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Eine Dissertation ist ein schwierigeres Unterfangen, als ich mir anfangs vorstellen konnte. So handelt es sich bei dieser nicht einfach um eine "lange Diplomarbeit", sondern stellt sie vielmehr ein komplexes vielschichtiges Forschungsprojekt dar, deren Fragestellungen einer eigenständigen Erarbeitung bedarf. Da eine erfolgreiche Dissertation ohne seelische und intellektuelle Unterstützung nicht möglich gewesen wäre, möchte ich hiermit die Gelegenheit ergreifen meinen Kollegen, Freunden und Familie zu danken. An erster Stelle möchte ich meinem Betreuer Hans Auer und Audun Botterud danken. Hans hat mich erfolgreich überredet in die Energiewirtschaft einzusteigen und war mir in den letzten Jahren ein wichtiger Diskussionspartner. Audun hat mir die Möglichkeit gegeben die Top-Forschung am MIT kennenzulernen und war mir ein herausfordernder Sparringspartner. So hat er maßgeblich zur Schärfung der Fragestellung, Methode und Ergebnisse beigetragen. Durch deren Diskussionsbereitschaft war es mir möglich "Energiegemeinschaften" aus unterschiedlichen akademischen Blinkwinkeln verstehen zu können. Da eine Dissertation in dieser Tiefe ohne eine universitäre Anstellung und Forschungsprojekte nicht möglich gewesen wäre, möchte ich zwei weiteren Personen danken. Zunächst möchte ich Reinhard Haas danked erwähnen, der mir die Chance gegeben hat in die universitäre Lehre einzutauchen. Anschließend Georg Lettner, welcher mich jederzeit unterstützt hat. Außerdem durfte ich mit ihm viele spannende Fragestellungen diskutieren und lösen. Weiters danke ich auch der Technischen Universität Wien, dem österreichischen Bundesministerium für Verkehr, Innovation und Technologie[1],

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Abstract

As requested by the European Commission,the development and integration of decentralized renewable energy sources require, among other things, the introduction of energy communities. Energy communities are a voluntary group of local consumers and generators. They are capable of increasing the economics of renewable generation as well as appropriately reflecting the interests of their members. This thesis aims to give a comprehensive analysis of energy communities. Therefore, three scientific approaches provide insights into (i) the value creation of energy communities, (ii) the functionality of allocation algorithms and (iii) safeguarding a stable community. This work's modeling approaches use methods from optimization and game theory. Methodical contributions and quantitative case studies demonstrate that energy communities reduce costs and emissions, if the frameworks are designed appropriately. Additionally, efficient distribution and clearing algorithms increase the participants' utility the energy communities' stability. The three approaches investigate different case studies and discuss the implications for actors within and outside the energy community. Finally, a critical reflection allows identifying future directions of research for energy communities.

Kurzfassung

Wie von der europäischen Kommission gefordert, bedarf der Ausbau und die Integration von dezentralen erneuerbaren Energieträgern unter anderem die Einführung von Energiegemeinschaften. Energiegemeinschaften stellen einen freiwilligen Zusammenschluss von räumlich lokalen Verbrauchern und Erzeugern dar, welche in der Lage sind die Wirtschaftlichkeit von erneuerbarer Erzeugung zu steigern und das Interesse der Mitglieder besser abzubilden. Das Ziel dieser Dissertation ist die umfassende Analyse dieser Energiegemeinschaften. Hierzu geben drei wissenschaftliche Ansätze Einblicke in (i) die Wertschöpfung von Energiegemeinschaften, (ii) die Funktionsweise von möglichen Verrechnungsalgorithmen und (iii) die Sicherstellung einer stabilen Gemeinschaft. Für die Modellierung der Energiegemeinschaften werden Methoden aus der Optimierung und Spieltheorie genutzt. Durch die methodische Beiträge und quantitativen Fallbeispiele kann diese Arbeit zeigen, dass Energiegemeinschaften, unter den richtigen Rahmenbedingungen, in der Lage sind Kosten und Emissionen zu reduzieren, während es effiziente Verteilungs- und Abrechungsalgorithmen ermöglichen, den Verbrauchernutzen und die Stabilität der Energiegemeinschaft zu steigern. Die drei Ansätze untersuchen unterschiedliche Ausprägungen von Energiegemeinschaften und erörtern die Konsequenzen für Akteure innerhalb und außerhalb der Energiegemeinschaft. Abschließend ermöglicht eine kritische Reflektion zukünftige Forschungsrichtungen für Energiegemeinschaften zu identifizieren.

