

# Contents

## Preface xvii

<b>1</b>	<b>Introduction: The Need for Sector Coupling and the Energy Transition Goals</b>	<b>1</b>
	<i>Marialaura Di Somma, Christina Papadimitriou, Giorgio Graditi, and Koen Kok</i>	
1.1	Introduction	1
1.1.1	The Needs and Challenges of the Current Energy System	1
1.1.2	What Is Sector Coupling?	2
1.2	Opportunities for Sector Coupling to Contribute to Decarbonization	4
1.2.1	Electrification and Sector Coupling	4
1.2.2	Enhancing System Stability and Reliability at the Grid Level Through Sector Coupling	6
1.2.3	Decarbonization of Heating and Cooling in Building Environment (End-User Level) Through Sector Coupling	9
1.3	European Energy Legislation and Initiatives Supporting Sector Coupling	10
1.3.1	Directives	10
1.3.2	Policy	11
1.3.3	Initiatives	11
1.4	Main Barriers to Implementation	12
1.5	The Integrated Local Energy Community Concept to Foster Sector Coupling at the Local Level Through End-Users Engagement	14
	List of Abbreviations	16
	References	17
<b>2</b>	<b>Current Status of Multi-carrier Energy Systems in Europe with Main Limitations and Shortcomings to the Optimal Use of Local Energy Resources</b>	<b>19</b>
	<i>Andrei Morch, Hanne Sæle, Jesús Fraile Ardanuy, Giuseppe Conti, Gabriele Comodi, and Mosè Rossi</i>	
2.1	Introduction	19
2.2	Methodology	19

2.3	The Scoping Study: Road Maps and the Overall Pan-European Priorities	20
2.3.1	Energy Policies, Which Are Preferred in Europe (2020–2050)	20
2.3.1.1	The Pan-European Dimension	21
2.3.1.2	The Reference Scenario Toward 2050	22
2.3.1.3	Vision 2050	23
2.3.2	Expected Roll-Out of the Different Technologies in the 2030 Horizon	24
2.3.2.1	Deployment of Hydrogen Infrastructure	24
2.3.2.2	Energy Storage	25
2.3.2.3	Hydrogen Storage	27
2.3.2.4	Hybrid Solutions	27
2.3.2.5	Smart Metering System as a Key Enabling Technology	28
2.3.3	Overview of Policies Supporting the Empowerment of the Final Consumer	28
2.3.4	Energy Communities – Different Actors and Operations	29
2.3.5	Summarizing the Scoping Study	29
2.4	Review of Sector Coupling Technologies for Integrated Local Energy Communities	30
2.4.1	Definition of Connecting Technologies	31
2.4.2	Connecting Technologies (Prosumer Level)	31
2.4.2.1	Heat Pump	32
2.4.2.2	Combined Cooling Heat and Power (CCHP)	32
2.4.2.3	EV Charging Station	32
2.4.3	Connecting Technologies (Community Level)	32
2.4.3.1	Electrolyzers	33
2.4.3.2	Electric Planes, Electric Ferries, and Hydrogen Transport such as Trains, Vessels, and Lorries	34
2.4.3.3	Desalination	34
2.5	Review of Limitations and Barriers for the Optimal Use of the Local Energy Resources	35
2.5.1	Introduction	35
2.5.2	Technical Limitations	35
2.5.2.1	Low Efficiency	35
2.5.2.2	Low Flexibility	37
2.5.2.3	Security Concerns	38
2.5.2.4	Environmental Issues	38
2.5.2.5	Spatial Issues	38
2.5.2.6	Cost and Cost-effectiveness	39
2.5.3	Regulatory Limitations	39
2.5.3.1	Market-Related Issues	40
2.5.3.2	Need for Revising Grid Codes at the Distribution Level	40
2.5.3.3	Definition of Roles and Responsibilities of Energy Communities	41

2.5.3.4	Efficiency Targets for Cogeneration	41
2.5.3.5	Regulatory Barriers Related to Hydrogen	41
2.5.3.6	Integration of Energy Storage	42
2.5.3.7	Standardization of the Infrastructure for EVs	44
2.5.3.8	Integration of EVs into the Electricity Market	44
2.6	Conclusions and Lessons Learned	45
	Acknowledgment	46
	List of Abbreviations	46
	References	47

