust machine learning approach incorporating global sensitivity analysis”. In: *Applied Energy* 267.November 2019 (2020), p. 114903. ISSN: 03062619. DOI: `10.1016/j.apenergy.2020.114903`. URL: `https://doi.org/10.1016/j.apenergy.2020.114903`.

[283] H. Gadd and S. Werner. “Heat load patterns in district heating substations”. In: *Applied Energy* 108 (2013), pp. 176–183. ISSN: 0306-2619. DOI: `10.1016/j.apenergy.2013.02.062`. URL: `http://dx.doi.org/10.1016/j.apenergy.2013.02.062`.

[284] E. Calikus, S. Nowaczyk, A. S. Anna, H. Gadd, and S. Werner. “A data-driven approach for discovering heat load patterns in district heating”. In: 252.June (2019). DOI: `10.1016/j.apenergy.2019.113409`.

[285] K. Sernhed, K. Lygnerud, and S. Werner. “Synthesis of recent Swedish district heating research”. In: *Energy* 151 (2018), pp. 126–132. ISSN: 0360-5442. DOI: `10.1016/j.energy.2018.03.028`. URL: `https://doi.org/10.1016/j.energy.2018.03.028`.

[286] K. Lygnerud and S. Werner. “Risk assessment of industrial excess heat recovery in district heating systems”. In: *Energy* 151 (2018), pp. 430–441. ISSN: 0360-5442. DOI: `10.1016/j.energy.2018.03.047`. URL: `https://doi.org/10.1016/j.energy.2018.03.047`.

[287] R. Lund and U. Persson. “Mapping of potential heat sources for heat pumps for district heating in Denmark”. In: *Energy* 110 (2016), pp. 129–138. ISSN: 0360-5442. DOI: `10.1016/j.energy.2015.12.127`. URL: `http://dx.doi.org/10.1016/j.energy.2015.12.127`.

[288] Z. Tian, S. Zhang, J. Deng, J. Fan, J. Huang, W. Kong, B. Perers, and S. Furbo. “Large-scale solar district heating plants in Danish smart thermal grid : Developments and recent trends”. In: *Energy Conversion and Management* 189.March 2019 (2020), pp. 67–80. ISSN: 0196-8904. DOI: `10.1016/j.enconman.2019.03.071`. URL: `https://doi.org/10.1016/j.enconman.2019.03.071`.

[289] T. E. D. Wildt, A. R. Boijmans, E. J. L. Chappin, and P. M. Herder. “An ex ante assessment of value conflicts and social acceptance of sustainable heating systems An agent-based modelling approach”. In: *Energy Policy* 153.March (2021), p. 112265. ISSN: 0301-4215. DOI: `10.1016/j.enpol.2021.112265`. URL: `https://doi.org/10.1016/j.enpol.2021.112265`.

[290] E. M. Gui and I. MacGill. “Typology of future clean energy communities: An exploratory structure, opportunities, and challenges”. In: *Energy Research and Social Science* 35.March 2017 (2018), pp. 94–107. ISSN: 22146296. DOI: `10.1016/j.erss.2017.10.019`. URL: `https://doi.org/10.1016/j.erss.2017.10.019`.

[291] Z. Tomor. “The Citipreneur: How a local entrepreneur creates public value through smart technologies and strategies”. In: *International Journal of Public Sector Management* 32.5 (2019), pp. 489–510. ISSN: 09513558. DOI: `10.1108/IJPSM-02-2018-0060`.

[292] F. Fiedler, S. Nordlander, T. Persson, and C. Bales. “Thermal performance of combined solar and pellet heating systems”. In: *Renewable Energy* (2006). ISSN: 09601481. DOI: `10.1016/j.renene.2005.03.007`.

[293] X. H. H. H. “Multi-energy Cooperative Optimization of Integrated Energy System in Plant Considering Stepped Utilization of Energy”. eng. In: *Dianli Xitong Zidonghua/Automation of Electric Power Systems* 42.14 (2018), pp. 123–130. ISSN: 10001026.

[294] H. Wolisz, C. Punkenburg, R. Streblow, and D. Müller. “Feasibility and potential of thermal demand side management in residential buildings considering different developments in the German energy market”. In: *Energy Conversion and Management* 107 (2016), pp. 86–95. ISSN: 01968904. DOI: `10.1016/j.enconman.2015.06.059`. URL: `http://dx.doi.org/10.1016/j.enconman.2015.06.059`.

[295] H. Kazmi, S. D’Oca, C. Delmastro, S. Lodeweyckx, and S. P. Corgnati. “Generalizable occupant-driven optimization model for domestic hot water production in NZEB”. In: *Applied Energy* 175.2016 (2016), pp. 1–15. ISSN: 03062619. DOI: `10.1016/j.apenergy.2016.04.108`. URL: `http://dx.doi.org/10.1016/j.apenergy.2016.04.108`.

[296] J. Xu, R. Z. Wang, and Y. Li. “A review of available technologies for seasonal thermal energy storage”. In: *Solar Energy* (2014). ISSN: 0038092X. DOI: `10.1016/j.solener.2013.06.006`.

[297] D. Magnusson. “Who brings the heat? – From municipal to diversified ownership in the Swedish district heating market post-liberalization”. In: *Energy Research and Social Science* 22 (2016), pp. 198–209. ISSN: 22146296. DOI: `10.1016/j.erss.2016.10.004`. URL: `http://dx.doi.org/10.1016/j.erss.2016.10.004`.

[298] F. Knobloch, H. Pollitt, U. Chewpreecha, V. Daioglou, and J. F. Mercure. “Simulating the deep decarbonisation of residential heating for limiting global warming to 1.5 °C”. In: *Energy Efficiency* 12.2 (2019), pp. 521–550. ISSN: 15706478. DOI: `10.1007/s12053-018-9710-0`.

[299] A. Eisentraut, B. Adam, and I. International Energy Agency. “Heating without global warming”. In: *Featured Insight* (2014), p. 92.

[300] M. van Middelkoop, K. Vringer, and H. Visser. “Are Dutch residents ready for a more stringent policy to enhance the energy performance of their homes?” In: *Energy Policy* (2017). ISSN: 03014215. DOI: `10.1016/j.enpol.2017.02.050`.

[301] J. Student, E. Papyrakis, and P. van Beukering. “Buildings behaving badly: a behavioral experiment on how different motivational frames influence residential energy label adoption in the Netherlands”. In: *Journal of Housing and the Built Environment* 32.1 (2017), pp. 107–132. ISSN: 15737772. DOI: `10.1007/s10901-016-9500-y`.

[302] M. Martiskainen. “The role of community leadership in the development of grassroots innovations”. In: *Environmental Innovation and Societal Transitions* 22 (2017), pp. 78–89. ISSN: 22104224. DOI: `10.1016/j.eist.2016.05.002`. URL: `http://dx.doi.org/10.1016/j.eist.2016.05.002`.

[303] D. Gallego Carrera and A. Mack. “Sustainability assessment of energy technologies via social indicators: Results of a survey among European energy experts”. In: *Energy Policy* (2010). ISSN: 03014215. DOI: `10.1016/j.enpol.2009.10.055`.

[304] E. R. Frederiks, K. Stenner, and E. V. Hobman. “Household energy use: Applying behavioural economics to understand consumer decision-making and behaviour”. In: *Renewable and Sustainable Energy Reviews* (2015). ISSN: 13640321. DOI: `10.1016/j.rser.2014.09.026`.

[305] J. Dvarioniene, I. Gurauskiene, G. Gecevicius, D. R. Trummer, C. Selada, I. Marques, and C. Cosmi. “Stakeholders involvement for energy conscious communities: The Energy Labs experience in 10 European communities”. In: *Renewable Energy* 75.2015 (2015), pp. 512–518. ISSN: 18790682. DOI: `10.1016/j.renene.2014.10.017`. URL: `http://dx.doi.org/10.1016/j.renene.2014.10.017`.

[306] C. Brandoni and F. Polonara. “The role of municipal energy planning in the regional energy-planning process”. In: *Energy* 48.1 (2012), pp. 323–338. ISSN: 03605442. DOI: `10.1016/j.energy.2012.06.061`. URL: `http://dx.doi.org/10.1016/j.energy.2012.06.061`.

[307] M. Oteman, M. Wiering, and J. K. Helderman. “The institutional space of community initiatives for renewable energy: a comparative case study of the Netherlands, Germany and Denmark”. In: *Energy, Sustainability and Society* 4.1 (2014). ISSN: 21920567. DOI: `10.1186/2192-0567-4-11`.

[308] B. Vitéz and S. Lavrijssen. “The energy transition: Democracy, justice and good regulation of the heat market”. In: *Energies* 13.5 (2020). ISSN: 19961073. DOI: `10.3390/en13051088`.

[309] M. A. Heldeweg, M. P. T. Sanders, and A. V. Brunnekreef. “Legal governance of smart heat infrastructure development under modes of liberalization; how to analyze and overcome deadlocks in heat projects”. In: *Energy, Sustainability and Society* 7.1 (2017). ISSN: 21920567. DOI: `10.1186/s13705-017-0127-y`.

[310] B. J. Van de Wiel, E. Vignon, P. Baas, I. G. van Hooijdonk, S. J. van der Linden, J. A. van Hooft, F. C. Bosveld, S. R. de Roode, A. F. Moene, and C. Genthon. “Regime transitions in near-surface temperature inversions: A conceptual model”. In: *Journal of the Atmospheric Sciences* 74.4 (2017), pp. 1057–1073. ISSN: 15200469. DOI: `10.1175/JAS-D-16-0180.1`.

[311] R. P. Raven, R. M. Mourik, C. F. Feenstra, and E. Heiskanen. “Modulating societal acceptance in new energy projects: Towards a toolkit methodology for project managers”. In: *Energy* (2009). ISSN: 03605442. DOI: `10.1016/j.energy.2008.08.012`.

[312] G. Perlaviciute and L. Steg. “The influence of values on evaluations of energy alternatives”. In: *Renewable Energy* (2015). ISSN: 18790682. DOI: `10.1016/j.renene.2014.12.020`.

[313] W. Abrahamse and L. Steg. “How do socio-demographic and psychological factors relate to households’ direct and indirect energy use and savings?” In: *Journal of Economic Psychology* (2009). ISSN: 01674870. DOI: `10.1016/j.joep.2009.05.006`.

[314] E. H. Noppers, K. Keizer, J. W. Bolderdijk, and L. Steg. “The adoption of sustainable innovations: Driven by symbolic and environmental motives”. In: *Global Environmental Change* (2014). ISSN: 09593780. DOI: `10.1016/j.gloenvcha.2014.01.012`.

[315] N. M. A. Huijts, E. J. E. Molin, and L. Steg. “Psychological factors influencing sustainable energy technology acceptance: A review-based comprehensive framework”. In: *Renewable and Sustainable Energy Reviews* (2012). ISSN: 13640321. DOI: `10.1016/j.rser.2011.08.018`.

[316] F. P. Boon and C. Dieperink. “Local civil society based renewable energy organisations in the Netherlands: Exploring the factors that stimulate their emergence and development”. In: *Energy Policy* (2014). ISSN: 03014215. DOI: `10.1016/j.enpol.2014.01.046`.

[317] M. Martiskainen. “Environmental Innovation and Societal Transitions The role of community leadership in the development of grassroots innovations”. In: *Environmental Innovation and Societal Transitions* 22 (2017), pp. 78–89. ISSN: 2210-4224. DOI: `10.1016/j.eist.2016.05.002`. URL: `http://dx.doi.org/10.1016/j.eist.2016.05.002`.

[318] J. Young and M. Brans. “Analysis of factors affecting a shift in a local energy system towards 100% renewable energy community”. In: *Journal of Cleaner Production* 169 (2017), pp. 117–124. ISSN: 09596526. DOI: `10.1016/j.jclepro.2017.08.023`. URL: `https://doi.org/10.1016/j.jclepro.2017.08.023`.

[319] O. E. Williamson. “Transaction cost economics: How it works; where it is headed”. In: *Economist* 146.1 (1998), pp. 23–58. ISSN: 0013063X. DOI: `10.1023/A:1003263908567`.

[320] J. D. Westaby. “Behavioral reasoning theory : Identifying new linkages underlying intentions and behavior”. In: 98 (2005), pp. 97–120. DOI: `10.1016/j.obhdp.2005.07.003`.

[321] “DIFFERENT TYPES OF REGULATION FOR DIFFERENT TYPES OF TRANSACTIONS; A framework of analysis based on Oliver Williamson and John R. Commons.” In: October (2006).

[322] A. Ghorbani, A. Ligtvoet, I. Nikolic, and G. Dijkema. *Using institutional frameworks to conceptualize agent-based models of socio-technical systems*. Vol. 3. January. 2010, pp. 33–41. ISBN: 9781905986279.

[323] R. Ku and T. Fens. “Ownership unbundling in electricity distribution : The case of The Netherlands”. In: 35 (2007), pp. 1920–1930. DOI: `10.1016/j.enpol.2006.05.008`.

[324] R. W. Ku. “Institutional reform and technological practice : the case of electricity”. In: 17.2 (2008), pp. 233–265. DOI: `10.1093/icc/dtn002`.

[325] P. Stern. “Understanding Individuals’ Environmentally Significant Behavior”. In: *Environmental Law Report* 35 (Jan. 2005).

[326] J. E. Lewin, D. Strutton, and A. K. Paswan. “Conflicting Stakeholder Interests and Natural Gas : A Macromarketing Perspective”. In: 31.4 (2011), pp. 340–358. DOI: `10.1177/0276146711405529`.

[327] J. G. Koomey and L. Berkeley. “THE ENERGY AND CLIMATE CHANGE IMPACTS OF DIFFERENT MUSIC DELIVERY METHODS”. In: (2009).

[328] A. Kumar, R. K. Padhy, and A. Dhir. “Envisioning the future of behavioral decision-making : A systematic literature review of behavioral reasoning theory”. In: *Australasian Marketing Journal (AMJ)* xxxx (2020). ISSN: 1441-3582. DOI: `10.1016/j.ausmj.2020.05.001`. URL: `https://doi.org/10.1016/j.ausmj.2020.05.001`.

[329] J. D. Westaby, T. M. Probst, and B. C. Lee. “Leadership decision-making: A behavioral reasoning theory analysis”. In: *Leadership Quarterly* 21.3 (2010), pp. 481–495. ISSN: 10489843. DOI: `10.1016/j.leaqua.2010.03.011`. URL: `http://dx.doi.org/10.1016/j.leaqua.2010.03.011`.

[330] B. Sleutjes, H. A. G. D. Valk, and J. Ooijevaar. “The Measurement of Ethnic Segregation in the Netherlands : Differences Between Administrative and Individualized Neighbourhoods”. In: *European Journal of Population* 34.2 (2018), pp. 195–224. ISSN: 1572-9885. DOI: `10.1007/s10680-018-9479-z`. URL: `https://doi.org/10.1007/s10680-018-9479-z`.

[331] "Average energy rates for consumers :" in: (2021), p. 84672.

[332] D. J. Watts and S. H. Strogatz. "Collective dynamics of small-world networks". In: *Nature* 393 (1998), pp. 440–442.

[333] L. A. Amaral, A. Scala, M. Barthélémy, and H. E. Stanley. "Classes of small-world networks". In: *Proceedings of the National Academy of Sciences of the United States of America* 97.21 (2000), pp. 11149–11152. ISSN: 00278424. DOI: `10.1073/pnas.200327197`.