Contents

Abbreviations

AC	Alternating current
COP	Coefficient-of-performance
B	Apartment building
BESS	Battery energy storage system
C	Consumer
CC	Combined-cycle
CoS	Cost of Stability
DC	Direct current
DER	Distributed energy resource
DG	Distributed generation
DHW	Domestic hot water
E	Single-family housing
EC	Energy community
EH	Electric Heater
EoS	Economies of Scale
ESS	Energy storage system
ERCOT	Electric Reliability Council of Texas
ESCO	Energy Service Company
EV	Electric vehicle
DER	Distributed energy resource
G	Grid
GC	Grand coalition
GIS	Geographic information system
HEC	Homeowner Energy Community
HECwR	Homeowner Energy Community with Resources
HECw/oR	Homeowner Energy Community without Resources

HECrR	Homeowner Energy Community renting Resources
HERO	Hybrid Energy Optimization
HP	Heat pump
HVAC	Heating, ventilation, and air conditioning
IPCC	Intergovernmental Panel on Climate Change
JIOP	Joint investment and operation problem
MG	Microgrid
MILP	Mixed-integer linear program
MPEC	Mathematical Program with Equilibrium Constraints
NBS	Nash Bargaining Solution
NG	Natural gas
NREL	National Renewable Energy Laboratory
O	Owner of an apartment building or resource for solar PV
OD	Open data
OSM	Open source model
PV	Photovolatic plant
SH	Space heating
ST	Solar thermal plant
SOC	State-of-charge of a storage system
SWOT	Strengths, Weaknesses, Opportunities and Threats
TEC	Tenant Energy Community
TESS	Thermal energy storage system (heating and hot-water)
WTP	Willigness-to-Pay
Z	Large-panel system building

1. Introduction

1.1. Motivation

Rapid climate change is one the biggest challenge humanity is facing today. As stated by the Intergovernmental Panel on Climate Change (IPCC) the continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems (IPCC et al., 2018). Globally, the use of energy represents the largest source of greenhouse gas emissions from human activities (OECD/IEA, 2018). As stated by the OECD/IEA and IPCC documents about two-thirds of global greenhouse gas emissions are linked to burning fossil fuels for energy to be used for heating, electricity, transport, and industry (EEA, 2017). For example, in Europe, energy processes, i.e., fossil fuels used for heating, electricity, transport and industry, are the largest emitter of greenhouse gases, being responsible for 78 % of total EU emissions in 2015 (European Commission, 2018b). Due to the current state of research, the limitation of the greenhouse gas emission, together with adaptation, can limit climate change risks (UN, 2016).

In this respect and as discussed within the Paris Agreement, renewable and sustainable energy generation, energy efficiency measures is among other options necessary to limit the greenhouse gas emission (UN, 2016). Additionally, IPCC reports define multiple pathways to renewable energy resources (RES) to supply 70-85 % of the electricity consumption by 2050 to limit global warming to 1.5 °C. The World Energy Outlook (OECD/IEA, 2018) identifies solar energy and photovoltaics (PV) in particular as a strategically important technology option to transform the energy system. During the last decade, PV costs have decreased and PV deployment increased faster than the most optimistic calculation expected (Fraunhofer ISE, 2019). Creutzig et al. (2017) calculate that PV can be the dominant electricity supply technology with a share of 30-50 % of the future electricity generation, even as the energy system will become more electricity-intensive than today's (Lechtenböhmer et al., 2016). While solar PV on the rooftop on single-family houses is a well-established (Biermayr et al., 2017) and integrated solution, there have been relatively few such installations on multi-unit apartment buildings so far (Roberts et al., 2015).

One concern of RES is the variability of the generation due to weather conditions. Besides short-term fluctuations (e.g., the alternation of day and night), RES follow the seasonal cycle of the weather. It is also expected that the future energy system faces increasing flexibility requirements in order to balance supply and demand (Kondziella and Bruckner, 2016). According to Bertsch et al. (2012), "*flexibility is the capability to balance rapid changes in renewable generation and forecast errors within a power system.*" As stated by Kondziella and Bruckner flexibility may be provided by highly flexible power plants, energy storage systems (ESS), curtailment of renewable surplus generation, Demand-side Management (DSM), grid extension, virtual power plants and the coupling of energy markets (i.e., electricity and heat demand).