### **3 The Concept of Integrated Local Energy Communities: Key Features and Enabling Technologies 55**

*Amedeo Buonanno, Martina Caliano, Gianfranco Chicco, Marialaura Di Somma, Giorgio Graditi, Valeria Palladino, Christina Papadimitriou, and Hanne Sæle*

3.1	Introduction	55
3.2	Key Features of ILECs	56
3.2.1	Policy and Regulation Analysis for REC and CEC	57
3.2.2	Differences Between CEC, REC, and ILEC	58
3.2.3	Organizational Structure	58
3.2.4	Involved Stakeholders	59
3.2.5	Motivation for Establishment	59
3.2.6	Energy Carriers	60
3.2.7	Energy Technologies	61
3.3	Enabling Technologies	62
3.3.1	Demand-Side Flexibility Technologies	62
3.3.1.1	Energy Conversion Technologies	62
3.3.1.2	Storage Technologies	66
3.3.2	Distributed Renewable Energy Technologies	75
3.3.2.1	Photovoltaic Systems	75
3.3.2.2	Interactions Between Photovoltaic Supply and Demand	77
3.3.3	Information and Communication Technologies	79
3.3.3.1	Data Management Technologies	80
3.3.3.2	Control and Management Technologies	81
3.3.3.3	Technologies for Analytics	82
3.3.3.4	Internet of Things (IoT)	84
3.3.3.5	Communication Technologies	85
3.3.3.6	Computing Technologies	86
3.3.3.7	Cybersecurity	87
3.3.3.8	Blockchain	88
3.4	Summary of Main Barriers to the Use of Enabling Technologies in the ILEC	89
	Acknowledgments	91
	List of Abbreviations	91
	References	92

<b>4</b>	<b>Actors, Business Models, and Key Issues for the Implementation of Integrated Local Energy Communities</b>	<b>99</b>
	<i>Martina Caliano, Alberto Borghetti, Amedeo Buonanno, Marialaura Di Somma, Salvatore Fabozzi, Giorgio Graditi, Carlo Alberto Nucci, Christina Papadimitriou, and Peter Richardson</i>	
4.1	Introduction	99
4.2	Actors' Roles and Interactions Within ILECs	101
4.3	Key Issues for the Implementation of ILECs	105
4.3.1	Key Technological Issues	106
4.3.1.1	Grid Integration	109
4.3.1.2	Implementing Energy Management Systems	109
4.3.1.3	Promoting Energy Storage	110
4.3.1.4	Implementation of Smart Metering	110
4.3.1.5	Data Management and Cybersecurity	110
4.3.1.6	Scalability	111
4.3.1.7	Local Ancillary Services	111
4.3.2	Key Socioeconomic Issues	111
4.3.2.1	High Initial Costs, Inadequate Economic Incentives, and Split-Incentives	111
4.3.2.2	Increasing Energy Autonomy and Security of Supply and Reducing Energy Poverty	112
4.3.2.3	Increasing Community Engagement and Willingness to Pay	113
4.3.3	Key Environmental Issues	113
4.3.3.1	Spatial and Noise Issues	114
4.3.3.2	Waste Management and Disposal	115
4.3.3.3	Emission Mitigation	116
4.3.4	Key Institutional Issues	117
4.3.4.1	Increasing Trust and Motivation of Citizens	117
4.3.4.2	Promoting Energy Democracy	118
4.3.4.3	ILEC Ownership Model	118
4.3.4.4	Funding Local Projects	118
4.3.4.5	Support Schemes, Incentives, and Targets	119
4.3.4.6	(Self-)governance	119
4.3.4.7	Regulatory Issues and Policy Framework	120
4.3.4.8	Institutional (Re-)design	120
4.4	Business Models for ILECs	121
4.4.1	Overview of Selected Business Models	121
4.4.2	Development of Business Models	124
4.4.2.1	BM A – Flexibility for Local Balancing and Increase of Self-consumption for Multicarrier Systems	124
4.4.2.2	BM G – Heat Recovery and Storage for Effective Integration of District Heating and Cooling	127
4.5	Conclusion and Lessons Learned on Barriers, Benefits, and Policy Implications for ILECs Implementation	130
4.5.1	Barriers	130