[334] N. Verkade and J. Höffken. "Collective energy practices: A practice-based approach to civic energy communities and the energy system". In: *Sustainability (Switzerland)* 11.11 (2019). ISSN: 20711050. DOI: `10.3390/su11113230`.

[335] M. Bloemendal, M. Jaxa-rozen, and T. Olsthoorn. "Methods for planning of ATES systems". In: *Applied Energy* 216.February (2018), pp. 534–557. ISSN: 0306-2619. DOI: `10.1016/j.apenergy.2018.02.068`. URL: `https://doi.org/10.1016/j.apenergy.2018.02.068`.

[336] E. V. D. Roest, T. Fens, M. Bloemendal, S. Beernink, J. P. V. D. Hoek, and A. J. M. V. Wijk. "The Impact of System Integration on System Costs of a Neighborhood Energy and Water System". In: (2021).

[337] O. Gudmundsson, J. E. Thorsen, and L. Zhang. "Cost analysis of district heating compared to its competing technologies". In: *WIT Transactions on Ecology and the Environment* 176 (2013), pp. 107–118. ISSN: 17433541. DOI: `10.2495/ESUS130091`.

[338] M. Airaksinen and M. Vuolle. "Heating Energy and Peak-Power Demand in a Standard and Low Energy Building". In: (2013), pp. 235–250. DOI: `10.3390/en6010235`.

[339] A. F. Sandvall, E. O. Ahlgren, and T. Ekvall. "Cost-efficiency of urban heating strategies – Modelling scale effects of low-energy building heat supply". In: *Energy Strategy Reviews* 18 (2017), pp. 212–223. ISSN: 2211467X. DOI: `10.1016/j.esr.2017.10.003`. URL: `https://doi.org/10.1016/j.esr.2017.10.003`.

[340] K. Kontu, J. Vimpari, P. Penttinen, and S. Junnila. "Individual ground source heat pumps : Can district heating compete with real estate owners ' return expectations ?" In: *Sustainable Cities and Society* 53.November 2019 (2020), p. 101982. ISSN: 2210-6707. DOI: `10.1016/j.scs.2019.101982`. URL: `https://doi.org/10.1016/j.scs.2019.101982`.

[341] E. A. Clean. "THE TRANSITION OF THE RESIDENTIAL HEATING SYSTEM". In: (2017).

[342] D. A. A. A. "Multicriteria approach for a multisource district heating". eng. In: *Green Energy and Technology* 9783319757735 (2018), pp. 21–33. ISSN: 18653529.

[343] T. Tsoutsos, M. Drandaki, N. Frantzeskaki, E. Iosifidis, and I. Kiosses. "Sustainable energy planning by using multi-criteria analysis application in the island of Crete". In: 37 (2009), pp. 1587–1600. DOI: `10.1016/j.enpol.2008.12.011`.

[344] R. Sadiq, H. Karunathilake, and K. Hewage. "Renewable energy selection for net-zero energy communities : Life cycle based decision making under uncertainty". In: 130 (2019), pp. 558–573. DOI: `10.1016/j.renene.2018.06.086`.

[345] R. McKenna, V. Bertsch, K. Mainzer, and W. Fichtner. “Combining local preferences with multi-criteria decision analysis and linear optimization to develop feasible energy concepts in small communities”. In: *European Journal of Operational Research* 268.3 (2018), pp. 1092–1110. ISSN: 03772217. DOI: `10.1016/j.ejor.2018.01.036`. URL: `https://doi.org/10.1016/j.ejor.2018.01.036`.

[346] N. Osman. “Barriers to district heating development in the Netherlands: a business model perspective”. In: (2017), pp. 1–108.

[347] X. Liu and Z. Jin. “An analysis of the interactions between electricity, fossil fuel and carbon market prices in Guangdong, China”. In: *Energy for Sustainable Development* 55 (2020), pp. 82–94. ISSN: 23524669. DOI: `10.1016/j.esd.2020.01.008`. URL: `https://doi.org/10.1016/j.esd.2020.01.008`.

[348] S. Borenstein, J. Bushnell, F. A. Wolak, and M. Zaragoza-watkins. “Expecting the Unexpected : Emissions Uncertainty and Environmental Market Design Online Appendix”. In: (2020).

[349] H. C. Frey and S. R. Patil. “Identification and Review of Sensitivity Analysis Methods”. In: 22.3 (2002).

[350] J. C. Thiele, W. Kurth, and V. Grimm. “Jan C . Thiele , Winfried Kurth and Volker Grimm ( 2014 ) Facilitating Parameter Estimation and Sensitivity Analysis of Agent-Based Models : A Cookbook Using NetLogo and R”. In: *Journal of Artificial Societies and Social Simulation* 17.3 (2015), pp. 1–45. ISSN: 1460-7425. DOI: `10.18564/jasss.2503`.

[351] A. Societies and S. Simulation. “Which Sensitivity Analysis Method Should I Use for My Agent-Based Model ?” In: (2016), pp. 1–35. DOI: `10.18564/jasss.2857`.

[352] M. Schouten, T. Verwaart, and W. Heijman. “Environmental Modelling & Software Comparing two sensitivity analysis approaches for two scenarios with a spatially explicit rural agent-based model”. In: *Environmental Modelling and Software* 54 (2014), pp. 196–210. ISSN: 1364-8152. DOI: `10.1016/j.envsoft.2014.01.003`. URL: `http://dx.doi.org/10.1016/j.envsoft.2014.01.003`.

[353] I. Ajzen. “The theory of planned behavior”. In: *Organizational Behavior and Human Decision Processes* 50.2 (1991), pp. 179–211. ISSN: 07495978. DOI: `10.1016/0749-5978(91)90020-T`.

[354] D. Diran, T. Hoppe, J. Ubacht, A. Slob, and K. Blok. “A data ecosystem for data-driven thermal energy transition: Reflection on current practice and suggestions for re-design”. In: *Energies* 13.2 (2020). ISSN: 19961073. DOI: `10.3390/en13020444`.

[355] B. Edmonds, C. L. Page, M. Bithell, V. Grimm, R. Meyer, C. Montañola-, P. Ormerod, H. Root, and F. Squazzoni. “Di erent Modelling Purposes”. In: ().

[356] A. Itten, F. Sherry-brennan, A. Sundaram, and T. Hoppe. *State-of-the-art report for co-creation approaches and practices*. April. 2020. ISBN: 2019000059. DOI: `10.13140/RG.2.2.22835.17440`.

[357] M. Fulhu, M. Mohamed, and S. Krumdieck. “Voluntary demand participation (VDP) for security of essential energy activities in remote communities with case study in Maldives”. In: *Energy for Sustainable Development* 49 (2019), pp. 27–38. ISSN: 23524669. DOI: `10.1016/j.esd.2019.01.002`. URL: `https://doi.org/10.1016/j.esd.2019.01.002`.

[358] V. Rai and A. D. Henry. “Agent-based modelling of consumer energy choices”. In: *Nature Climate Change* 6.6 (2016), pp. 556–562. ISSN: 17586798. DOI: `10.1038/nclimate2967`.

[359] A. Fichera, A. Pluchino, and R. Volpe. “From self-consumption to decentralized distribution among prosumers : A model including technological , operational and spatial issues”. In: *Energy Conversion and Management* 217.May (2020), p. 112932. ISSN: 0196-8904. DOI: `10.1016/j.enconman.2020.112932`. URL: `https://doi.org/10.1016/j.enconman.2020.112932`.

[360] A. Fichera, A. Pluchino, and R. Volpe. “A multi-layer agent-based model for the analysis of energy distribution networks in urban areas”. In: *Physica A* 508 (2018), pp. 710–725. ISSN: 0378-4371. DOI: `10.1016/j.physa.2018.05.124`. URL: `https://doi.org/10.1016/j.physa.2018.05.124`.

[361] S. Bellekom, M. Arentsen, and K. V. Gorkum. “Prosumption and the distribution and supply of electricity”. In: *Energy, Sustainability and Society* (2016), pp. 1–17. ISSN: 2192-0567. DOI: `10.1186/s13705-016-0087-7`. URL: `http://dx.doi.org/10.1186/s13705-016-0087-7`.

[362] M. Lee and T. Hong. “Hybrid agent-based modeling of rooftop solar photovoltaic adoption by integrating the geographic information system and data mining technique”. In: *Energy Conversion and Management* 183 (2019), pp. 266–279.

[363] A. Mittal, C. C. Krejci, and M. C. Dorneich. “An agent-based approach to designing residential renewable energy systems”. In: *Renewable and Sustainable Energy Reviews* 112 (2019), pp. 1008–1020.

[364] J. M. Fritz and M. Dirk. “Development of an Agent-Based System for Decentralized Control of District Energy Systems”. In: (2019), pp. 582–587.

[365] J. Castro, S. Drews, F. Exadaktylos, and J. Foramitti. “A review of agent-based modeling of climate-energy policy”. In: March (2020), pp. 1–26. DOI: `10.1002/wcc.647`.

[366] C. Berger and A. Mahdavi. “Review of current trends in agent-based modeling of building occupants for energy and indoor-environmental performance analysis”. In: *Building and Environment* 173.February (2020), p. 106726. ISSN: 0360-1323. DOI: `10.1016/j.buildenv.2020.106726`. URL: `https://doi.org/10.1016/j.buildenv.2020.106726`.

[367] L. X. W. Hesselink and E. J. L. Chappin. “Adoption of energy efficient technologies by households – Barriers , policies and agent-based modelling studies”. In: *Renewable and Sustainable Energy Reviews* 99.September 2018 (2019), pp. 29–41. ISSN: 1364-0321. DOI: `10.1016/j.rser.2018.09.031`. URL: `https://doi.org/10.1016/j.rser.2018.09.031`.

[368] P. Hansen, X. Liu, and G. M. Morrison. “Energy Research & Social Science Agent-based modelling and socio-technical energy transitions : A systematic literature review”. In: *Energy Research & Social Science* 49.June 2018 (2019), pp. 41–52. ISSN: 2214-6296. DOI: `10.1016/j.erss.2018.10.021`. URL: `https://doi.org/10.1016/j.erss.2018.10.021`.

[369] J. Reichl, M. Schmidthaler, and F. Schneider. “The value of supply security : The costs of power outages to Austrian households , firms and the public sector”. In: *Energy Economics* 36 (2013), pp. 256–261. ISSN: 0140-9883. DOI: `10.1016/j.eneco.2012.08.044`. URL: `http://dx.doi.org/10.1016/j.eneco.2012.08.044`.

[370] V. Grimm, S. F. Railsback, C. E. Vincenot, U. Berger, C. Gallagher, D. L. Deangelis, B. Edmonds, J. Ge, J. Giske, J. Groeneveld, A. S. Johnston, A. Milles, J. Nabe-Nielsen, J. G. Polhill, V. Radchuk, M. S. Rohwäder, R. A. Stillman, J. C. Thiele, and D. Ayllón. “The ODD protocol for describing agent-based and other simulation models: A second update to improve clarity, replication, and structural realism”. In: *Jasss* 23.2 (2020). ISSN: 14607425. DOI: `10.18564/jasss.4259`.

[371] M. Jung and J. Hwang. “Structural dynamics of innovation networks funded by the European Union in the context of systemic innovation of the renewable energy sector”. In: *Energy Policy* 96 (2016), pp. 471–490. ISSN: 0301-4215. DOI: `10.1016/j.enpol.2016.06.017`. URL: `http://dx.doi.org/10.1016/j.enpol.2016.06.017`.

[372] G. Seyfang, J. Jin, and A. Smith. “A thousand flowers blooming ? An examination of community energy in the UK”. In: *Energy Policy* 61 (2013), pp. 977–989. ISSN: 0301-4215. DOI: `10.1016/j.enpol.2013.06.030`. URL: `http://dx.doi.org/10.1016/j.enpol.2013.06.030`.

[373] A. Ranjan and L. Hughes. “Energy security and the diversity of energy flows in an energy system”. In: *Energy* 73 (2014), pp. 137–144. ISSN: 03605442. DOI: `10.1016/j.energy.2014.05.108`.

[374] B. W. Ang, W. L. Choong, and T. S. Ng. “A framework for evaluating Singapore’s energy security”. In: *Applied Energy* 148 (2015), pp. 314–325. ISSN: 03062619. DOI: `10.1016/j.apenergy.2015.03.088`.

[375] M. Londo, R. Matton, O. Usmani, M. V. Klaveren, C. Tigchelaar, and S. Brunsting. “Alternatives for current net metering policy for solar PV in the Netherlands : A comparison of impacts on business case and purchasing behaviour of private homeowners , and on governmental costs”. In: *Renewable Energy* 147 (2020), pp. 903–915. ISSN: 0960-1481. DOI: `10.1016/j.renene.2019.09.062`. URL: `https://doi.org/10.1016/j.renene.2019.09.062`.

[376] R. O. Murphy and K. A. Ackermann. “Social Value Orientation : Theoretical and Measurement Issues in the Study of Social Preferences”. In: (2014). DOI: `10.1177/1088868313501745`.

[377] G. d. C. Nava-Guerrero, H. H. Hansen, G. Korevaar, and Z. Lukszo. “The effect of group decisions in heat transitions: An agent-based approach”. In: *Energy Policy* 156.April (2021), p. 112306. ISSN: 03014215. DOI: `10.1016/j.enpol.2021.112306`. URL: `https://doi.org/10.1016/j.enpol.2021.112306`.

[378] K. A. Babatunde, F. F. Said, N. G. M. Nor, R. A. Begum, and M. A. Mahmoud. “Coherent or conflicting? Assessing natural gas subsidy and energy efficiency policy interactions amid CO2 emissions reduction in Malaysia electricity sector”. In: *Journal of Cleaner Production* 279 (2021), p. 123374.

[379] J. A. Moncada, Z. Tao, P. Valkering, F. Meinke-Hubeny, and E. Delarue. “Influence of distribution tariff structures and peer effects on the adoption of distributed energy resources”. In: *Applied Energy* 298 (2021), p. 117086.

[380] K. Poplavskaya, J. Lago, S. Strömer, and L. De Vries. “Making the most of short-term flexibility in the balancing market: Opportunities and challenges of voluntary bids in the new balancing market design”. In: *Energy Policy* 158 (2021), p. 112522.

[381] P. H. Burli, R. T. Nguyen, D. S. Hartley, L. M. Griffel, V. Vazhnik, and Y. Lin. “Farmer characteristics and decision-making: A model for bioenergy crop adoption”. In: *Energy* 234 (2021), p. 121235.

[382] F. Gagliardi. “Institutions and economic change : A critical survey of the new institutional approaches and empirical evidence”. In: 37 (2008), pp. 416–443. DOI: `10.1016/j.socec.2007.03.001`.

[383] K. K. Iychettira, R. A. Hakvoort, P. Linares, and R. de Jeu. “Towards a comprehensive policy for electricity from renewable energy: Designing for social welfare”. In: *Applied Energy* 187 (2017), pp. 228–242.

[384] R. O. Murphy, K. A. Ackermann, and M. J. J. Handgraaf. “Measuring Social Value Orientation”. In: 6.8 (2011), pp. 771–781.