In comparison to the much more centralized conventional energy production, RES and ESS offer opportunities for the local government and communities (Schoor and Scholtens, 2015). The opportunities include generation of local welfare, the creation of jobs, the reduction of emissions and pushing forward the energy transition. As stated in Schoor and Scholtens (2015) some communities and regions have expressed goals in transforming their energy system into an efficient renewable energy system. In this context, the type of generation units allocated close to the energy consumers are called "distributed generation" (DG)[1] or "distributed resource" (DER). Nevertheless, DG is

[1] Pepermans et al. (2005) conclude that the most appropriate definition of DG is "*an electric power generation source that is connected directly to the distribution network or on the customer side of the meter*".

not entirely new. Decades ago, electricity was generated by local generation facilities and distributed to neighbors. The emergence of AC grids and the Economies-of-Scale (EoS)[2] led to central power plants and therefore to a central organized energy system (Pepermans et al., 2005). However, the trend towards centralization is changing and a "second era of decentralization" can be seen today (Alanne and Saari, 2006).

In recent years, academia and policymakers promote microgrids (MG) and energy communities (ECs) to transform the central energy system toward a local one and increasing the share of RES and ESS. The following gives a brief introduction in the similarities and differences of MGs and ECs, beginning with a definition of both. Rakos et al. (2012) defines an MG as *a localized group of electricity sources and loads that it operates typically connected to, that acts as a single controllable entity and in a synchronized way with the conventional utility grid, but can be disconnected and independently operated according to physical and/or economic conditions.* There are multiple notations for ECs in the literature. An excerpt are "local energy community", "clean energy community" and "prosumer community" (Gui and MacGill, 2018; Espe et al., 2018). The term "energy community" is recently defined by the legislation. The European Commission defines an EC as a "*legal entity which is effectively controlled by local shareholders or members ... involved in the distributed generation and in performing activities of a distribution system operator, supplier or aggregator at a local level, including across borders*" (European Commission, 2017a; European Commission, 2017b)[3]. In this way, ECs shall be entitled to share electricity from generation and storages within ECs based on market principles (Pause and Wimmer, 2018).

[2]Christensen and Greene (1976) find that until 1955 significant EoS were available to nearly all firms, but changed in the 1970s towards flat costs. They conclude that a small number of large firms are not required for efficient production and that policies designed to promote competition in electric power generation cannot be faulted in terms of sacrificing EoS.

[3]At the time of writing, the revised versions of the Electricity Directive (2016/0380(COD)) and Regulation (2016/0379(COD)) are approved by the European Parliament. The next steps are that the Council of Ministers of the EU will have to approve the proposals. While the Regulations will enter into force immediately (with a date of application of 1 January 2020 for the Electricity Regulation), the Directive will have to be transposed into national law within 18 months. (European Commission, 2019b)

Most studies consider MGs to be a well-defined part of the distribution system where all connected members (e.g., consumers) are part of the MG (Hossain et al., 2014). MGs are also used for emergencies. As an example, MGs are placed near hospitals, police stations, etc. for providing power to during power shutdowns (Costa and Fichera, 2014). They may also support the restoration of the energy system after a shutdown (Li et al., 2014). On the contrary, ECs intend to be voluntary communities with the objective to increase the members' satisfaction. Eligible members (e.g., if they are part of the same neighborhood) can choose if they want to be part of the EC or not. As a community, resources could be shared between the members. As an example, excess generation of DG may be sold to other community members or stored in a collective ESS. In this respect, the concept of MGs is a technical-based, while ECs are a market-based solution of the same problem. As the electricity markets as well as the electricity grids in Europe are well developed and keeping in mind the proposition of the European Commission, this thesis is focusing on the concept of ECs.

The literature shows that ECs can be interpreted in different configurations (Gui and MacGill, 2018). EC are embedded in the market design and legal and regulatory framework of a country, region, and city respectively. The following gives a brief introduction to key players and processes necessary to fund and operate ECs, as shown in Figure 1.1.

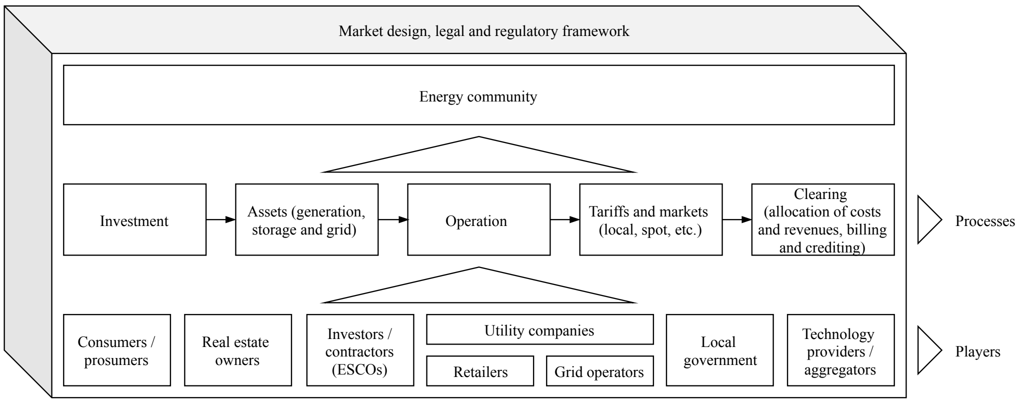

Figure 1.1.: Fundamental players and actors necessary to fund ECs.