4.5.2	Benefits	131
4.5.3	Policy Implications	132
	Acknowledgments	133
	List of Abbreviations	133
	References	134
<b>5</b>	<b>Comprehensive Analysis and Future Outlook of Planning and Operation Approaches for Multicarrier Energy Systems Under the Integrated Local Energy Community Concept</b>	<b>139</b>
	<i>Christina Papadimitriou, Marialaura Di Somma, Dimitrios Tzelepis, Koen Kok, and Giorgio Graditi</i>	
5.1	Introduction	139
5.2	Optimal Planning of Multicarrier Energy Systems	141
5.2.1	Introduction to Optimal Planning and Technical Aspects	141
5.2.2	Decision-making Process for Multicarrier Energy Systems Planning	142
5.2.3	Features and Modeling Approaches of Optimization Problems for the Multicarrier Energy Systems Planning	143
5.2.4	Exact Modeling/Exact Optimization Dilemma	144
5.2.5	Need for a Multiobjective Approach	145
5.2.6	Analysis of Works in the Literature Dealing with Multicarrier Energy Systems Planning	147
5.3	Operational Planning of Multicarrier Energy Systems for Day-Ahead Optimization and Decision-Making Under Uncertainties	147
5.4	Optimal Operation of Multicarrier Energy Systems in Real Time Under Multiobjective Approaches Considering Demand-Response Programs and Market Interaction	152
5.4.1	Real-Time Operation of Multicarrier Energy Systems: Drivers and Challenges	152
5.4.2	Multiobjective Approaches for Optimal Real-Time Operation	153
5.4.3	Demand-Response Programs and Market Interaction	154
5.4.3.1	Demand-Response Programs in Multicarrier Energy Systems	154
5.4.3.2	Market Interaction with Multicarrier Energy Systems	154
5.5	Data Architectures, Control Technologies, and the Scaling of Energy Systems	156
5.5.1	The Importance of Visibility and Controllability in Managing Multicarrier Energy Systems	156
5.5.2	Outlook on the Complexities and Challenges of Data and Data Architectures	158
5.5.3	Developments and Trends on System Architectures and Control Technologies	160
5.5.3.1	Energy Management Systems	162
5.5.3.2	Energy Systems Modeling	163
5.5.3.3	Virtualization	164
5.5.3.4	Cloud Computing	164
5.5.3.5	Digital Twins	165

5.5.3.6	Cybersecurity	165
5.6	Holistic Approach in Planning and Operating an ILEC	166
5.6.1	Higher Hierarchical Level: Planning Phase	166
5.6.2	Lower Hierarchical Layer: Operational Analysis	167
5.6.3	Lowest Hierarchical Layer: Real-Time Operation and Assets' Control	168
5.6.4	Interaction with External Entities	170
5.6.4.1	Network Interaction	171
5.6.4.2	Local Market Interaction	172
5.6.4.3	Wholesale Market Interaction	172
5.6.4.4	Interaction with Aggregators/Retailers	172
5.7	Conclusion	172
	List of Abbreviations	173
	References	174
<b>6</b>	<b>Analytical Framework for Coordinated Planning and Operation of Multicarrier Energy Systems</b>	<b>187</b>
	<i>Mariakura Di Somma, Christina Papadimitriou, Anastasios Oulis Rousis, Angelos Patsidis, Miadreza Shafie-Khah, Vahid Shahbazzbegian, and Magnus Askeland</i>	
6.1	Introduction	187
6.1.1	Benefits of Local Multicarrier Energy Systems	187
6.1.2	The Optimization Framework for Coordinated Planning and Operation of MCES	189
6.2	Modeling of Energy Technologies in MCES	191
6.2.1	Renewable Energy Sources (RESs)	191
6.2.1.1	Solar PV	192
6.2.1.2	Solar Thermal	192
6.2.1.3	Wind Turbines	192
6.2.2	Primary Energy Technologies	192
6.2.2.1	Cogeneration Plants	192
6.2.2.2	Boilers	193
6.2.3	Secondary Energy Technologies	193
6.2.3.1	Reversible Heat Pump	193
6.2.3.2	Single-Stage Absorption Chiller	194
6.2.4	Storage Systems	194
6.2.4.1	Electrical Energy Storage	194
6.2.4.2	Thermal Energy Storage	194
6.2.4.3	Hydrogen Storage	195
6.2.4.4	Electric Vehicles	195
6.3	The Optimal Design Problem for MCES	196
6.3.1	Objective Function	196
6.3.2	Constraints	197
6.3.3	Solution Methodology	198
6.3.4	Case Study and Simulation Results	198