[385] C. K. W. D. Dreu and T. L. Boles. “Share and Share Alike or Winner Take All ?: The Influence of Social Value Orientation upon Choice and Recall of Negotiation Heuristics”. In: 76.3 (1998), pp. 253–276.

[386] S. Pahl, P. R. Harris, H. A. Todd, and D. R. Rutter. “Comparative optimism for environmental risks”. In: 25 (2005), pp. 1–11. DOI: `10.1016/j.jenvp.2004.12.004`.

[387] S. G. Roch, J. A. S. Lane, C. D. Samuelson, S. T. Allison, and J. L. Dent. “Cognitive Load and the Equality Heuristic : A Two-Stage Model of Resource Overconsumption in Small Groups”. In: 83.2 (2000), pp. 185–212. DOI: `10.1006/obhd.2000.2915`.

[388] I. Kastner and E. Matthies. “Energy Research & Social Science Investments in renewable energies by German households : A matter of economics , social influences and ecological concern ?” In: *Chemical Physics Letters* 17 (2016), pp. 1–9. ISSN: 2214-6296. DOI: `10.1016/j.erss.2016.03.006`. URL: `http://dx.doi.org/10.1016/j.erss.2016.03.006`.

[389] D. P. Kaundinya, P. Balachandra, and N. H. Ravindranath. "Grid-connected versus stand-alone energy systems for decentralized power-A review of literature". In: *Renewable and Sustainable Energy Reviews* 13.8 (2009), pp. 2041–2050. ISSN: 13640321. DOI: `10.1016/j.rser.2009.02.002`.

[390] F. Filippidou and N. Nieboer. "Energy efficiency measures implemented in the Dutch non-profit housing sector". In: ().

[391] D. Majcen and L. Itard. "Energy labels in Dutch dwellings – their actual energy consumption and implications for reduction targets". In: (1947), pp. 1947–1952.

[392] F. Filippidou, N. Nieboer, and H. Visscher. "Are we moving fast enough ? The energy renovation rate of the Dutch non- pro fi t housing using the national energy labelling database". In: *Energy Policy* 109.December 2016 (2017), pp. 488–498. ISSN: 0301-4215. DOI: `10.1016/j.enpol.2017.07.025`. URL: `http://dx.doi.org/10.1016/j.enpol.2017.07.025`.

[393] K. J. H. J. J.H. "Climate change, security of supply and competitiveness: Does Europe have the means to implement its ambitious energy vision?" eng. In: *The New Energy Crisis: Climate, Economics and Geopolitics* (2016), pp. 192–216.

[394] G. Escribano Francés, J. M. Marín-Quemada, and E. San Martín González. "RES and risk: Renewable energy's contribution to energy security. A portfolio-based approach". In: *Renewable and Sustainable Energy Reviews* 26 (2013), pp. 549–559. ISSN: 13640321. DOI: `10.1016/j.rser.2013.06.015`. URL: `http://dx.doi.org/10.1016/j.rser.2013.06.015`.

[395] H. Turton and L. Barreto. "Long-term security of energy supply and climate change". In: *Energy Policy* 34.15 (2006), pp. 2232–2250. ISSN: 03014215. DOI: `10.1016/j.enpol.2005.03.016`.

[396] V. Rostampour, M. Jaxa-Rozen, M. Bloemendal, J. Kwakkel, and T. Keviczky. "Aquifer Thermal Energy Storage (ATES) smart grids: Large-scale seasonal energy storage as a distributed energy management solution". In: *Applied energy* 242 (2019), pp. 624–639.

[397] K. Li, M. Ma, X. Xiang, W. Feng, Z. Ma, W. Cai, and X. Ma. "Carbon reduction in commercial building operations: A provincial retrospection in China". In: *Applied Energy* 306 (2022), p. 118098.

[398] S. Zhang, M. Ma, K. Li, Z. Ma, W. Feng, and W. Cai. "Historical carbon abatement in the commercial building operation: China versus the US". In: *Energy Economics* 105 (2022), p. 105712.

[399] K. Lichtenegger, A. Leitner, T. Märzinger, C. Mair, A. Moser, D. Wöss, C. Schmidl, and T. Pröll. "Decentralized heating grid operation: A comparison of centralized and agent-based optimization". In: *Sustainable Energy, Grids and Networks* 21 (2020), p. 100300. ISSN: 23524677. DOI: `10.1016/j.segan.2020.100300`. URL: `https://doi.org/10.1016/j.segan.2020.100300`.

[400] W. Liang, G. Shen, B. Wang, S. Cao, D. Yu, L. Zhao, and X. Duan. “Space heating approaches in Chinese schools: Results from the first Chinese Environmental Exposure-Related Human Activity Patterns Survey-Children (CEERHAPS-C)”. In: *Energy for Sustainable Development* 56 (2020), pp. 33–41. ISSN: 23524669. DOI: `10.1016/j.esd.2020.03.001`. URL: `https://doi.org/10.1016/j.esd.2020.03.001`.

[401] A. Blumberga, R. Vanaga, R. Freimanis, D. Blumberga, J. Antužs, A. Krastiņš, I. Jankovskis, E. Bondars, and S. Treija. “Transition from traditional historic urban block to positive energy block”. In: *Energy* 202 (2020). ISSN: 03605442. DOI: `10.1016/j.energy.2020.117485`.

[402] H. u. Rehman, F. Reda, S. Paiho, and A. Hasan. “Towards positive energy communities at high latitudes”. In: *Energy Conversion and Management* 196.May (2019), pp. 175–195. ISSN: 01968904. DOI: `10.1016/j.enconman.2019.06.005`. URL: `https://doi.org/10.1016/j.enconman.2019.06.005`.

[403] V. N. Duy, K. N. Duc, D. N. Cong, H. N. Xa, and T. Le Anh. “Experimental study on improving performance and emission characteristics of used motorcycle fueled with ethanol by exhaust gas heating transfer system”. In: *Energy for Sustainable Development* 51 (2019), pp. 56–62. ISSN: 23524669. DOI: `10.1016/j.esd.2019.05.006`. URL: `https://doi.org/10.1016/j.esd.2019.05.006`.

[404] A. X. X. X. “Study on Integrated DLC Coordination Optimization of Electric-thermal-gas Coupling System Considering Demand Response”. eng. In: *Dianwang Jishu/Power System Technology* 43.4 (2019), pp. 1160–1169. ISSN: 10003673.

[405] S. Gerber, A. J. Rix, and M. J. Booysen. “Combining grid-tied PV and intelligent water heater control to reduce the energy costs at schools in South Africa”. In: *Energy for Sustainable Development* 50 (2019), pp. 117–125. ISSN: 23524669. DOI: `10.1016/j.esd.2019.03.004`. URL: `https://doi.org/10.1016/j.esd.2019.03.004`.

[406] B. S. S. S. *Energy modeling methodology for community master planning*. eng. 2018. ISBN: 23782129.

[407] M. Roux, M. Apperley, and M. J. Booysen. “Comfort, peak load and energy: Centralised control of water heaters for demand-driven prioritisation”. In: *Energy for Sustainable Development* 44 (2018), pp. 78–86. ISSN: 09730826. DOI: `10.1016/j.esd.2018.03.006`. URL: `https://doi.org/10.1016/j.esd.2018.03.006`.

[408] D. A. Katsaprakakis and M. Voumvoulakis. “A hybrid power plant towards 100% energy autonomy for the island of Sifnos, Greece. Perspectives created from energy cooperatives”. In: *Energy* 161 (2018), pp. 680–698. ISSN: 03605442. DOI: `10.1016/j.energy.2018.07.198`. URL: `https://doi.org/10.1016/j.energy.2018.07.198`.

[409] Z. Zheng and Y. Zhang. “State-of-The-Art of Modeling Methodologies and Optimization Operations in Integrated Energy System”. In: *IOP Conference Series: Earth and Environmental Science* 83.1 (2017). ISSN: 17551315. DOI: `10.1088/1755-1315/83/1/012002`.

[410] S. Magazine. “Electrification in Non-Interconnected Areas”. In: December (2017), pp. 73–79.

[411] M. GREEN, K. EMERY, Y. HISHIKAWA, W. WARTA, E. DUNLOP, D. BARKHOUSE, O. GUNAWAN, T. GOKMEN, T. TODOROV, and D. MITZI. “Solar cell efficiency tables (version 40)”. In: *Ieee Trans Fuzzy Syst* 20.6 (2012), pp. 1114–1129. DOI: `10.1002/pip`.

[412] K. Vinther, R. J. Nielsen, K. M. Nielsen, P. Andersen, T. S. Pedersen, and J. D. Bendtsen. “Absorption cycle heat pump model for control design”. In: *2015 European Control Conference, ECC 2015* (2015), pp. 2228–2234. DOI: `10.1109/ECC.2015.7330870`.

[413] J. Hirvonen, G. Kayo, A. Hasan, and K. Sirén. “Local sharing of cogeneration energy through individually prioritized controls for increased on-site energy utilization”. In: *Applied Energy* 135 (2014), pp. 350–363. ISSN: 03062619. DOI: `10.1016/j.apenergy.2014.08.090`. URL: `http://dx.doi.org/10.1016/j.apenergy.2014.08.090`.

[414] Z. A. M. A. A.M. *Energy master planning towards net-zero energy communities/campuses.* eng. 2014. ISBN: 00012505.

[415] A. Escobedo, S. Briceño, H. Juárez, D. Castillo, M. Imaz, and C. Sheinbaum. “Energy consumption and GHG emission scenarios of a university campus in Mexico”. In: *Energy for Sustainable Development* 18.1 (2014), pp. 49–57. ISSN: 09730826. DOI: `10.1016/j.esd.2013.10.005`. URL: `http://dx.doi.org/10.1016/j.esd.2013.10.005`.

[416] K. A. A. A. *From U.S. Army installation to zero energy community: The BO Bad Aibling Park looks to the future.* eng. 2014. ISBN: 00012505.

[417] B. K. Sovacool. “Confronting energy poverty behind the bamboo curtain: A review of challenges and solutions for Myanmar (Burma)”. In: *Energy for Sustainable Development* 17.4 (2013), pp. 305–314. ISSN: 09730826. DOI: `10.1016/j.esd.2013.03.010`. URL: `http://dx.doi.org/10.1016/j.esd.2013.03.010`.

[418] L. J.-H. J. J.-H. “An optimal operation model of a centralized micro-energy network”. eng. In: *Transactions of the Korean Institute of Electrical Engineers* 62.10 (2013), pp. 1451–1457. ISSN: 19758359.

[419] K. B. B. B. *Ultra-low energy Army installations.* eng. 2011.

[420] M. Amer and T. U. Daim. “Selection of renewable energy technologies for a developing county: A case of Pakistan”. In: *Energy for Sustainable Development* 15.4 (2011), pp. 420–435. ISSN: 09730826. DOI: `10.1016/j.esd.2011.09.001`. URL: `http://dx.doi.org/10.1016/j.esd.2011.09.001`.

[421] S. J. J. J. *Colorado community benefits from installing waste heat recovery system.* eng. 2010.

[422] H. T. T. T. *Energy systems analyses for ultra low energy communities.* eng. 2009.

[423] K. P. Ijumba, A. B. Sebitosi, P. Pillay, and K. Folly. “Impact of extensive residential solar water heating on power system losses”. In: *Energy for Sustainable Development* 13.2 (2009), pp. 85–95. ISSN: 09730826. DOI: `10.1016/j.esd.2009.04.004`. URL: `http://dx.doi.org/10.1016/j.esd.2009.04.004`.

[424] P. Thy, K. H. Esbensen, and B. M. Jenkins. “On representative sampling and reliable chemical characterization in thermal biomass conversion studies”. In: *Biomass and Bioenergy* 33.11 (2009), pp. 1513–1519. ISSN: 09619534. DOI: `10.1016/j.biombioe.2009.07.015`. URL: `http://dx.doi.org/10.1016/j.biombioe.2009.07.015`.

[425] M. D. R. D. D.R. “The solar resource”. eng. In: *Solar Hydrogen Generation: Toward a Renewable Energy Future* (2008), pp. 19–39.

[426] R. J. J. J. *Sustainable ecological habitat: Towards zero energy building*. eng. 2008.

[427] L. Lianzhong and M. Zaheeruddin. “Dynamic modeling and fuzzy augmented PI control of a high-rise building hot water heating system”. In: *Energy for Sustainable Development* 12.2 (2008), pp. 49–55. ISSN: 09730826. DOI: `10.1016/S0973-0826(08)60428-7`. URL: `http://dx.doi.org/10.1016/S0973-0826(08)60428-7`.

[428] D. B. Crawley, J. W. Hand, M. Kummert, and B. T. Griffith. “Contrasting the capabilities of building energy performance simulation programs”. In: *Building and Environment* 43.4 (2008), pp. 661–673. ISSN: 03601323. DOI: `10.1016/j.buildenv.2006.10.027`.

[429] C. M. M. M. *CasaNova, a low energy quarter*. eng. 2008.

[430] B. S. Reddy and P. Balachandra. “Climate change mitigation and business opportunities - the case of the household sector in India”. In: *Energy for Sustainable Development* 10.4 (2006), pp. 59–73. ISSN: 09730826. DOI: `10.1016/S0973-0826(08)60556-6`. URL: `http://dx.doi.org/10.1016/S0973-0826(08)60556-6`.

[431] H. J. C. J. J.C. *Technology evaluation of thermal destratifiers and other energy-saving technologies*. eng. 2006.

[432] H. J. C. J. J.C. *Technology evaluation of oil-free compressors and thermal destratifiers*. eng. 2005.

[433] R. De Vos. “Harmonizing RE”. In: *Refocus* 6.5 (2005), pp. 58–59. ISSN: 14710846. DOI: `10.1016/S1471-0846(05)70464-9`.

[434] A. Der Minassians, K. H. Aschenbach, and S. R. Sanders. “Low-cost distributed solar-thermal-electric power generation”. In: *Nonimaging Optics: Maximum Efficiency Light Transfer VII* 5185.January 2004 (2004), p. 89. ISSN: 0277786X. DOI: `10.1117/12.509785`.

[435] Y. J. J. J. *Drying of wood chips as a supplementary business of energy co-operatives*. eng. 2004. ISBN: 03579387.

[436] M. Alam, A. Rahman, and M. Eusuf. “Diffusion potential of renewable energy technology for sustainable development: Bangladeshi experience”. In: *Energy for Sustainable Development* 7.2 (2003), pp. 88–96. ISSN: 09730826. DOI: `10.1016/S0973-0826(08)60358-0`. URL: `http://dx.doi.org/10.1016/S0973-0826(08)60358-0`.

[437] K. V. Murthy, G. D. Sumithra, and A. K. Reddy. “End-uses of electricity in households of Karnataka state, India”. In: *Energy for Sustainable Development* 5.3 (2001), pp. 81–94. ISSN: 09730826. DOI: `10.1016/S0973-0826(08)60278-1`. URL: `http://dx.doi.org/10.1016/S0973-0826(08)60278-1`.

[438] P. Henderick and R. H. Williams. “Trigeneration in a northern Chinese village using crop residues”. In: *Energy for Sustainable Development* 4.3 (2000), pp. 26–42. ISSN: 09730826. DOI: `10.1016/S0973-0826(08)60251-3`. URL: `http://dx.doi.org/10.1016/S0973-0826(08)60251-3`.