The lower part of Fig. 1.1 shows the most relevant players involved in the funding and operation of ECs. Firstly, consumers and prosumer are key members of ECs, as they either consume, generate or store energy. As ECs are often linked to real estates (e.g., by the need of green-fields or rooftop areas), the owners of those have also be involved as well. Thirdly, external investors, mostly in the form of contractors or energy service companies (ESCOs), may be of relevance for investing in DERs and ESSs. Utility companies, a term used in the USA, include two types of players, retailer, and grid operators (which are seperate agents in Europe). Both players are relevant for ECs, as retailers provide access to the energy markets and grid operators are responsible for the connection to and the operation of the grids. Also, in most European countries grid operators are responsible for metering (JRC, 2019). Fifthly, the local government is significant since it is in charge of enforcing the local regulation and legislation (e.g., dedication acts). New players, such as technology providers and aggregators are relevant since they provide access to new markets (e.g., balancing markets) or technology services (e.g., data exchanges).

The next step is the definition of the processes, as shown in the second line of Figure 1.1. Firstly, it is necessary to invest in assets for generating (DERs), storing (ESSs) and distributing (grids) energy. As a result of this, the players as mentioned above may be involved in different configurations, e.g., the investment may be conducted by consumers, utilities, third party or any combination. As transmission and distribution grids already exist in Europe and the USA, it may be expected that the DSO operates the grid which includes managing ECs. As mentioned earlier, it is expected that the value of flexibility such as flexible DERs and ESSs increases in the future energy systems (Schwabeneder et al., 2019). Therefore, utilities, ESCOs, aggregators, retailers or technology providers may operate the DERs and ESSs on behalf of ECs. Value-driven operation strategies may be triggered by markets prices (e.g., local, spot markets or balancing markets) or tariffs (e.g., peak pricing). Alternative operation strategies involve the system's carbon emissions or increase the degree of self-consumption. The last step is the clearing process. The use of metered data (generation and consumption) shall allow a fair and transparent allocation of energy and subsequently allocating costs and revenues. In this way, values should be provided to all players giving a motivation to stay in the ECs.

1.2. Research Questions

The objective of this thesis is to provide insights into the value creation, allocation of energy and costs as well as the stability of ECs. The objective is addressed by three contributions, each following a specific research question. While the first contribution gives insight into the economic and environmental advantages of ECs including the investment decision, the second contribution is an operation and clearing concept. The third contribution combines the investment and operational concepts and aims at keeping ECs stable, i.e., providing incentives for each member to stay in ECs. The following section states the research questions, the corresponding hypotheses and the individual contribution of this thesis to the scientific literature.

Research Question 1: *What is the value in respect of emission and cost reductions, if energy communities are implemented on a large scale?*

As stated in the previous section, the intention of introducing ECs is at least twofold[4], to reduce carbon emissions additional of being cost competitive to central organized energy systems. It is assumed that the reduction of emissions and costs may be conflicting with each other. If ECs are designed towards least possible costs, it differs to a "low carbon" ECs. Therefore, the intention of Research Question 1 of this thesis is to give insights into the relationship between emission avoidance and cost increase.

Different types of consumers and producers compose ECs. As the consumer choice is not part of this contribution, it may be concluded that the EC investigated in this work is identical to an MG approach. Although technical restriction, as well as access to energy markets, is considered, detailed technical considerations are no studied. Furthermore, the first contribution develops methods to give decision makers the tool to calculate the capabilities and restrictions of the local energy system. As it is expected that the energy markets' design changes in the future, a sub-question is how those changes influence the prosperity of ECs.

[4] Other objectives may be the democratization of the energy system, an increase in the customer satisfaction, etc.

Research Question 2: *If an energy community is implemented, how should the energy be shared and priced between the members of the community?*

The second Research Question 2 addresses the energy allocation in ECs. With this, sub-questions have to consider what the motives and drivers of ECs' members are. An essential part of ECs is the voluntary and active participation of consumers, and consumer choice has to be addressed accordingly. Therefore, it has to be understood what drives consumers in buying and selling electricity. For the design of appropriate energy sharing models, it is necessary to include the aspects as mentioned earlier.