6.4	Optimal Day-Ahead Scheduling of MCES Under Uncertainties and by Considering DR Programs	200
6.4.1	Objective Function	201
6.4.2	Constraints	201
6.4.2.1	Electricity Network Constraints	201
6.4.2.2	Gas Network Constraints	202
6.4.2.3	Demand Response Constraints	203
6.4.2.4	Uncertainty Consideration	203
6.4.3	Solution Methodology	204
6.4.4	Case Study and Simulation Results	204
6.4.4.1	Simulation Results	205
6.5	Optimal Real-Time Operation of MCES	209
6.5.1	Objective Function	210
6.5.2	Constraints	210
6.5.3	Solution Methodology	211
6.5.4	Case Study and Simulation Results	212
6.6	Analysis of Commercial Tools for the Optimal Design and Operation of MCES	215
6.7	Conclusions and Lessons Learned	220
	List of Abbreviations	220
	References	221

## **7 Integrated Flexibility Solutions for Effective Congestion Management in Distribution Grids**

*Bart van der Holst, Gijs Verhoeven, Milad Kazemi, Christina Papadimitriou, Marialaura Di Somma, and Koen Kok*

7.1	Introduction	225
7.2	Congestion Management in Distribution Systems	226
7.2.1	The Distribution System and The System Operator	226
7.2.2	Developments in the Distribution Grid	228
7.2.2.1	Growth of Distributed Renewable Energy Resources	229
7.2.2.2	Electrification of Demand	229
7.2.2.3	Improved Metering	230
7.2.2.4	Higher Controllability of Assets	230
7.2.3	Congestion in Distribution Grids	231
7.2.4	Traditional Mitigation Strategies for Congestion	232
7.2.4.1	Grid Reinforcements	233
7.2.4.2	Grid Reconfiguration	233
7.2.4.3	Using Reserve Capacity	233
7.2.4.4	Rejecting Grid Access	234
7.3	Integrated Flexibility in ILECs	234
7.3.1	The Concept of Integrated Flexibility	235
7.3.2	Optimal Flexibility Management of Electric Vehicles in ILEC Context	237
7.3.3	Optimal Home (Building) Energy Management System	241

7.3.3.1	Mathematical Model	242
7.3.3.2	Case Study and Results	245
7.4	Instruments for Flexibility Activation for Congestion Management	247
7.4.1	Developments in Europe	247
7.4.2	Examples of Market-Based Instruments in Practice	248
7.4.2.1	GOPACS	248
7.4.2.2	Piclo Flex	249
7.4.3	Examples of Tariff Instruments in Practice	250
7.4.3.1	Capacity Tariff	250
7.4.3.2	Bandwidth Tariff	250
7.4.4	Simulation Case Study	251
7.5	Challenges and Outlook	254
7.5.1	Market Barriers	254
7.5.2	Regulatory Barriers	254
7.5.3	Technological Barriers	255
7.5.4	Customer-Related Barriers	255
	Nomenclature	256
	References	259

## **8 Peer-to-Peer Energy Trading Approaches: Maximizing the Active Participation of the Prosumers in the Multi-carrier Energy Communities** 265

*Andrés F. Cortés-Borray, Amaia González-Garrido, Ander Z. Gómez, Joseba J. Huarte, and Nerea R. Carames*

8.1	Introduction	265
8.2	Background and P2P Concept	266
8.2.1	Background, Alternatives, Initiatives, and Trends	266
8.2.2	P2P Energy Trading Concept and Challenges	268
8.3	P2P Methods and Logical Architecture	270
8.3.1	P2P Market Design	270
8.3.1.1	Community-Based or Centralized Markets	271
8.3.1.2	Full P2P or Decentralized Markets	272
8.3.1.3	Hybrid or Distributed Markets	272
8.3.2	P2P Market Implementation	272
8.3.2.1	Peer Decision-Making Process	272
8.3.2.2	Transaction Price Determination Process	273
8.3.2.3	Market Simulation and Clearing	275
8.4	Literature Review	276
8.4.1	Market Design and P2P Trading	276
8.4.2	Interaction with the Wholesale and Multi-energy Markets	279
8.4.3	Contribution to Ancillary Services	284
8.4.4	Consideration of Multi-energy Network Constraints	285
8.5	P2P Approach in the eNeuron Project	288
8.5.1	Overview of the eNeuron Concept	288
8.5.2	eNeuron P2P Market Platform	289