[439] M. W. H. W. W.H. *SOLAR COMMUNITY - ENERGY FOR RESIDENTIAL HEATING, COOLING, AND ELECTRICAL POWER*. eng. 1974. ISBN: 02784017.

[440] M. Dombi, I. Kuti, and P. Balogh. “Sustainability assessment of renewable power and heat generation technologies”. In: *Energy Policy* 67 (2014), pp. 264–271. ISSN: 0301-4215. DOI: `10.1016/j.enpol.2013.12.032`. URL: `http://dx.doi.org/10.1016/j.enpol.2013.12.032`.

[441] “Solar PV cost update Department of Energy & Climate Change Solar PV cost update”. In: May (2012).

[442] U. Kingdom. “Heat Pump Implementation Scenarios until 2030 Heat Pump Implementation Scenarios until 2030 An analysis of the technology ’ s potential in the building”. In: ().

[443] V. N. V. A. Report. “Fossil-free within one generation”. In: (2019).

[444] J. Gerdes and R. Segers. “fossiel energiegebruik en het rendement van elektriciteit in Nederland”. In: September (2012).

[445] R. McKenna, L. Hofmann, E. Merkel, W. Fichtner, and N. Strachan. “Analysing socioeconomic diversity and scaling effects on residential electricity load profiles in the context of low carbon technology uptake”. In: *Energy Policy* 97 (2016), pp. 13–26. ISSN: 03014215. DOI: `10.1016/j.enpol.2016.06.042`. URL: `http://dx.doi.org/10.1016/j.enpol.2016.06.042`.

# A

## A.1. OVERVIEW OF DOCUMENTS

Table A.1.: Thermal energy community literature .

Begin of Table

| Study | Year | Publication | H/E | Approach | | | Source |
|---|---|---|---|---|---|---|---|
| | | | | D | F | C | |
| [172] | 2020 | Journal of Cleaner Production | H/E | X | | | SET |
| [399] | 2020 | Sustainable Energy, Grids and Networks | H | | | X | SET |
| [244] | 2020 | IEEE Transactions on Smart Grid | H/E | | X | X | Electricity, PV, storage |
| [238] | 2020 | Energies | H | X | X | X | Electricity/ air conditioning |
| [216] | 2020 | Green Energy and Technology (book chapter)/ 7th Global Conference on Global Warming | H/E | X | | X | RET, geo, PVT, wind |
| [147] | 2020 | Green Energy and Technology (book chapter) | H | X | | | RET |
| [400] | 2020 | Energy for Sustainable Development | H | | X | | All |
| [217] | 2020 | Energies | H | | X | X | Geothermal |
| [188] | 2020 | Renewable Energy | H/E | | X | X | RETs |
| [178] | 2020 | Energy for Sustainable Development | H/E | X | | X | PV and collector |
| [247] | 2020 | Physics and Chemistry of the Earth | H | | X | | Solar |
| [239] | 2020 | Energy for Sustainable Development | H | | X | X | All |

Continuation of Table A.1

| Study | Year | Publication | H/E | Approach |  |  | Source |
|---|---|---|---|---|---|---|---|
|  |  |  |  | D | F | C |  |
| [401] | 2020 | Energy | H/E | X | X | X | Sustainable |
| [211] | 2020 | Energy for Sustainable Development | H |  | X | X | Bio |
| [261] | 2019 | IEEE conference on Energy Internet and Energy System Integration | H/E | X |  | X | All |
| [229] | 2019 | Applied Energy | H/E | X | X | X | All |
| [9] | 2019 | Energies | H/E | X |  | X | Electricity, PV, electric vehicle, heat pump, storage |
| [196] | 2019 | Energy | H/E |  | X | X | Solar, HP, storage, district heating |
| [173] | 2019 | IEEE Transactions on Industry Applications | H/E |  |  | X | Electricity |
| [150] | 2019 | Solar Energy | H/E | X |  | X | Solar, storage, PV, collector |
| [402] | 2019 | Energy Conversion and Management | H/E | X |  | X | Electricity, solar, electric vehicles, storage |
| [174] | 2019 | 2019 IEEE Energy Conversion Congress and Exposition | H/E | X |  | X | Solar, electricity |
| [113] | 2019 | Renewable and Sustainable Energy Reviews | H | X | X |  | Biomass district heating |
| [197] | 2019 | ASME 2019 13th International Conference on Energy Sustainability | H |  | X | X | Solar thermal |
| [202] | 2019 | IEEE Transactions on Industry Applications | H/E | X | X | X | Solar, heat pump, storage |

Continuation of Table A.1

| Study | Year | Publication | H/E | Approach | | | Source |
|---|---|---|---|---|---|---|---|
| | | | | D | F | C | |
| [258] | 2019 | IEEE Sustainable Power and Energy Conference: Grid Modernization for Energy Revolution | H/E | | X | X | HP, storage, electricity |
| [235] | 2019 | Applied Energy | H/E | X | | X | PV, HP, gas |
| [236] | 2019 | IEEE Transactions on Smart Grid | H/E | | | X | PV, HP, electricity, storage |
| [218] | 2019 | Sustainable Cities and Society | H/E | | X | X | PV, solar thermal, geothermal, storage |
| [221] | 2019 | Renewable and Sustainable Energy Reviews | H/E | | X | X | Solar, HP |
| [212] | 2019 | Energy Policy | H | | X | X | Bio |
| [198] | 2019 | Energy for Sustainable Development | H | | | X | Solar |
| [403] | 2019 | Energy for Sustainable Development | H | | X | | Bio |
| [262] | 2019 | International Journal of Critical Infrastructures | H/E | X | X | | Waste to energy |
| [176] | 2019 | Dianli Xitong Zidonghua/Automation of Electric Power Systems | H/E | | X | X | Efficiency and all together |
| [404] | 2019 | Dianwang Jishu/Power System Technology | H/E | X | | X | All |
| [226] | 2019 | Innovative Smart Grid Technologies Asia | H/E | | | X | All |
| [231] | 2019 | Energy for Sustainable Development | H | X | X | X | Bio |
| [213] | 2019 | Energy for Sustainable Development | H | X | X | X | Building consumption |
| [232] | 2019 | Energy for Sustainable Development | H/E | | | X | Electricity |
| [405] | 2019 | Energy for Sustainable Development | H/E | | X | X | Electricity / solar |

Continuation of Table A.1

| Study | Year | Publication | H/E | Approach | | | Source |
|---|---|---|---|---|---|---|---|
| | | | | D | F | C | |
| [199] | 2019 | Sustainable Energy Technologies and Assessments | H/E | | X | X | Solar + gas/CHP |
| [177] | 2018 | Energy Efficiency | H | X | X | X | Energy efficiency |
| [228] | 2018 | 2018 IEEE International Conference on Environment and Electrical Engineering | H/E | X | | X | SET |
| [184] | 2018 | 2018 IEEE International Conference on Environment and Electrical Engineering | H/E | X | | X | SET |
| [406] | 2018 | ASHRAE Conference-Papers | H/E | X | X | | SET |
| [267] | 2018 | Energy Procedia | H/E | X | X | X | SET |
| [249] | 2018 | Energy Research and Social Science | H/E | X | X | | Electricity |
| [183] | 2018 | Energy for Sustainable Development | H | X | | X | RET and efficiency |
| [181] | 2018 | Energy for Sustainable Development | H/E | | X | X | RET |
| [407] | 2018 | Energy for Sustainable Development | H/E | X | | X | Electricity |
| [408] | 2018 | Energy | H/E | | X | X | Seawater Pumped Hydro Storage system |
| [293] | 2018 | Dianli Xitong Zidonghua/Automation of Electric Power Systems | H/E | | | X | Integrated, probably solar |
| [243] | 2018 | Energy for Sustainable Development | H/E | X | | X | All |
| [237] | 2018 | Energy for Sustainable Development | H/E | | | X | RET/Battery/vehicle |
| [409] | 2017 | IOP Conference Series: Earth and Environmental Science | H/E | X | | | All |

Continuation of Table A.1

| Study | Year | Publication | H/E | Approach | | | Source |
|---|---|---|---|---|---|---|---|
| | | | | D | F | C | |
| [270] | 2017 | 2017 IEEE Manchester PowerTech | H/E | X | | X | hot water, base electricity, space heating/cooling), thermal and electrical energy storage, and solar photo-voltaic generation |
| [191] | 2017 | Computers and Chemical Engineering | H | X | | X | Solar, storage |
| [410] | 2017 | IEEE Technology and Society Magazine | H/E | | X | | RET |
| [214] | 2017 | Energy for Sustainable Development | H | X | X | | Bio |
| [240] | 2017 | Energy for Sustainable Development | H | | X | X | Efficiency, RET |
| [271] | 2017 | Energy for Sustainable Development | H | X | X | | F.F. |
| [192] | 2017 | Energy for Sustainable Development | H | | | X | Solar |
| [200] | 2017 | ISES Solar World Congress 2017 | H/E | | X | | Solar |
| [204] | 2017 | Energy for Sustainable Development | H | X | X | | Bio, waste |
| [175] | 2017 | World Sustainability Series (book chapter) | H/E | | X | X | Electricity |
| [187] | 2016 | Energy for Sustainable Development | H | | X | X | Bio |
| [170] | 2016 | Energy for Sustainable Development | H/E | | X | | Electrical heating |
| [193] | 2016 | Energy for Sustainable Development | H | X | | | Solar |
| [241] | 2016 | Energy for Sustainable Development | H | | X | X | Solar, efficiency |

Continuation of Table A.1

| Study | Year | Publication | H/E | Approach | | | Source |
|---|---|---|---|---|---|---|---|
| | | | | D | F | C | |
| [257] | 2016 | Journal of Settlements and Spatial Planning | H | X | X | | District heating |
| [411] | 2016 | Progress in Photovoltaics: Research and Applications | H/E | | X | X | Solar PV |
| [205] | 2015 | 5th International Conference on Industrial Engineering and Operations Management | H | | X | X | Biogas |
| [265] | 2015 | Applied Energy | H/E | X | | X | PV, collector, fuel cell |
| [252] | 2015 | Conference on Human Factors in Computing Systems | H/E | X | X | | Building consumption |
| [412] | 2015 | 2015 European Control Conference | H/E | | X | X | Electricity |
| [157] | 2015 | Energy for Sustainable Development | H | | X | X | Bio |
| [222] | 2015 | Energy for Sustainable Development | H/E | | | X | Solar, CHP |
| [179] | 2015 | IEEE Innovative Smart Grid Technologies | H/E | | | X | Electricity from grid |
| [206] | 2015 | Energy for Sustainable Development | H | X | | | Bio |
| [210] | 2015 | Energy for Sustainable Development | H | | X | | Bio |
| [171] | 2015 | Energy for Sustainable Development | H/E | | X | X | Electricity, gas |
| [413] | 2014 | Applied Energy | H/E | | X | X | CHP |
| [414] | 2014 | ASHRAE Transactions | H/E | | X | | RET |
| [415] | 2014 | Energy for Sustainable Development | H/E | X | | X | All |
| [201] | 2014 | Energy for Sustainable Development | H | | X | X | Technical design |

Continuation of Table A.1

| Study | Year | Publication | H/E | Approach | | | Source |
|---|---|---|---|---|---|---|---|
| | | | | D | F | C | |
| [416] | 2014 | ASHRAE Transactions | H | | X | X | biomass-fired boiler and a number of decentralized solar thermal facilities, district heating |
| [151] | 2014 | Applied Energy | H/E | | X | X | Solar PV |
| [269] | 2014 | Fusion Engineering and Design | H | | | X | Pure technical |
| [207] | 2013 | International Journal of Thermodynamics | H | | | X | Bio, waste, CHP, solar |
| [219] | 2013 | Energy for Sustainable Development | H | X | X | | Solar |
| [417] | 2013 | Energy for Sustainable Development | H/E | X | | | RETs |
| [418] | 2013 | Transactions of the Korean Institute of Electrical Engineers | E | | | X | Pure electricity |
| [180] | 2013 | Energy for Sustainable Development | H | | X | | All |
| [194] | 2012 | Energy for Sustainable Development | H | | X | X | Solar |
| [208] | 2012 | Energy for Sustainable Development | H/E | X | X | | Bio with CHP |
| [230] | 2012 | 11th International Conference on Environment and Electrical Engineering | H/E | | X | X | RET |
| [419] | 2012 | 11th International Conference on Environment and Electrical Engineering | H/E | | X | X | RET |
| [152] | 2012 | Energy Procedia | H | | | X | Solar, storage |

Continuation of Table A.1

| Study | Year | Publication | H/E | Approach |  |  | Source |
|---|---|---|---|---|---|---|---|
|  |  |  |  | D | F | C |  |
| [209] | 2012 | 25th International Conference on Efficiency, Cost, Optimization and Simulation of Energy Conversion Systems and Processes | H |  |  | X | Bio, waste, CHP, solar |
| [268] | 2012 | ASME Design Engineering Technical Conference | H/E |  |  | X | All |
| [195] | 2011 | Journal of Solar Energy Engineering, Transactions of the ASME | H/E |  | X | X | Solar |
| [224] | 2011 | Energy for Sustainable Development | H |  | X |  | Bio |
| [182] | 2011 | Energy for Sustainable Development | H/E | X |  | X | All |
| [419] | 2011 | 2011 Conference on Smart Materials, Adaptive Structures and Intelligent Systems | H/E | X |  |  | RET |
| [223] | 2011 | 24th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems | H | X |  |  | Solar |
| [420] | 2011 | Energy for Sustainable Development | H/E | X |  | X | RETs for Electricity, wind, PV, Solar thermal |
| [421] | 2010 | 4th International Conference on Energy Sustainability | H |  | X | X | Wastewater, HP |
| [422] | 2009 | 3rd International Conference on Energy Sustainability | H |  | X | X | RET |
| [186] | 2009 | Utilities Policy | H/E |  | X | X | Electricity |

Continuation of Table A.1

| Study | Year | Publication | H/E | Approach D | F | C | Source |
|---|---|---|---|---|---|---|---|
| [423] | 2009 | Energy for Sustainable Development | H/E | X | X |  | Solar |
| [424] | 2009 | Biomass and Bioenergy | H |  | X | X | Bio |
| [227] | 2009 | 42nd Annual Hawaii International Conference on System Sciences | H/E |  | X | X | Solar, electric vehicle, storage |
| [425] | 2008 | Solar Hydrogen Generation: Toward a Renewable Energy Future | H/E | X |  |  |  |
| [426] | 2008 | Towards Zero Energy Building: 25th PLEA International Conference on Passive and Low Energy Architecture | H |  | X | X | Sustainable sewage system, a waste treatment and food production systems |
| [427] | 2008 | Energy for Sustainable Development | H |  |  | X | heating systems |
| [220] | 2008 | Energy for Sustainable Development | H | X |  |  | Bio |
| [263] | 2008 | Energy for Sustainable Development | H/E |  | X |  | All |
| [428] | 2008 | Building and Environment | H | X |  |  | Heating systems inside the buildings |
| [234] | 2008 | 25th PLEA International Conference on Passive and Low Energy Architecture | H |  | X | X | RET |
| [429] | 2008 | 25th PLEA International Conference on Passive and Low Energy Architecture | H | X | X |  | RET and district |
| [242] | 2007 | 36th ASES Annual Conf. | H/E |  | X | X | Solar, efficiency |
| [430] | 2006 | Energy for Sustainable Development | H/E | X | X |  | All |
| [431] | 2006 | World Energy Engineering Congress | H/E | X | X |  | All |

Continuation of Table A.1

| Study | Year | Publication | H/E | Approach |  |  | Source |
|---|---|---|---|---|---|---|---|
|  |  |  |  | D | F | C |  |
| [432] | 2005 | World Energy Engineering Congress | H/E | X | X |  | All |
| [225] | 2005 | Energy for Sustainable Development | H/E |  | X |  | Bio |
| [433] | 2005 | Refocus | H/E | X |  |  | RET |
| [434] | 2004 | The International Society for Optical Engineering | H/E | X |  | X | Solar |
| [435] | 2004 | VTT Symposium (Valtion Teknillinen Tutkimuskeskus) | H | X |  | X | Bio |
| [185] | 2004 | Energy for Sustainable Development | H/E | X | X |  | Bio |
| [436] | 2003 | Energy for Sustainable Development | H/E | X | X |  | RETs |
| [437] | 2001 | Energy for Sustainable Development | H/E | X | X |  | Electricity |
| [438] | 2000 | Energy for Sustainable Development | H/E |  |  | X | Bio/CHP |
| [439] | 1974 | energy Symp, Energy Delta/Supply vs Demand, 140th Annu Meet of Am Assoc for Adv of Sci | H/E | X |  | X | Solar |

End of Table

Table A.2.: The list of dominating topics of 134 documents .