Other sub-questions tackle the issue of welfare allocation. As ECs enable the members to produce and consume local energy, the traditional business model of retailers is effected. In this context, the allocation of energy as well as the local pricing schemes define each member's slice of the pie.

Research Question 3: *If an energy community is implemented, how to share the value and how to provide incentives that the members stay within the community?*

Research Question 3 combines Research Questions 1 and 2, as it contributes to the fact how the total value of ECs is allocated among it's members. The allocation considers realistic relationships between the consumers of energy and potential outside investors while accounting for investment and operation of DERs. The second part of Research Question 3 puts the attention to the fact that ECs are market-based models, i.e., the members can decide, if they want to stay in the EC or not. So, ECs have to be designed by sustainable criteria and, most important, stable from the beginning. How this can be achieved is part of this thesis's third contribution.

As an overview, shows Figure 1.2 the relation of research questions as well as the contributing chapters of this thesis. First, the spatial resolution of all three contributions is different. While the first considers a whole city district, the latter two are considering small scale ECs. More precisely, they study two different apartment houses. The first contribution elaborates on the combined value of the EC, and the remaining two consider individual objectives of the consumers. The intention of the second contribution is the development of efficient allocation and clearing algorithms based on the consumers' preferences. Thus, it contributes to operational strategies for ECs. On the contrary, Research Question 3 studies investment strategies aiming for cost reduction and how to ensure stable ECs.

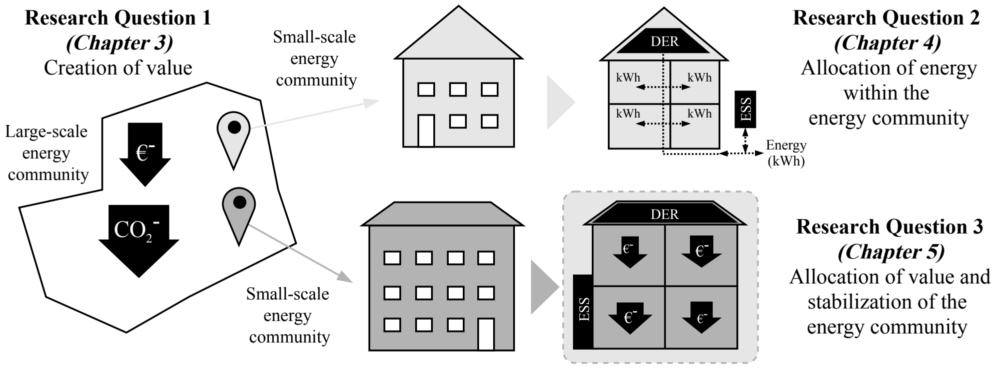

Figure 1.2.: Relation between the contributions of this thesis.

1.3. Structure of the Thesis

The structure of this thesis is as follows. Chapter 2 provides insights into the current state of scientific knowledge in the modeling of ECs. It does not only enlist the contribution of the literature, but it also states where to start answering Research Questions 1 to 3. In detail, the first part of this chapter analyzes the essential strands in the literature. Secondly, the progress beyond the state of the art is provided.

In the next step, three quantitative contributions are presented giving insights into the functionality and management of ECs. As shown in Figure 1.2 different geographical scales as well as aspects of ECs are covered. The contributions are described in three consecutive chapters.

Chapter 3 tackles Research Question 1 (large scale EC; creation of value) and bases on the work Fleischhacker et al. (2019b). The EC is modeled as a multi-energy system including all grid-bound energy carriers. This work expands two existing open source energy models with a Pareto optimization, including two objectives: costs and carbon emissions. Also, clustering algorithms support the models' scalability and performance. The models are scaled by a case study in the city of Linz, Austria. Multiple scenarios help to understand how exogenous parameters and market designs (e.g., building stock, energy efficiency measures) affects the creation of value.

Chapter 4 elaborates on Research Question 2 (small scale EC; allocation of energy), bases on the publication Fleischhacker et al. (2018) and aims at understanding the effect of sharing distributed generation. Therefore, it develops two energy sharing models, welfare optimization, and a non-cooperative game theoretical model. Furthermore, it includes consumer preferences by means of multi-objective optimization. The framework is applied to a use case from Texas, USA.

Then, Chapter 5 concludes the methodological input of this work by focusing on Research Question 3 (small scale EC; allocation of value and stabilization of the EC). It bases on Fleischhacker et al. (2019a). This work develops a value allocation algorithms for energy communities based on the cooperative game theory. Furthermore, it proposes stabilization algorithms for ECs helping them from breaking apart. The method considers different relationships between the consumers of energy and investors reflecting the real-life setup. The value allocation and EC stabilization algorithms are applied to a numerical example using data from the Austrian electricity market.