- 8.5.2.1 Architecture 289
- 8.5.2.2 Algorithm Definition 290
- 8.6 Conclusion 291
- Acknowledgment 291
- List of Abbreviations 292
- References 293

## 9 **Integration of Multiple Energy Communities: Transaction Prices, Reactive Power Control, and Ancillary Services** 299

*Alberto Borghetti, Tohid Harighi, Carlo Alberto Nucci, Giorgio Graditi, Marialaura Di Somma, and Martina Caliano*

- 9.1 Introduction 299
- 9.2 Multiple Energy Communities 300
  - 9.2.1 Optimization Model 300
  - 9.2.2 Case Study and Analysis of the Results 304
- 9.3 Provision of Reactive Power Compensation Services 307
  - 9.3.1 Optimization Model 309
  - 9.3.2 Calculation of the Maximum Up and Down Flexibilities 311
  - 9.3.3 Case Study and Analysis of the Results 312
- 9.4 Electromobility Integration 315
- 9.5 Conclusion and Key Learnings 317
- Acknowledgments 317
- List of Abbreviations 318
- References 318

## 10 **Validation of Energy Hub Solutions Through Simulation and Testing in a Lab Environment and Real World** 323

*Gabriele Comodi, Mosè Rossi, Alessandro Romagnoli, Alessio Tafone, and Andreas Tuerk*

- 10.1 Introduction 323
- 10.2 Energy Hub and Micro Energy Hub Architecture 324
  - 10.2.1 “mEH” and “EH” 325
    - 10.2.1.1 mEH 325
    - 10.2.1.2 EH 328
- 10.3 EH and mEH Validation Through Simulation and Testing in Lab Environment 329
  - 10.3.1 EH of Università Politecnica delle Marche 329
    - 10.3.1.1 Technologies, Energy Vectors, and Networks 330
  - 10.3.2 EH for Aggregators: EV-Charging Station 331
  - 10.3.3 SMES Project in Singapore 333
    - 10.3.3.1 The Cryo-polygeneration Demonstrator (CPD) for Nanyang Technological University 334
    - 10.3.3.2 Hydrogen Hub for the Decarbonization of Singapore Industrial Port Area (IPA) 337

10.4	EH and mEH Validation Through Simulation and Testing in Real World	339
10.4.1	Italian City Scale Multi-energy Microgrid (Osimo)	339
10.4.1.1	EH Architecture	340
10.4.1.2	mEH: Large User (CHP)	340
10.4.1.3	mEH: Battery in the MV/LV Network	340
10.4.1.4	mEH: Smart Building	341
10.4.1.5	mEH: Local Energy Community	342
10.4.1.6	Flexibility Results	342
10.5	EH and mEH: An Architecture for Renewable Energy Communities	343
10.5.1	An Overview of Energy Communities Rollout in Europe	344
10.6	Conclusions and Lessons Learned	347
	Acknowledgments	347
	List of Abbreviations	348
	References	348
<b>11</b>	<b>Energy Communities as an Alternative Way of Organizing the Energy System in Europe: Key Societal Aspects</b>	<b>353</b>
	<i>Anna J. Wiecek, Natascha van Bommel, Amira El-Feiaz, Nikki Kluskens, Irene Niet, Luc van Summeren, Johanna Höffken, Floor Alkemade, Laura van den Berghe, Claudia Meloni, Giorgio Graditi, and Marialaura Di Somma</i>	
11.1	Introduction	353
11.2	A Sociotechnical Approach	354
11.3	Changing Energy System	356
11.4	Energy Communities as New Actors	358
11.4.1	Energy Communities' Characteristics, Activities, and Scale of Deployment	359
11.4.2	Other Emerging Actors	360
11.4.3	Community Acceptance	361
11.5	Technology Facilitating or Hindering Energy Communities?	363
11.5.1	Three Types of Relevant Technologies	364
11.5.2	Opportunities, Barriers, and Impacts of Digitalization	365
11.6	Regulations and Markets as Key Institutional Structures	367
11.6.1	Markets Reproducing Path Dependencies	367
11.6.2	Clean Energy Package – New Opportunities for European Energy Communities?	368
11.7	How It Looks in Practice	370
11.7.1	Energética Cooperativa in Spain – How to Foster Social Acceptance	370
11.7.2	cVPP in Loenen Gent – How to Harness the Power of ICT	372
11.7.3	Service Local Token Economy in Italy – How to Deal with Market Barriers	373
11.8	Conclusions	374
	List of Abbreviations	376
	References	376