Begin of Table

| Dominating topics: “common repeated words” | Occurrences | Total link |
|---|---|---|
| Heating | 45 | 351 |
| Energy efficiency | 33 | 248 |
| Energy utilization | 28 | 206 |
| Renewable energy resources | 23 | 194 |
| Energy conservation | 20 | 163 |
| Solar power | 16 | 154 |
| Energy policy | 13 | 142 |
| Electricity generation | 14 | 138 |
| Housing | 13 | 124 |
| Sustainable development | 15 | 124 |

Continuation of Table A.2

| Dominating topics: “common repeated words” | Occurrences | Total link |
|---|---|---|
| Renewable energies | 13 | 121 |
| Investments | 14 | 119 |
| Photovoltaic system | 10 | 107 |
| Alternative energy | 11 | 106 |
| Energy storage | 14 | 103 |
| Solar water heaters | 10 | 103 |
| Biomass | 11 | 102 |
| Carbon dioxide | 9 | 100 |
| Gas emissions | 9 | 98 |
| Emission control | 7 | 97 |
| Heat storage | 13 | 95 |
| Greenhouse gases | 7 | 94 |
| Energy use | 13 | 92 |
| Commerce | 10 | 90 |
| Costs | 12 | 90 |
| Solar heating | 10 | 89 |
| Solar energy | 15 88 | |
| Water heaters | 9 | 84 |
| Climate change | 8 | 81 |
| Renewable resource | 8 | 81 |
| Economics | 10 | 80 |
| District heating | 10 | 78 |
| Solar water heating | 7 | 77 |
| Hot water distribution systems | 7 | 76 |
| Renewable energy technologies | 7 | 72 |
| Carbon emission | 6 | 71 |
| Electric power transmission network | 10 | 68 |
| Greenhouse gas | 5 | 68 |
| Economic analysis | 9 | 67 |
| Fuels | 9 | 66 |
| Household energy | 7 | 66 |
| Energy resource | 7 | 64 |
| Electric energy storage | 8 | 61 |
| Cooling | 8 | 60 |
| Heating equipment | 8 | 59 |
| Renewable energy | 6 | 59 |
| Thermal power | 6 | 58 |
| Combined heat and power | 6 | 56 |
| Optimization | 9 | 56 |
| Buildings | 6 | 55 |
| Energy market | 5 | 55 |
| Thermal energy | 5 | 55 |

Continuation of Table A.2

| Dominating topics: "common repeated words" | Occurrences | Total link |
|---|---|---|
| Sustainability | 7 | 54 |
| Combustion | 6 | 53 |
| Power generation | 5 | 53 |
| Fossil fuels | 6 | 52 |
| South Africa | 6 | 52 |
| Natural gas | 6 | 51 |
| Domestic hot water | 5 | 50 |
| Rural areas | 7 | 50 |
| Smart grid | 6 | 49 |
| Smart power grids | 6 | 47 |
| Digital storage | 5 | 46 |
| Renewable energy source | 6 | 46 |
| Residential energy | 5 | 45 |
| Solar collectors | 6 | 45 |
| Environmental impact | 8 | 44 |
| Residential building | 5 | 44 |
| Solar power generation | 5 | 44 |
| Electric power generation | 5 | 42 |
| Energy resources | 5 | 41 |
| Natural resources | 5 | 41 |
| Atmospheric pollution | 5 | 40 |
| Cost benefit analysis | 6 | 38 |
| Intelligent buildings | 6 | 38 |
| Modeling | 5 | 37 |
| Photovoltaic cells | 6 | 37 |
| Water | 5 | 37 |
| Cooling systems | 5 | 35 |
| Solar radiation | 6 | 32 |
| Air conditioning | 5 | 31 |
| Integer programming | 7 | 29 |
| Cooking appliance | 5 | 28 |
| Biogas | 6 | 26 |
| Design | 6 | 26 |
| Energy systems | 5 | 25 |
| Heat pump systems | 5 | 25 |
| Multi-energy systems | 5 | 25 |
| Multi energy | 5 | 23 |
| Heating system | 5 | 18 |

End of Table

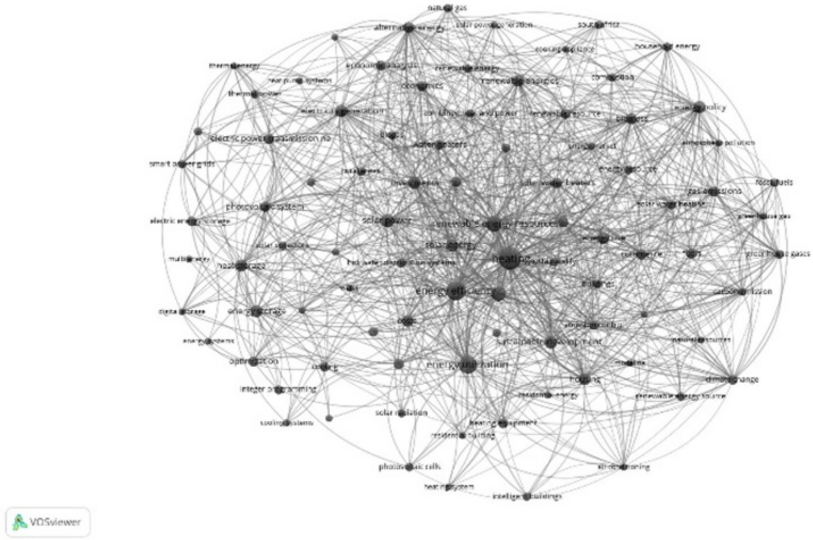


Figure A.1.: Dominating topics of 134 documents

# B

## B.1. HOUSEHOLDS ATTRIBUTES

The calculations for the households' decision to join TEC initiatives are presented as follows:

### B.1.1. DRIVERS TO JOIN

The four key values that influence a person's degree of participation in a community energy system, which are included in the model, are: environmental concern, financial concern, energy independence concern, and sense of community. The survey conducted in [58] asked respondents to rate the environmental and socio-economic drivers using Likert-type scales with 7 points. The results for four of the drivers included in this survey was used as input for the values held by the households in the model (see Table B.1).

Table B.1.: Mean and standard deviation values for drivers used to model the values system of households in the model

| | Drivers | Mean | SD | Scale |
|---|---|---|---|---|
| Environmental | Good for the environment | 5.45 | 1.55 | 7-point |
| Socio-economic-institutional | Economic benefits | 5.19 | 1.54 | 7-point |
| | Sense of community | 3.80 | 1.72 | 7-point |
| | Independence of national grid | 3.62 | 1.87 | 7-point |

Since the survey was done on a scale of 7 points, the information was first calibrated for a 10-point scale to fit the data input for the model. Then, the information on the mean and standard deviation were inputted in an online tool to produce a normal distribution dataset. The tool produced a dataset of 100 values ranging from 1 to 10 which was then visualised as a histogram. The histogram presented the results by frequency of responses for each point in the scale. Finally, the information on the histogram was used to create Table B.2. The information on this table was used to assign a value to each household for each value type.

Table B.2.: Percentage of the neighbourhood population that is initially related to each point in the scale for each value type

| Scale | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Environmental concern | - | 1 | 2 | 3 | 10 | 13 | 11 | 10 | 13 | 37 | 100 |
| Economic concern | 1 | 1 | 4 | 8 | 10 | 15 | 20 | 10 | 16 | 15 | 100 |
| Independence concern | 9 | 9 | 10 | 13 | 13 | 16 | 14 | 7 | 5 | 4 | 100 |
| Sense of community | 6 | 6 | 10 | 16 | 17 | 15 | 14 | 8 | 4 | 4 | 100 |

### **B.1.2.** HOUSEHOLD SVO

Once every household in the neighbourhood has been assigned a value for each value type, the social value orientation (SVO) of the household is calculated. The two-stage classification method was used to classify the households into one of the four social value orientation groups (altruistic, cooperative, individualistic, competitive) [97]. The overall drive to join the community is calculated using the following expression in:

$$\delta drive = S_{environment} + S_{senseof\ community} - (S_{economic\ concern} + S_{independence\ concern}) \tag{B.1}$$

The first stage was to identify the households that fall under the altruistic and the individualistic social value orientation. For that, it is assumed that the altruistic households are those who place a higher value to the environmental concern and sense of community ($\delta$drive > 1). As opposed to the more individualist households that score higher in the financial and energy independence concern ($\delta$drive < -1).

However, those individuals whose final score ($\delta$drive) is close to 0 (-1≤ $\delta$drive ≤1), move onto the second stage of the classification method. For these, the focus is how high they score in the sense of community driver. Those with a score lower than 5 will be classified under the competitive SVO and those that score higher than 5 under the cooperative SVO.

The results shown in Table B.3 indicate that most of the households have a more prosocial orientation (62%) and most of the households fall under the altruistic and individualist group (92%).

Table B.3.: Example of initial SVO distribution for an average Dutch neighbourhood, given the model output

| | SVO 1 (Altruistic) | SVO 2 (Cooperative) | SVO 3 (Individualistic) | SVO 4 (Competitive) |
|---|---|---|---|---|
| Neighbourhood-share (%) | 58 | 4 | 34 | 4 |

### B.1.3. PAY-BACK TIME (PBT) & WILLINGNESS TO PAY (WTP)

Based on the SVO group each household falls into, the household is assigned a specific expected payback time period. Following [388] line of reasoning, which is that the more an individual has a pro-social value orientation, the higher they will be willing to invest. Additionally, the results from [58] survey that [97] prepared, substantiated this assumption. Table B.4 shows the range of PBT period linked to each SVO category. For instance, a household that falls under the SVO 1 will be assigned an expected PBT of between 15 to 20 years.

Table B.4.: Example of initial SVO distribution for an average Dutch neighbourhood, given the model output

| | SVO 1 (Altruistic) | SVO 2 (Cooperative) | SVO 3 (Individualistic) | SVO 4 (Competitive) |
|---|---|---|---|---|
| Expected PBT | 15-20 | 10-15 | 5-10 | 1-5 |

Based on this expected PBT, assigned to each household, a limit to how much the household is willing to invest (WTP) in the thermal energy community is then calculated. The following equations explain how this attribute is calculated. The willingness to invest is calculated based on the accumulated savings the household will make during the time period of their PBT. The accumulated savings are calculated by the sum of the difference between what the household would pay in the reference scenario and what they expect to pay in the new technology scenario, based on the expected annual gas and heat price. In the model, the household has the information on the current gas price and the expected gas price increase for the 10-year period. The heat price is assumed not to vary throughout time.

$$\text{Willingness to invest(WTP)} = \sum_{i=1}^{PBT} (\text{gas cost}_{(r,i)} - \text{heat costs}_i) \tag{B.2}$$

where

$$\begin{aligned} \text{gas cost}_{(r,i)} &= \text{heat demand}_r \times \text{gas price}_i \\ \text{heat costs}_i &= \text{heat demand}_i \times \text{heat price}_i \end{aligned} \tag{B.3}$$

### B.1.4. $CO_2$ EMISSIONS

Another important attribute of each household is the amount of $CO_2$ emissions related to the heat consumption emitted per year. Equation 1 shows the way in which this is calculated. The calculation of the $CO_2$ intensity, is presented in:

$$\begin{aligned} CO_2 \text{ emissions}_{HH} = &\text{heat demand}_{collective} \times CO_{2(int,collect)} \\ &+ \text{heat demand}_{individual} \times CO_{2(int,ind)} \end{aligned} \tag{B.4}$$

### B.1.5. OTHER PARAMETERS

Table 16 shows other important attributes that are assigned to the households.

Table B.5.: Other variables assigned to households in the model

| Parameter | Value | Unit |
|---|---|---|
| Heat demand | 13500 | kWh/year |
| Insulation heat demand reduction | 50 | % |
| Space heating share | 0.835 | |
| Hot water share | 0.165 | |

## B.2. ARRANGEMENT OF THE NEIGHBOURHOODS

### B.2.1. NUMBER OF NEIGHBOURHOODS & NUMBER OF HOUSEHOLDS

When developing the parameter of how many neighbourhoods should be included in what the model is representing as one municipality in the Netherlands, the focus was on estimating the average number of neighbourhoods per municipality that are expected to be disconnected from the gas grid by 2030.

The Netherlands Environment Assessment Agency (PBL) concluded that the measures proposed in the Climate Accord published on 13 March, 2019 would result in some 250,000 to 1,070,000 buildings being made ‘gas-free’. However, the target is for 1.5 million buildings. With the information of the number of municipalities in the Netherlands (277) and assuming there is an average of 1440 inhabitants per neighbourhood [330], and 2.17 inhabitants per household (CBS), the number of neighbourhoods per municipality that should make the transmission from gas can be estimated (Equation 4). The calculation results in an average of 664 households per neighbourhood and a range of between 1.19 and 5.08 neighbourhoods, using the proposed measures, with 7.11 neighbourhoods being the target.

$$\frac{\text{Number neighbourhoods off gas}}{\text{municipality}} = \frac{\text{households off gas}}{\text{municipality}} \div \frac{\text{households}}{\text{neighbourhood}} \tag{B.5}$$

$$\frac{\text{Number neighbourhoods off gas}}{\text{municipality}} = \frac{\text{households off gas}}{\text{municipality}} \div \frac{\text{households}}{\text{neighbourhood}} \tag{B.6}$$

$$\frac{\text{households off gas}}{\text{municipality}} = \frac{\text{gas free buildings}}{\text{municipality}} \times \text{share residential stock} \tag{B.7}$$

$$\frac{\text{households}}{\text{neighbourhood}} = \frac{\text{inhabitants}}{\text{neighbourhood}} \div \frac{\text{inhabitants}}{\text{household}} \tag{B.8}$$

As a result, the decision was made to model one neighbourhood as 660 households and run the model for a number of neighbourhoods per municipality, ranging from 1 to 7, to consider the scenarios with the current policies and the target for 2030, and to be able to analyse whether the most suitable institutional conditions vary across municipality sizes. Therefore, three municipality sizes will be included in the experimentation: 1, 3 and 7 neighbourhoods.