The overall findings and a synthesis of the results are discussed in Chapter 6. Chapter 7 concludes the thesis and recommends future directions of research.

2. State of the Art in Modeling of Energy Communities

While the previous chapter introduces the motivation of analyzing energy communities, this chapter gives insights in methods necessary for answering the research questions. As shown in Figure 2.1 there is an ongoing scientific interest in ECs. According to Scopus (2019) the number of published scientific documents including the keywords “local energy community” is 643 for the year 2018.

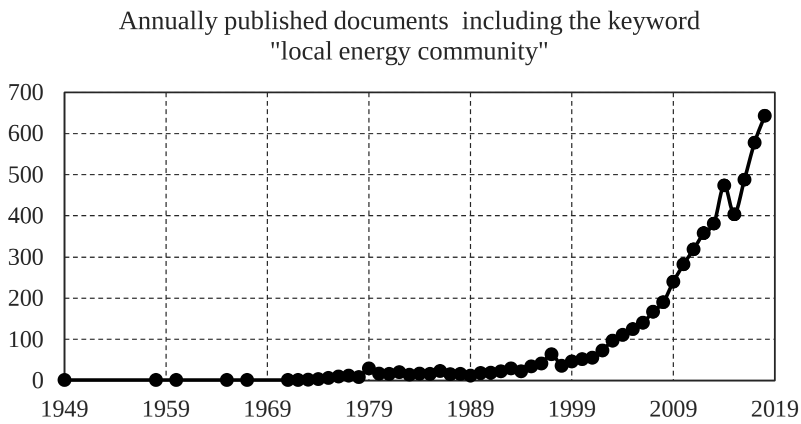

Figure 2.1.: Annually published documents (including articles, books, conference papers) for the keyword `local energy community`. Own representation basing on Scopus (2019).

This chapter gives an introduction in the most relevant methods for describing ECs in a techno-economic way. As the research questions covers different areas, they require a variation of methods. As a starting point, Figure 2.2 gives an insight into the literature’s relevance to this thesis’ contributions.

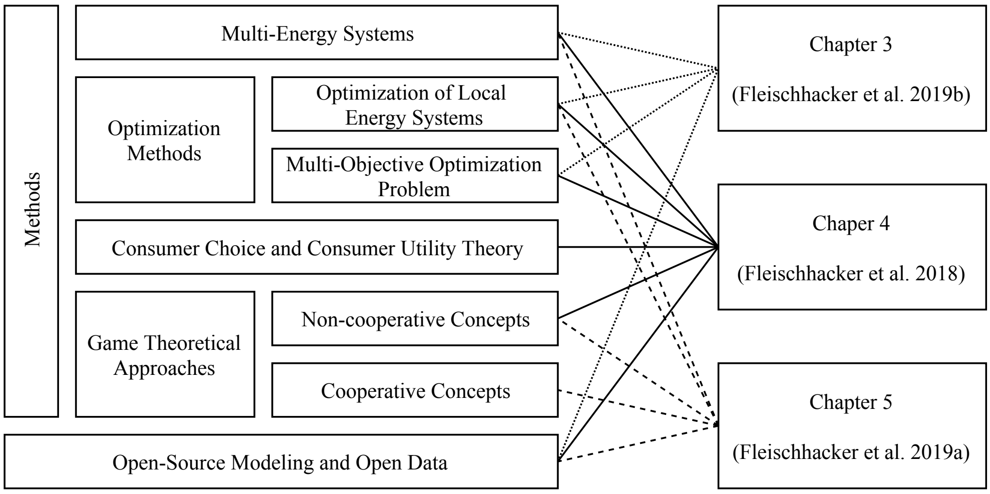

Figure 2.2.: Relevance of the literature to the contributions of this thesis.

The literature review begins by pointing out the relevance of multi-energy systems in Section 2.1. Then, optimization methods play a core role (Section 2.2). More precisely, Section 2.2.1 introduces optimization models for local energy systems. As techno-economic methods tackle the research questions of this work, the majority of optimization models developed in this work are parameterized by technical restrictions and solved toward economic objectives. If an optimization model is solved towards opposing objectives (e.g., cost reduction and emission avoidance), the problem may be described by multi-objective optimization problems (Section 2.2.2). As consumers of energy may not only be described by the objective of cost reduction, the consumer choice and consumer utility theory gives insights in modeling complex consumers (Section 2.3). Another method used in this work, game theory is discussed in Section 2.4. This thesis applies of two concepts, non-cooperative and cooperative concepts. Besides methods, this thesis benefits from open source models and open data, which is appreciated in Section 2.5.