<b>12</b>	<b>Guidelines and Recommendations for Optimal Implementation of Integrated Local Energy Communities</b>	<b>389</b>
	<i>Leonard E.R. Perez, Bernadette Fina, Branislav Iglár, Carolin Monsberger, Klara Maggauer, Natália de A.B. Weber, Georgios Yiasoumas, George Georghiou, José Villar, João Mello, and Rad Stanev</i>	
12.1	Introduction	389
12.2	Main Challenges of Integrated Local Energy Communities Implementation at the European Level	390
12.3	Guidelines and Recommendations for Optimal Implementation of ILECs	391
12.3.1	Technical Dimension	392
12.3.1.1	Implementation of Strategies to Reduce Grid Reinforcement Needs due to the Installation of New Assets	392
12.3.1.2	Alternatives to Deal with Generation Source Fluctuations	393
12.3.1.3	Coordination and Control Between System Operators and ILECs	394
12.3.1.4	Determination of Suitable Location for ILEC Project Implementation Through Novel Assessment Tools and Technical Studies	394
12.3.1.5	Acceleration of Smart Meters Installation	394
12.3.1.6	New Research Lines in the Field of Energy Community	395
12.3.2	Regulatory Dimension	395
12.3.2.1	Standardization, Transposition, and Harmonization of Energy Community EU Directives	396
12.3.2.2	Simplification of License Procedures and Paperwork	396
12.3.2.3	Taxing and Incentive Schemes Reformulation Within Regulatory Frameworks	397
12.3.2.4	Regulations for the Data Exchange and Privacy	397
12.3.2.5	New Regulations for the Peer-to-Peer Trading	397
12.3.2.6	Creation of Policies in Favor of Vulnerable Social Communities	398
12.3.3	Environmental Dimension	398
12.3.3.1	Including Landscape Impact Cost Analysis and Life Cycle Assessment (LCA)	399
12.3.3.2	Recyclability of Raw Materials and Waste Management	400
12.3.3.3	Rising the Environmental Value of ILECs by Improving GHG Emissions Taxing Exemption Schemes	400
12.3.4	Economic Dimension	401
12.3.4.1	Need of Cost-effective Tools for Planning and Managing Energy Communities, Including New Energy Carriers	402
12.3.4.2	Suitable Economic Incentives	402
12.3.4.3	Flexibility Market Regulation and New Business Models	402
12.3.4.4	Providing Financial Tools to the Service of the ILECs	403
12.3.4.5	Enhancing the Competitiveness in the Energy Market and Supporting Financial Viability of Emerging ILEC Projects	403
12.3.4.6	Development of Blockchain Technologies for P2P Energy Trading	403
12.3.5	Social Dimension	404
12.3.5.1	Challenges of Introducing ILEC-related Projects into Communities	405

12.3.5.2	Engagement of Citizens Through Energy Communities	406
12.3.5.3	Implementation of Strategies to Increase the Social Acceptance of the Communities with Respect to the ILEC Paradigm	407
12.3.5.4	Engagement and Cooperation Between ILECs, Municipalities, Stakeholders and Other Actors	408
12.4	Conclusion	409
	Acknowledgment	410
	List of Abbreviations	410
	References	411
<b>13</b>	<b>Conclusions and Key Findings on the Integrated Local Energy Community Concepts and Related Applications</b>	<b>415</b>
	<i>Marialaura Di Somma, Christina Papadimitriou, Giorgio Graditi, and Koen Kok</i>	
	List of Abbreviations	423
	<b>Index</b>	<b>425</b>