### B.2.2. NEIGHBOURHOOD STRUCTURE AND DYNAMICS

The structure for the small world network of the neighbourhoods and the interactions between the households has been modelled by replicating and adapting the network generated by the "small worlds" model found in Netlogo library. This model is an adaptation of a model proposed by [332]. It begins with a network where each household (node) is connected to its two neighbours on either side. Then, with every time step, which corresponds to one month, 10% of the nodes rewire one of their edges to connect with a different node. After rewiring, the households involved in the interactions will update their value systems leaning towards that of the neighbour's opinion. Since the household's SVO depends on its value systems, this might also be altered as a result of these neighbourhood interactions.

### B.2.3. SHARE OF NEIGHBOURHOOD

This attribute relates to the minimum share of the neighbourhood that needs to find consensus over each decision in the model before being able to move to the next stage. The PAW subsidy website states that the feasibility studies, presented as part of the subsidy application, should take into consideration the participation of all the households in the neighbourhood. However, from conversations with experts, it was concluded that it is improbable that this will be achieved and that in practice, municipalities are having conversations with any neighbourhood willing to start a TEC project regardless of the initial neighbourhood participation levels. Since there is not a clear understanding of where to draw the line in this attribute, a sensitivity analysis was conducted to give this attribute a specific value.

The sensitivity analysis was conducted following the OFAT (one-factor-at-a-time) approach [349, 351]. All the parameters were fixed at a certain value and only the value of the study was altered. For each parameter the model was run 30 times. The amount of $CO_2$ emissions avoided per neighbourhood and the share of households connected at a municipality level were gathered as the output to determine the attribute's value. These were considered to be the most important KPIs out of the nine KPIs developed since they account for both the sustainability and acceptability of the thermal energy project.

A first sensitivity analysis was conducted for a range between 0 and 1 in steps of 0.2. However, it was observed that after 0.4, the average share was 0. As a result, a second sensitivity analysis for a range between 0 and 0.5 in steps of 0.1 was done. Figure B.1 and Figure B.2 show the outcome of the sensitivity analysis for the indicators of $CO_2$ emissions avoided per neighbourhood and the share of households in the municipality connected to the district heating network. On the x-axis the figures show the parameter ranges (0-0.5) and on the y axis the two outcomes of the sensitivity analysis. Each box represents the range in the results and the black line the mean for each parameter value.

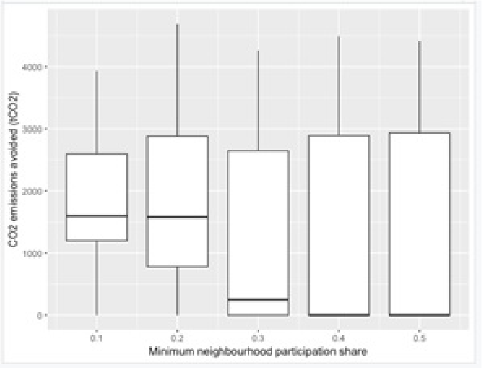


Figure B.1.: Sensitivity analysis outcome for the share of the neighbourhood ($C0_2$ emission reduction)

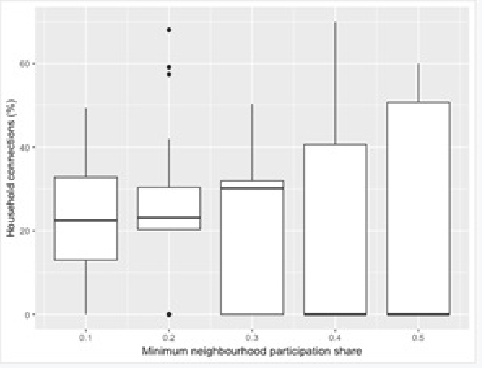


Figure B.2.: Sensitivity analysis outcome for the share of the neighbourhood (household participation)

The results show that when the minimum neighbourhood share is set higher than 0.3, few neighbourhoods reach the set-up phase. However, between the other two values, 0.1 and 0.2, the conclusion is not as straightforward. On the one hand, the average and maximum $CO_2$ emissions avoided is higher when the minimum share is set at 0.1, yet, on the other hand, the average share of connections is higher when the share is set at 0.2. In the end, it was decided to leave the share at the minimum possible value (10% of the neighbourhood), since it's the one closer to the reality in the Netherlands.

### **B.2.4.** HOUSEHOLD INTERACTIONS IN NEIGHBOURHOOD

Research has previously been conducted which qualitatively studies the degree of involvement and participation of Dutch neighbours in their neighbourhood. However, when gathering quantitative information on the matter, little information was found. A survey conducted in the Netherlands with 2108 respondents asked participants to describe their level of household participation (see Figure B.3). The results, which are presented below, show that at least 4% of the neighbourhood is very active and involved in the neighbourhood and 24% are sometimes involved. Provided with this information, a sensitivity analysis was conducted to fix the parameter somewhere in the range of between 4% and 30%.

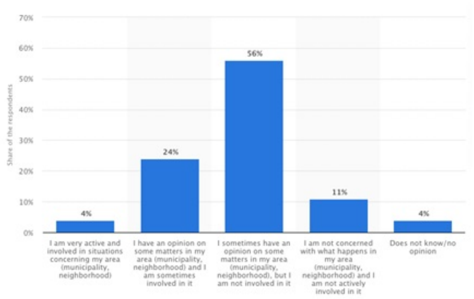
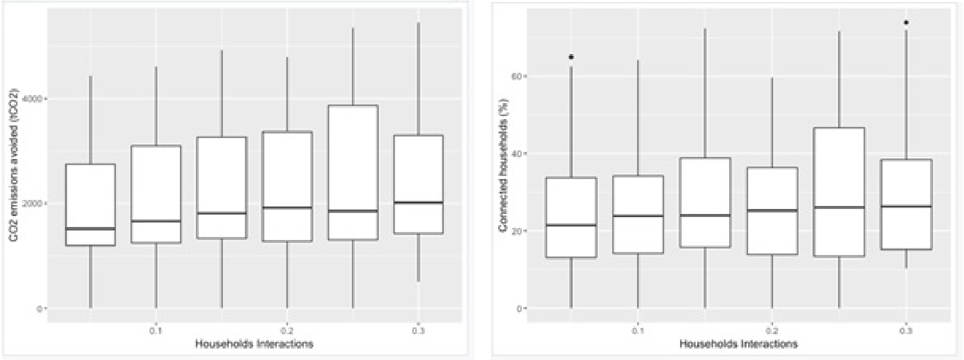


Figure B.3.: Neighborhood participation in the Netherlands

Figure B.4a and Figure B.4b, displaying the output from the sensitivity analysis, show that the projects are more successful when the interaction rate is 10% or higher. However, between 10% and 30%, the change in the indicators is not significant enough. Going back to the statistics gathered in [58], 10% of the neighbourhood seemed like a reasonable assumption for the model since it would include the 4% of highly involved neighbours and 25% of the ones that sometimes get involved.



(a) Sensitivity analysis outcome for household interactions ($CO_2$ emissions reduction)

(b) Sensitivity analysis outcome for household interactions (Household participation)

Figure B.4.: The sensitivity analyses results

## B.3. DISTRICT HEATING TECHNOLOGY

Table B.6.: District heating systems

| Type | Variable | Value | Units |
|---|---|---|---|
| MH/LH/VLH | Connection fee | 4500 | €/connection |
| | OPEX | 524 | €/year |
| | Lifetime | 40 | years |
| Insulation | Investment costs to achieve B-grade energy label | 10000 | € |

## B.4. DATA ON COLLECTIVE HEATING TECHNOLOGY

Table B.7.: Collective bio-energy data

| Variable | Units | Bio-boiler (wood pellets) |
|---|---|---|
| Average capacity | kW | 950 |
| CAPEX | €/kW | 415 |
| OPEX fixed | €/kW | 25 |
| OPEX variable | €/kWh | 0.003 |
| Load hours | hour/year | 3000 |
| Electricity consumption | kWh/year | - |
| $CO_2$ emissions | kg/kWh | 0.26 |
| Lifetime | years | 20 |
| SDE++ subsidy | €/kWh | 0.03 |
| Subsidy time | year | 12 |
| Peak demand | % | 10 |
| Min required household | number | 50 |
| Land use | km2/kWh | 59,5 |
| Efficiency | % | 0,85 |

Table B.8.: Collective aqua-thermal energy storage (ATES) data

| Variable | Units | ATES |
|---|---|---|
| Average capacity | kW | 800 |
| CAPEX | €/kW | 2401 |
| OPEX fixed | €/kW | 113 |
| OPEX variable | €/kWh | 0.0019 |
| Load hours | hour/year | 3500 |
| Electricity consumption | kWh/year | 994000 |
| $CO_2$ emissions | kg/kWh | 0.152 |
| Lifetime | years | 30 |
| SDE++ subsidy | €/kWh | 0.08 |
| Subsidy time | year | 15 |
| Peak demand | % | 10 |
| Min required household | number | 50 |
| Land use | km2/kWh | 2.68 |

Table B.9.: Collective residual heat from surface water (TEA) data

| Variable | Units | TEA |
|---|---|---|
| Average capacity | kW | 1000 |
| CAPEX | €/kW | 2369 |
| OPEX fixed | €/kW | 170 |
| OPEX variable | €/kWh | 0.0019 |
| Load hours | hour/year | 6000 |
| Electricity consumption | kWh/year | 1935000 |
| $CO_2$ emissions | kg/kWh | 0.138 |
| Lifetime | years | 30 |
| SDE++ subsidy | €/kWh | 0.042 |
| Subsidy time | year | 15 |
| Peak demand | % | 10 |
| Min required household | number | 50 |
| Land use | km2/kWh | 3 |

Table B.10.: Collective heat pump data

| Variable | Units | Collective heat pump data |
|---|---|---|
| Average capacity | kW | 45 |
| CAPEX | €/kW | 848 |
| OPEX fixed | €/kW | 21 |
| OPEX variable | €/kWh | 0.015 |
| Load hours | hour/year | 8000 |
| Electricity consumption | kWh/year | - |
| $CO_2$ emissions | kg/kWh | 0.000 |
| Lifetime | years | 20 |
| SDE++ subsidy | €/kWh | 0.017 |
| Subsidy time | year | 15 |
| COP |  | 3.5 |
| Peak demand | % | 10 |
| Min required household | number | 50 |

## B.5. DATA ON INDIVIDUAL HEATING TECHNOLOGY

Table B.11.: Individual heat pump systems

| Variable | Value | Units |
|---|---|---|
| Min capacity (brine-water) | 0 | kW |
| Max capacity (brine-water) | 70 | kW |
| Average capacity | 1 | kW |
| CAPEX | 1770 | €/kW |
| OPEX | 35.4 | €/kW |
| $CO_2$ emissions | 0.14 | kg/kWh |
| Lifetime | 20 | years |
| COP | | 3 |
| Subsidy (SDE++) | 500 | € |
| Load hours | 1500 | hour/year |

Table B.12.: Individual solar thermal systems

| Variable | Value | Units |
|---|---|---|
| Average capacity | 2 | m2 |
| Generation | 540 | kWh/m2 |
| CAPEX | 1666 | €/kW |
| OPEX | 22,491 | €/kW |
| Load hours | 700 | hour/year |
| $CO_2$ emissions | 0.086 | kg/kWh |
| Lifetime | 30 | years |
| Subsidy (SDE++) | 0.678 | €/kWh |
| Subsidy (SDE++) | 732.24 | € |
| Electric water supply | 20 | % |

## B.6. ENVIRONMENTAL ATTRIBUTES AND OTHER DATA

Table B.13.: Data on environmental attributes and other data

| Variable | Value | Units |
|---|---|---|
| Gas price | 0.097 | €/kWh |
| Gas price increase | 0.003 | €/kWh/year |
| Heat price | 0.096 | €/kWh |
| Electricity price | 0.136 | €/kWh |
| Electricity price increase | 0.0014 | €/kWh/year |
| $CO_2$ price (ETS) | 22 | €/t $CO_2$ |
| $CO_2$ price growth | 2.5 | €/year |
| $CO_2$ price of 22 Euros: effect on natural gas price | 0.009 | €/kWh |
| Gas price increase with initial tax at 22 Euros | 0.001022727 | €/kWh/year |
| Ticks | 1 | month |
| Total duration of model | 10 | year |
| $CO_2$ emissions (gas) | 0.2 | kg/kWh |
| $CO_2$ emissions (electricity) | 0.429 | kg/kWh |
| $CO_2$ emissions (biomass) | 0.225 | kg/kWh |
| Conversion factor (gas to kWh) | 10 | kWh/m3 gas |

## B.7. VALUE-BASED MULTI-CRITERIA DECISION-MAKING PROCEDURE

The calculation regarding the criteria presented in Table 3.5 (Section 3.6.1 is presented as follows:

### B.7.1. FINANCIAL CRITERIA

The investment and maintenance costs were calculated by multiplying the capacity per household by the investment costs. The operating costs were calculated in the following way:

$$\text{Costs}_{main} = \text{Capex}_{tech} \times \text{Operating costs}_{fixed} + (\text{heat demand}) \times \text{Operating costs}_{var} \tag{B.9}$$

The payback time period of the technology was calculated by dividing the total costs for a period of 30 years by the savings:

$$\text{PBT}_{tech} = \frac{\text{total costs}}{\text{Annual energy cost savings}} = \frac{\text{invest}_{cost} + \text{operating}_{costs} \times 30}{\text{heat demand reduction}_{annual} \times \text{price}_{naturalgas}} \tag{B.10}$$

For the percentage of subsidy coverage, the following information on the SDE++ subsidy amount per technology, found in the reports published by PBL, were used:

The share was calculated by dividing the total subsidy amount dispatched through the SDE++ subsidy scheme by the total cost of the technology throughout its lifetime, presented in Equation 7.

Table B.14.: Data input for subsidy coverage sub-criteria for each collective technology alternative

| | Units | Bio-boiler | ATES | TEA |
|---|---|---|---|---|
| Subsidy amount | €/kWh | 0.030 | 0.080 | 0.042 |
| Subsidy time | year | 12 | 15 | 15 |

$$\text{Subsidy}_{coverage} = \frac{\text{total subsidy}}{\text{total costs}} = \frac{\text{heat demand} + \text{subsidy}_{SDE++} \times \text{subsidy time}}{\text{investment}_{costs} + \text{operating}_{costs} \times \text{lifetime}} \quad \text{(B.11)}$$

### B.7.2. ENVIRONMENTAL CRITERIA

The annual $CO_2$ emissions per household were calculated by multiplying the intensity of the $CO_2$ emissions of the technologies by the annual household heat demand.

The data for the second environmental sub-criteria - land use - was taken from the study conducted on the sustainability assessment of renewable power and heat generation technologies [440]. They describe land use as the “amount of technological demand on land used for agricultural, forestry or nature conservation purposes”. Information for the land demand of a district heating system connected to a wastewater treatment plant was not found and it was then assumed to be similar to that of the ATES system (see Table B.15).