2.1. Multi-Energy Systems

Although ECs are often stated in the context with electricity generation and consumption, ECs offer the opportunity to maximize the potential of different local resources (Good and Mancarella, 2019). In this context, many studies (e.g., Martinez-Mares and Fuerte-Esquivel (2013) and Good and Mancarella (2019)) highlight the importance of considering energy in a multi-energy system context (e.g., electricity, heat, cooling, fuels, transport) rather than focusing on electricity only. Other terms for multi-energy systems are sector coupling or integrated energy systems. As different types of demand, storages, and generation are coupled, synergies and opportunities may be defined.

Mancarella (2014) reviews 172 studies on multi-energy systems and concludes that they have a better technical, economic and environmental performance relative to “classical” independent or separate energy systems at both the operational and the planning stage. Some specific outcomes of other studies are: Ma et al. (2018) show that the distributed multi-energy systems have better economic and synergistic performances than the conventional centralized energy systems. Widl et al. (2018) propose a method to assess multi-carrier energy grids under a holistic scope, systematically. As a proof-of-concept, the method is applied to a real-world use case of a hybrid thermal-electrical distribution grid in a central European city. The application of a multi-energy system reduces the imported heat by 20 %.

Consequentially, this thesis models ECs as a multi-energy system focusing on the two most relevant energy carriers for end-consumers: electricity and heat. As the European European Commission (2018b) expects that electric vehicles will be an essential factor for the future energy system, private transport is included in the electricity demand.

2.2. Optimization Methods

There exist multiple ways to quantify the effort and impact of integrating DERs into energy systems. Hereby, it can be distinguished between Top-Down and Bottom-Up energy planning models (Huang et al., 2015). Top-Down models rely on macroeconomic data and models to calculate for example growth in energy demand, supply and prices. Typically, top-down models are linked with equilibrium models. Those models seek to explain the behavior of supply, demand, and prices in a whole economy or part of an economy (general or partial) with several or many markets (Connolly et al., 2010). On the contrary, Bottom-Up models identify and analyse specific energy technologies in detail (e.g., considering technical restrictions) (Reinhart and Cerezo Davila, 2016).

This thesis has a particular interest in Bottom-Up models. Hereby, Després et al. (2015) and Connolly et al. (2010) present classifications of Bottom-Up models for energy-systems:

Simulation tools simulate the operation of energy-systems to supply a given set of energy demands. Typically, this tool has a defined temporal resolution (e.g., one hour) and considers a given period (e.g., one year).

Scenario tools combine a series of periods into a scenario. Scenarios could be either short-term or long-term (typically 20–50 years). While the first one is used for operational problems, the second one gives insights for investment-related problems.

Optimization tools can either optimize the operation of a given energy-system or the investments in an energy-system due to a defined objective (e.g., cost-reduction). The solution gives an insight into the optimal state of the energy system.

Optimization tools are widely used in the scientific literature to tackle research questions similar to those defined in Chapter 1 (Mancarella, 2014; Mendes et al., 2011). For this reason, this thesis focuses on optimization models for ECs. This work investigates both, investment and operation strategies for ECs.

2.2.1. Optimization of Local Energy Systems

Optimization models are able to include different technologies. They are designed to optimize investment and dispatch decisions of processes (e.g., PV and heat pumps (HP)), storages (e.g., battery and hot water storage) and networks/grids (e.g., electricity or heat grid). There exists multiple optimization models in the scientific literature. Connolly et al. (2010) and Iqbal et al. (2014) list up the background, the functionality, and previous work of multiple tools. In this context, DER-CAM is an optimization model that determines the optimal capacity and dispatch strategy of distributed generation technologies to minimize global annualized cost on the customer level (Stadler et al., 2016). Geidl (2007) introduces the energy hub concept, which is designed to a couple of various energy systems and manage energy flows through process conversion, storage, and distribution of energy in an optimal way. Nazar and Haghifam (2009) use the energy hub approach of Geidl (2007) to optimize an urban electricity distribution system for investment and operational costs, and availability. Weber and Shah (2011) adapt mixed integer linear optimization techniques to design and optimize district energy systems.

Thus, various optimization models have been developed to optimize urban energy systems towards pre-defined objectives. The objectives are either costs, emissions, etc. or any combination known as multiple-objectives (introduced in Section 2.2.2). Investment and dispatch decisions are either modeled by continuous or integer variables. Since investments for DERs and ESSs include Economies of Scale (EoS) (see Loschan (2017)), they require the introduction of binary variables. Therefore, this work uses mixed-integer linear programs (MILP) for problems with EoS investment decisions.