Table B.15.: Data input for land use sub-criteria for collective technology alternatives

| | Bio-boiler | ATES | TEA |
|---|---|---|---|
| Land demand (km^2/kWh) | 59.5 | 2.68 | No info |

For the third environmental criteria - awareness of the technology - a more qualitative assessment was done. As discussed in Section 3.1 and Section 3.2, there are studies that focus on the social aspects and the interactions of stakeholders of energy communities. In the model, it is assumed that: the more a heating technology has been used in a sustainable heating project, the more easily accepted it will be by an actor, and the higher it will score in the awareness sub-criteria. The technologies are given a score from 1 to 10 on how aware Dutch households are about each technology.

To develop the awareness sub-criteria for the collective technology, a score from 1 to 10 was given to each technology by normalising the number of district heating projects that use each technology and multiplying the final value by 10. The data set on the current testing grounds of the PAW programme - the 25 neighbourhoods that received the subsidy - was used to count the number of projects that were planning to install each collective technology. Out of the 25 projects, a total number of 14 projects were planning on installing one of the technologies incorporated in the model. In particular, there were 8 biomass projects, 4 ATES projects and 2 aqua thermal projects. Taking current literature into account, that argues for a high awareness of heat pumps, and due to Dutch weather, which has an influence on the adaptation and awareness of solar thermal energy, a score of 3 and of 8, respectively, were given to the solar thermal systems and heat pumps for the level of awareness in the Netherlands:

Table B.16.: Score given for level of social awareness to each heating technology

| Heating technology | Bio-boiler | ATES | TEA | Heat pump | Solar thermal system |
|---|---|---|---|---|---|
| Awareness score | 7 | 5 | 2.5 | 8 | 3 |

### B.7.3. INDEPENDENCE CRITERIA

The third criteria used for the multi-criteria decision-making process is the energy dependence criteria. In this thesis, these criteria are defined as the amount of energy that is imported into the thermal energy community of study. With respect to the bio-boiler technology, this refers to the amount of energy stored in the wood pellets that are imported to the thermal energy community for the generation of heat. Regarding the ATES and TEA systems, since most of the heat is considered to be located within the boundaries of the thermal energy community, this energy refers to the amount of electricity consumed by the systems for the generation of heat.

For the bio-boiler, the energy import is calculated by dividing the annual household heat demand by the efficiency of a wood pellet bio-boiler (85%). For the ATES and the TEA system, the energy input to the system was derived by dividing the annual electricity consumption of the technology by the average installed capacity of the technology.

### B.7.4. CRITERIA CALCULATION

Table B.17 shows the calculation in absolute terms of each sub-criterion for each collective technology alternative.

Table B.17.: Calculation of data input on each sub-criteria

| Nr. Criteria | Criteria | Sub-criteria | Goal | Unit | Alternative rankings | | |
|---|---|---|---|---|---|---|---|
| | | | | | A1 | A2 | A3 |
| C1 | Financial | Investment costs | Min | €/h | 1402 | 4635 | 2668 |
| | | Maintenance costs | Min | €/year | 77 | 231 | 204 |
| | | PBT tech | Min | year | 4 | 13 | 10 |
| | | Subsidy coverage | Max | Fraction | 0.99 | 0.70 | 0.48 |
| C2 | Environmental | $CO_2$ emissions | Min | t/ h/year | 1757 | 1029 | 935 |
| | | Land use | Min | km2/kWh | 60 | 3 | 3 |
| | | Awareness | Max | number | 7.0 | 5.0 | 2.5 |
| C3 | Energy | Energy independence | Min | kWh/year | 7949 | 2399 | 2179 |
| | | Tech capacity | Min | kW/ h | 2.25 | 1.93 | 1.13 |

### B.7.5. CRITERIA RATING

Once the parameters for each alternative have been calculated, the rating of each alternative on each criterion is calculated by normalising the absolute values on the basis of whether the goal is to maximise or minimise such criteria.

When the goal is minimisation, a value of 0 is given to the alternative with the highest score in the sub-criteria and a value of 1 to the alternative with the lowest score. For the third alternative whose sub-criteria falls between the other two, the following expression is used to arrive at a value between 0 and 1:

$$\text{value}_{norm,AX} = \frac{\text{value}_{abs,AX} - \text{value}_{abs,Amax}}{\text{value}_{abs,Amin} - \text{value}_{abs,Amax}} \tag{B.12}$$

When the goal is maximisation, a value of 0 is given to the alternative with the lowest score in the sub-criteria and a value of 1 to the alternative with the highest score. For the third alternative whose sub-criteria falls between the other two, the following expression is used:

$$\text{value}_{norm,AX} = \frac{\text{value}_{abs,AX} - \text{value}_{abs,Amin}}{\text{value}_{abs,Amax} - \text{value}_{abs,Amin}} \tag{B.13}$$

Table B.19 shows the results for the normalisation of the criteria for the collective technology alternatives.

Table B.18.: Results for normalisation of sub-criteria information for each collective technology alternative

| Nr. Criteria | Criteria | Sub-criteria | Goal | Unit | Alternative rankings | | |
|---|---|---|---|---|---|---|---|
| | | | | | A1 | A2 | A3 |
| C1 | Financial | Investment costs | Min | €/h | 1.000 | 0.000 | 0.608 |
| | | Maintenance costs | Min | €/year | 1.000 | 0.000 | 0.173 |
| | | PBT tech | Min | year | 1.000 | 0.000 | 0.352 |
| | | Subsidy coverage | Max | Fraction | 1.000 | 0.432 | 0.000 |
| C2 | Environmental | $CO_2$ emissions | Min | t/h/year | 0.000 | 0.885 | 1.000 |
| | | Land use | Min | HA/kWh | 0.000 | 1.000 | 0994 |
| | | Awareness | Max | number | 1.000 | 0.556 | 0.000 |
| C3 | Energy | Energy independence | Min | kWh/year | 0.000 | 0.962 | 1.000 |

### B.7.6. CRITERIA WEIGHTING

First, the value system of the agent is normalised. Then, this normalised value is used for determining the preference weight for each criterion in the MCDM process. Then, the weight for each sub-criterion is calculated by dividing the weight for each criterion by the number of sub-criteria.

Table B.19.: Results for normalisation of sub-criteria information for each collective technology alternative

| Criteria | Values | Normalised value | Sub-criteria | Weight |
|---|---|---|---|---|
| Financial criteria | 6 | 0.3 | CAPEX | 0.075 |
| | | | OPEX | 0.075 |
| | | | PBT | 0.075 |
| | | | Subsidy coverage | 0.075 |
| Environmental criteria | 9 | 0.5 | $CO_2$ emissions | 0.16 |
| | | | Land use | 0.16 |
| | | | Social acceptance | 0.16 |
| Independence criteria | 4 | 0.2 | Energy input to the system | 0.2 |

## B.7.7. ALTERNATIVE SCORING

Once the rating of each alternative on each sub-criterion has been calculated and each sub-criterion has a weight assigned, the score for each alternative is calculated by multiplying all sub-criteria ratings for an alternative with their respective weights. The outcome provides a number from 0 to 1 and the alternative with the highest score is considered to be the preferred option.

$$\text{Alternative 1 (A1)} = (1+1+1+1)\times 0.075 + (0+1+0)\times 0.16 + 0\times 0.2 = 0.46 \tag{B.14}$$

# C

## C.1. MODEL'S KPIS

For each of the four mentioned model's KPIs in Section 4.5.5, the calculations are as follows:

### C.1.1. AVAILABILITY: AVERAGE VOLUNTARY DISCOMFORT PERCENTAGE:

For calculation of availability, Equation (C.1) is implemented.

$$\text{Availability= 100\%- average voluntary discomfort percentage} \tag{C.1}$$

To calculate the average voluntary discomfort/ shortage percentage, considering the current demand, the percentage of collective and individual renewable generation in CES (i.e. total RE), the baseline, and the average willingness to compensate (i.e. the average percentage of all agents are willing to avoid using the national grid, see Section 4.7), are subtracted (see Equation (C.2)).

$$\begin{aligned}&\text{Average voluntary shortage percentage (\%) = 100\%-total RE (\%)}\\&\quad -\text{baseline energy (\%)-average willingness to compensate (\%)}\end{aligned} \tag{C.2}$$

### C.1.2. AFFORDABILITY: AVERAGE COST

For the average cost, Equation (C.3) is implemented:

$$\begin{aligned}\text{Average costs (€)} &= \frac{1}{\text{Participating households}} \times (\text{Investment costs scenario (€)}\\&\quad + \text{costs energy import (€)+investment new community members (€)})\end{aligned} \tag{C.3}$$

### C.1.3. ACCESSIBILITY: DIVERSITY INDEX

A diversity index is implemented based on the Shannon index in the model as Equation (C.4) presents:

$$\begin{aligned}\text{Diversity index} = & -(\text{\% selected collective.RE} \times \ln(\text{\%selected collective.R})) \\ & -(\text{\% selected individual.RE} \times \ln(\text{\% selected individual.RE})) \\ & -(\text{\% selected national grid} \times \ln(\text{\% selected national grid}))\end{aligned} \tag{C.4}$$

### C.1.4. ACCEPTABILITY: $CO_2$ REDUCTION PER HOUSEHOLD

$CO_2$ emission reduction as an indicator for acceptability is implemented as presented in Equation (C.5):

$$\text{Carbon reduction (kg } CO_2) = \frac{\text{Emission of using national grid fully (kg } CO_2\text{)-Emission of CES (kg } CO_2)}{\text{Participating households}} \tag{C.5}$$

## C.2. ASSUMPTIONS AND INPUT DATA

Table D.10 presents the technical assumptions and input data for our modelling exercise. Technologies' costs are also calculated on [441], [442].

Table C.1.: Assumptions and input data

| Assumptions and input | Value (unit) | Reference |
|---|---|---|
| Overall efficiency | 0.85 | [443] |
| Carbon emission | 0.46 (kg/kWh) | [444] |
| Electricity price | 0.20 (€/kWh) | [331] |
| Average available solar radiation for the Netherlands | 4.38 (hours/day) | |
| Number of households in a neighbourhood | 500 n | [330] |
| Interacting connections per household | 13 n | [102] |

## C.3. SENSITIVITY ANALYSIS

Table D.11 presents the parameters and their ranges that have been explored through this sensitivity analysis.

Figure C.1 presents an example of OFAT sensitivity analysis results for the information exchange parameter.

As Figure C.1 shows, information exchange of 7 months leads to distributed outcomes (high, low and average values) for all four KPIs. Therefore, 7 has been taken as a parameter setting for the information exchange. The same procedure has been applied to the other parameter settings that have been analysed with the OFAT sensitivity analysis. This has led to each parameter's parameter settings, as presented in Figure D.1. The sensitivity analysis results are also in line with studies such as [339].

Table C.2.: Parameters' ranges for the OFAT sensitivity analysis

| Parameter | Range | Unit |
|---|---|---|
| Duration of the information exchange period | 1, 4, 7, 10, 13 | Months |
| Project time-horizon | 40, 45, 55, 60, 65, 70 | Years |
| Number connections per household | 10, 12, 14, 16, 18, 20 | Months |
| Technologies life-time | 10, 12, 14, 16, 18, 20 | Years |
| Minimum investment size on new technologies | 1, 2, 3, 4 | kW |
| Baseline energy (always be covered) | 5, 10, 15 | % |
| Percentage of new households that joins every year | 10, 15, 20, 25, 30 | % |

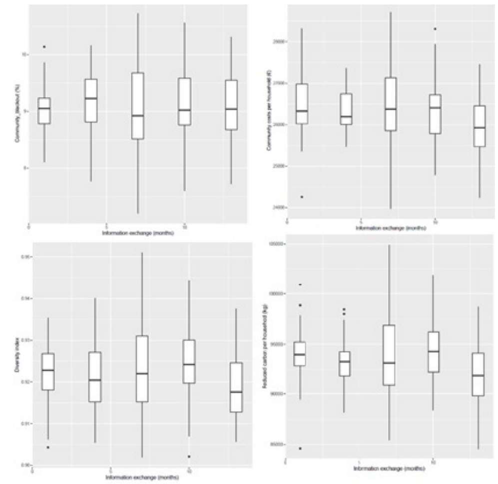


Figure C.1.: OFAT sensitivity analysis results for the duration of the information exchange period

Table C.3.: Sensitivity analysis results

| Parameter | Results | Unit |
|---|---|---|
| Duration of the information exchange period | 7 | Months |
| Project time-horizon | 55 | Years |
| Number connections per household | 13 | Months |
| Technologies life-time | 15 | Years |
| Minimum investment size on new technologies | 1 | kW |
| Baseline energy (always be covered) | 10 | % |
| Percentage of new households that joins every year | 20 | % |

# D

## D.1. INPUT DATA

### D.1.1. DATA FOR ATTRIBUTES OF THE COMMUNITY

In order to capture the community's attributes, the following criteria are used in the model based on the literature:

Table D.1.: Assumptions related to the attributes of community

| Criteria | Sub-criteria | Unit | Description | Reference |
|---|---|---|---|---|
| Financial criteria | CAPEX | € | Investment costs | [342] |
| | OPEX | € | Operational and maintenance costs during the lifetime of the system | [343] |
| | Payback time | Years | Years for the investment and maintenance cost to equal the accumulated energy savings from the change | [344] |
| | Subsidy coverage | % | Percentage of the capital costs covered by the subsidy (in the present study, this would be the SDE++ subsidy) | [343] |
| Environmental criteria | $CO_2$ emissions | Kg $CO_2$eq | The $CO_2$ emission intensity of technology based on capacity | [445] |
| | Land use | HA | Amount of land use required for technology based on capacity | [342] |
| | Social acceptance | 1 to 10 | The degree to which that technology is accepted, recognized and implemented | [343] |
| Independence criteria | The energy input to the system | kWh | Amount of energy input required for the technology to produce the heat to cover the neighbourhood heat demand | [445] |

### D.1.2. COLLECTIVE HEATING TECHNOLOGY

As discussed in model conceptualization, actors choose one of the three collective thermal energy technology options according to their values. According to [338], the peak demand is considered 10% for all three collective technologies, and the $CO_2$ intensity of electricity consumption is 0.429 Kg/kWh. The information is provided based on the "Stimuleringsregeling Duurzame Energie" scheme (SDE++). Furthermore, for each collective technology, the following information is used:

Table D.2.: Assumptions and input data for bioenergy

| Variable | Units | Bioenergy |
|---|---|---|
| Average capacity | kW | 950 |
| Capex | euros/kW | 825 |
| Opex fixed | euros/kW/yr | 55 |
| Opex variable | euros/kWh | 0.003 |
| Load hours | h/yr | 3000 |
| $CO_2$ emission | kg/kWh | 0.26 |
| Lifetime | yr | 20 |

Table D.3.: Assumptions and input data for ATES

| Variable | Units | Bioenergy |
|---|---|---|
| Average capacity | kW | 800 |
| Capex | euros/kW | 1600 |
| Opex fixed | euros/kW/yr | 113 |
| Opex variable | euros/kWh | 0.0019 |
| Load hours | h/yr | 3500 |
| $CO_2$ emission | kg/kWh | 0.152 |
| Lifetime | yr | 30 |

Table D.4.: Assumptions and input data for Electric boiler

| Variable | Units | Electric boiler |
|---|---|---|
| Average capacity | kW | 400 |
| Capex | euros/kW | 800 |
| Opex fixed | euros/kW/yr | 120 |
| Opex variable | euros/kWh | 0.025 |
| Load hours | h/yr | 2000 |
| $CO_2$ emission | kg/kWh | 0.14 |
| Lifetime | yr | 30 |

### D.1.3. INDIVIDUAL HEATING TECHNOLOGY

As mentioned in Section 5.2 after choosing and agreeing on the collective technology, households have four options: (i) using the collective technology to cover 100% of their consumption; (ii) combining the chosen collective technology with an individual heat pump; (iii) combining the chosen collective technology with the individual photovoltaic thermal hybrid solar collector (Solar PVT); and (iv) combining the chosen collective technology with individual small bioenergy (i.e. wood pallet).

Considering the Dutch electricity grid characteristics, $CO_2$ intensity is assumed to be 0.14 kg $CO_2$/ Kwh for the heat pumps in the model. For calculating the $CO_2$ intensity of the solar thermal systems, it was assumed that the solar water heater is used to supply hot water 80% of the time, and the electric water heater will supply the rest 20%. In other words, this 20% will be covered by the electricity grid. By calculating 20% of the grid's $CO_2$ intensity, we arrive at a $CO_2$ intensity for the water heater systems of 0.086 kg $CO_2$/kWh. Information about each of these individual technologies is summarized below.

Table D.5.: Assumptions and input data for Heatpump

| Variable | Units | Heatpump |
|---|---|---|
| Capex | euros/kW | 1770 |
| Opex | euros/kW/yr | 35.4 |
| Load hours | h/yr | 1500 |
| $CO_2$ emission | kg/kWh | 0.14 |
| Lifetime | yr | 15 |

Table D.6.: Assumptions and input data for Solar PVT

| Variable | Units | Solar PVT |
|---|---|---|
| Capex | euros/kW | 1450 |
| Opex | euros/kW/yr | 11 |
| Load hours | h/yr | 700 |
| $CO_2$ emission | kg/kWh | 0.086 |
| Lifetime | yr | 20 |

Table D.7.: Assumptions and input data for Woodpellet

| Variable | Units | Woodpellet |
|---|---|---|
| Capex | euros/kW | 415 |
| Opex | euros/kW/yr | 140 |
| Load hours | h/yr | 2000 |
| $CO_2$ emission | kg/kWh | 0.35 |
| Lifetime | Yr | 20 |

### D.1.4. DISTRIBUTION OF ENERGY LABELS IN THE DUTCH CONTEXT

Table D.8.: Distribution of energy labels in the Dutch context

| Label | Percentage |
|---|---|
| A | 5.3 |
| B | 18 |
| C | 32.5 |
| D | 24.4 |
| E | 11.6 |
| F | 6 |
| G | 2.2 |

### D.1.5. OTHER DATA

Table D.9.: Other data

| Variable | Units | Value |
|---|---|---|
| Average thermal energy demand per year | kWh | 12000 |
| Gas price | euros/kWh | 0.1 |
| $CO_2$ tax | euros/kg $CO_2$ | 0.025 |
| $CO_2$ emission of natural gas | kg/kWh | 0.2 |

## D.2. CALCULATIONS OF SEVEN ENERGY SECURITY KIPS

### D.2.1. AVAILABILITY: AVERAGE VOLUNTARY DISCOMFORT PERCENTAGE:

$$\text{Voluntarily discomfort for a household} = \frac{\sum_{i=1}^{\text{lifetime}}(\text{100\%demand-\%RETs generation-\%natural gas consumption})}{\text{lifetime}}$$

$$\text{Average percentage of voluntarily discomfort per household in the community} = \frac{\sum_{i=1}^{\text{number of households}}(\text{percentage of voluntarily discomfort for a household})}{\text{number of households}}$$

### D.2.2. ENERGY PRICES: AVERAGE COST PER HOUSEHOLD:

$$\text{Costs for a household} = \frac{\text{investment} + \text{yearly cost} \times \text{lifetime}}{\text{lifetime}}$$

$$\text{Average costs per household per month in the community} = \frac{\sum_{i=1}^{\text{number of households}} (\text{costs for a household})}{\text{number of households}}$$

### D.2.3. ENVIRONMENTAL: AVERAGE $CO_2$ EMISSION PER HOUSEHOLD:

$$\begin{aligned} CO_2\ \text{emission for the whole community} = \frac{1}{\text{lifetime}} \times \\ \Big( \sum_{1}^{\text{lifetime}} (\text{collective system emissions}) + \\ \sum_{1}^{\text{lifetime}} \sum_{1}^{\text{number of households}} (\text{individual system emissions}) \\ \sum_{1}^{\text{lifetime}} \sum_{1}^{\text{number of households}} (\text{natural gas emissions}) \Big) \end{aligned}$$

$$\text{Average } CO_2 \text{ emission per household in a community} = \frac{CO_2 \text{ emission for the whole community}}{\text{number of households}}$$

### D.2.4. INFRASTRUCTURE: AVERAGE DIVERSITY OF INFRASTRUCTURE:

$$\begin{aligned} \text{Diversity index} = &-(\%\ \text{selected collective.RE} \times \ln(\%\text{selected collective.R})) \\ &-(\%\ \text{selected individual.RE} \times \ln(\%\ \text{selected individual.RE})) \\ &-(\%\ \text{selected national grid} \times \ln(\%\ \text{selected national grid})) \end{aligned}$$

### D.2.5. ENERGY EFFICIENCY: AVERAGE THERMAL INSULATION PER HOUSEHOLD:

$$\text{Average insulation per households in a community} = \frac{\sum_{1}^{\text{number of households}} (\text{insulation of a household})}{\text{number of households}}$$

### D.2.6. GOVERNANCE: ESTABLISHMENT DURATION OF ENERGY COMMUNITIES

The time is calculated to count the months until the community generates collective renewable energy.

### D.2.7. SOCIETAL EFFECT: AVERAGE COMMUNITY BENEFIT

$$\text{Average social benefit per household} = \left(\frac{\text{Direct benefits+Indirect benefits}}{\text{lifetime}}\right)$$

$$\text{Direct benefits} = \frac{\sum_{1}^{\text{number of households}} \sum_{1}^{\text{lifetime}} (\text{Cost savings on bills})}{\text{number of households}}$$

$$\text{Indirect benefits} = \left(\frac{\sum_{1}^{\text{lifetime}} \left(\frac{\text{CO}_2 \text{ emission reduction}}{\text{Indirect costs of CO}_2 \text{ emissions}}\right)}{\text{number of households}}\right)$$

## D.3. ASSUMPTIONS AND INPUT DATA

Table D.10 presents the technical assumptions and input data for our modelling exercise. Technologies' costs are also calculated on [441, 442].

Table D.10.: Assumptions and input data

| Assumptions and input | Value (unit) | Reference |
|---|---|---|
| Overall efficiency | 0.85 | [443] |
| Carbon emission | 0.46 (kg/kWh) | [444] |
| Electricity price | 0.20 (€/kWh) | [331] |
| Average available solar radiation for the Netherlands | 4.38 (hours/day) | |
| Number of households in a neighbourhood | 500 n | [330] |
| Interacting connections per household | 13 n | [102] |

## D.4. SENSITIVITY ANALYSIS

There are often some uncertainty in the parametrisation of most, if not all, model variables. Where this uncertainty is considerable, the parametrisation can be systematically explored by experimenting with the input value of the variable by doing a sensitivity analysis [349]. A sensitivity analysis will reveal whether some values given to the parameters will lead to specific effects on the model outcomes [352]. One-factor-at-a-time (OFAT) was used [351], which essentially consists of selecting a base parameter setting (nominal set) and varying one parameter at a time while keeping all the other parameters fixed. This reveals the relationship between the varied parameter and the output, given that all parameters have their nominal values. Table D.11 presents the parameters and their ranges that have been explored through this sensitivity analysis.

After 50 times simulation, boxplots were generated for each parameter for four chosen KPIs. The reason for selecting these four KPIs, the average cost per household per month, average emission per household per month, average energy diversity and average community formation duration, is to reduce computation time in this step while using four well known KPIs for assessing energy community performance. Figure D.1 presents OFAT sensitivity analysis results for the information exchange parameter.

Table D.11.: Parameters' ranges for the OFAT sensitivity analysis

| Parameter | Range | Unit |
|---|---|---|
| Duration of information exchange | 5, 7, 9 | Months |
| Neighbourhood size | 500, 600, 700 | households |
| Steps of percentage preference reduction per SVO type | 10, 15, 20 | % |
| Number of connections each household has | 2, 3, 4 | |
| Number of neighbourhoods in a municipality | 3, 4, 5, 6 | Neighbourhood |
| Steps of yearly gas price increase | 0.005, 0.01, 0.015, 0.02 | (€/kWh) |
| Steps of yearly $CO_2$ tax increase | 0.01, 0.02, 0.03 | (€/kg) |

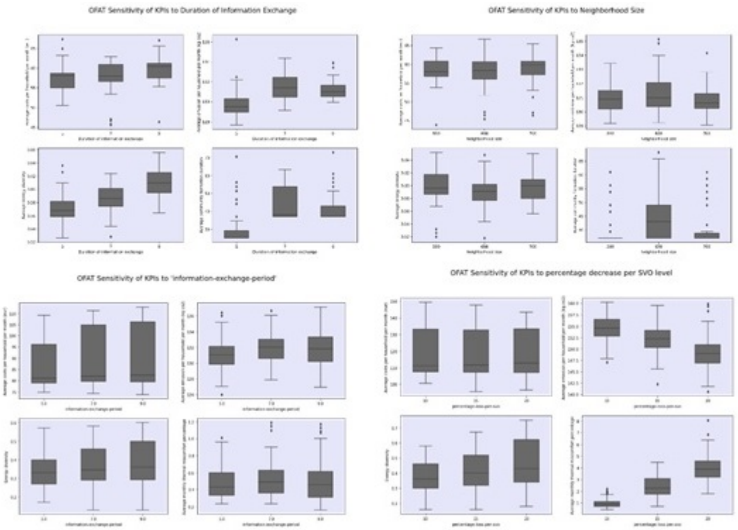


Figure D.1.: Sensitivity analysis results

# LIST OF PUBLICATIONS

## Peer reviewed publications

- **J. Fouladvand**, A. Ghorbani, Y.Sarı, T. Hoppe, R. Kunneke, and P. Herder, “Energy security in community energy systems: An agent-based modelling approach,” Journal of Cleaner Production, vol. 366, p. 132765, 2022.
- **J. Fouladvand**, M. Aranguren, T. Hoppe, and A. Ghorbani, “Simulating thermal energy community formation: Institutional enablers outplaying technological choice,” Applied Energy, vol. 306, p. 117897, 2022.
- **J. Fouladvand**, A. Ghorbani, N. Mouter, and P. Herder, “Analysing community-based initiatives for heating and cooling: A systematic and critical review,” Energy Research & Social Sciences, vol. 88, p. 102507, 2022.
- **J. Fouladvand**, D. Verkerk, I. Nikolic, A. Ghorbani, (2022). Modelling Energy Security: The Case of Dutch Urban Energy Communities. In: Czupryna, M., Kamiński, B. (eds) Advances in Social Simulation. Springer Proceedings in Complexity.
- **J. Fouladvand**, “Behavioural attributes towards collective energy security in thermal energy communities: Environmental-friendly behaviour matters,” Energy, vol. 261 B., p. 25353, 2022.
- **J. Fouladvand**, A. Ghorbani, N. Mouter, and P. Herder,"Formation and Continuation of Thermal Energy Community Systems: An Explorative Agent-Based Model for the Netherlands", Energies, vol. 13, p. 2829, 2020.
- **J. Fouladvand**, "Why and how to approach community energy systems by agent-based modelling? A systematic and critical review", Manuscript in review.

## Conference contributions

- **J. Fouladvand**, A. Ghorbani, Y.Sarı, T. Hoppe, R. Kunneke, and P. Herder, "Modelling energy security of thermal energy communities: An agent based modelling approach", virtual, 2021.
- **J. Fouladvand**, A. Ghorbani, “Thermal energy communities in urban districts: role of government incentives and behavioral attitude,” IASC 2021 Urban Commons Virtual Conference, virtual, 2021.
- **J. Fouladvand**, D. Verkerk, I. Nikolic, A. Ghorbani, “Exploring energy security of energy communities: an exploratory agent-based modelling approach,” presented at International Conference on Autonomous Agents and Multi-agent Systems, virtual, 2021.
- A. Akhatova, **J. Fouladvand**, L. Kranzl,“Conceptual agent-based model of neighborhood-level building retrofits based on energiesprong approach,” presented at International Association for Energy Economics (IAEE) conference, virtual, 2021.

- M. Arangouran Rojas, **J. Fouladvand**, T. Hoppe, A. Ghorbani, “Exploring formation of Dutch thermal energy communities,” presented at APEEN2021Energy Transition and Sustainability, virtual, 2021.

- D. Verker, **J. Fouladvand**, I. Nikolic, A. Ghorbani, “An agent-based model to explore energy security of energy communities,” APEEN2021Energy Transition and Sustainability, virtual, 2021.

- **J. Fouladvand**, A. Ghorbani, N. Mouter, and P. Herder, “Urban thermal commons: A model of the new community energy system,” presented at Social Simulation Conference 2019 (SSC 2019), Mainz, Germany, 2019.

- **J. Fouladvand**, A. Ghorbani, and P. Herder, “Urban thermal commons; The new community energy systems,” presented at 17th IASC Global Conference 2019 (International Association for the Study of the Commons), Lima, Peru, 2019.

- **J. Fouladvand**, A. Ghorbani, and P. Herder, “Looking at energy security through community lens, new perspective,” presented at Sustainable Urban Energy Systems Conference, Delft, The Netherlands 2018.

# CURRICULUM VITAE

Javanshir Fouladvand was born on May 23, 1990, in Tehran, Iran. Having completed his high school education in Mathematics and Physics, he was admitted to the Mechanical Engineering bachelor's program at the University of Tehran in 2009. During his bachelor's, he became especially interested in renewable energy systems. He gained experience inside the university as an energy system engineer and project manager. He was a research assistant at the University of Tehran in the Centre of Excellence in Design and Optimization of Energy Systems (CEDOES) and the Persian Gazelle Solar Car team. He also worked as an energy consultant in Iran.

Later, he received funding from the University of Twente to join the Master of Environmental and Energy Management (MEEM). During this period, he mainly focused on social and institutional aspects of the energy transition, particularly the heating energy transition. He became especially interested in topics related to energy security. After graduation, he worked as an energy consultant on projects in Friesland and North Holland provinces. However, his curiosity and passion brought him back into academia, and he decided to continue as a PhD researcher in an area where he could study a combination of technical and institutional aspects in a complex energy system.

In 2017, Javanshir started his PhD research in the Energy and Industry section at the Technology, Policy and Management (TPM) faculty of Delft University of Technology. By employing agent-based modelling (ABM), he studied the establishment and functioning of energy-secure thermal energy communities. He made great use of the knowledge of TPM faculty to study the technical, institutional and behavioural conditions of such unique collective energy systems. In 2021, he joined the Copernicus Institute of Sustainable Development at Utrecht University, where he has been working as a lecturer. Along with successful participation in a consortium for a Horizon Europe project (SKILLBILL), he also received several faculty-level funding.

*This CV was last updated on July 1st, 2022*