As stated in the introduction of this thesis, ECs consist of a countable number of entities (consumers, producers, and prosumers). Nevertheless, it is not clearly defined how many entities and which geographical structures are necessary to form an EC and how to apply them in an optimization model. Herby, different scales (e.g., buildings, blocks, districts) have different requirements. Various studies investigate optimum energy designs of cities and small entities of cities (such as districts and blocks, also name large-scale ECs in this thesis) (Ma et al., 2018). Orehounig et al. (2015) present a method of integrating energy from DES at the district level using the energy hub approach. The advantage is that the energy supply systems and local energy storage systems can be evaluated in a combined way at the district scale. The proposed approach can be used to evaluate and size urban energy systems according to their energy-autonomy, economic and ecological performance. McKenna et al. (2017) analyses the scale effects on the economics of energy autonomy in residential buildings. Different scale-levels have been investigated, and the results indicate a shift in the economically optimal level of electrical self-sufficiency with scale. In single-family houses this means from around 30 % at the individual building level (i.e., small-scale ECs) to almost 100 % in districts of 1000 households (i.e., large-scale ECs). Consequentially, this work develops and uses different optimization models regarding the ECs' size. Most important is the relevance of the distribution grid, since it is an essential entity allowing the exchange of energy.

The optimization models dealing with grids are very different to those studying the investment and operation of DERs and ESSs. Various network flow models have been developed in the past (Gómez et al., 2013). Most important, geographical dimensions of the grid have to be considered by the optimization model. Most models have to deal with a very long computation time when large networks are taken into account. Therefore, special tools are required to apply the model to larger districts (Sameti and Haghighat, 2017). Mehleri et al. (2012) present on a mathematical model to size decentralized energy generation systems including a district heating grid. Fichera et al. (2017) use a framework of encompassing complex networks theory and energy distribution issues. This work uses a combination of geographic information systems (GIS) and MILP to include the grid in the optimization approach.

2.2.2. Multi-Objective Optimization

As stated in Section 2.2.1, optimization models may be solved in respect of different objectives. Sameti and Haghighat (2017) show that objective functions at the district level (i.e., large-scale ECs) are typically carbon emission, production, revenue, operation costs, investment, fuel costs, and renewable exploitation. However, energy supply concepts with minimum costs are often incompatible with emission reduction targets. Multi-objective optimization models are frequently used in the literature to tackle the problem of including different objectives. Thus, the outcome of multi-objective optimization models can be used to quantify the trade-off curve of opposing objectives. At any point on the curve, the objective's value cannot be decreased without increasing the other (Molyneaux et al., 2010). This so-called Pareto front, mathematically defined by Ben-Tal (1980), shows the most efficient solutions concerning two or even more objectives. The results and changes in deployed technology along the Pareto front helps, e.g., to quantify the costs of emission reduction targets.

Examples of the literature are as follows: Stadler et al. (2014) show the trade-off between cost and emission reduction and reported on the optimal investment decisions. Similar to the aim of this work Stadler et al. (2014) calculates the Pareto front within the planning optimization algorithm. Voll (2014) introduces a mathematical programming framework for the operation and sizing of distributed energy supply systems based on a superstructure-based and superstructure-free methodologies. Additionally, multi-objective optimizations are used to generate Pareto fronts for the objectives of cumulative energy demand total investment costs. Morvaj et al. (2016) expand the previously introduced energy hub concept Geidl (2007) by a multi-objective optimization of the total cost (investment and operational) and carbon emissions. Fonseca et al. (2016) develops a framework for the analysis of building energy systems at the urban scale based on Pareto fronts. Wang et al. (2017) applied a similar method to a university campus in Stockholm. They clearly described that the Pareto front could give stakeholders an overview of designing the energy system and understanding the options and limitation that they face (e.g., concerning costs and emissions). Similar conclusions are drawn by Zhang et al. (2016), who applied multi-objective optimization for the design of a waste heat recovery network.

As the literature states, multi-objective optimization and Pareto fronts, in particular, are beneficial to decision makers. These approaches determine the optimal energy system (e.g., for district heating) from both environmental and economic perspectives. Therefore, multi-objective optimization models are preferable to support decision makers, because the effects of (often) conflicting objectives can be quantified and allow them to make reasoned (investment) decisions. One aim of this work is to integrate the functionality of multi-objective optimization to the models of ECs. Additionally, as the following Section 2.3 describes, multiple objectives may be used to describe consumers' preferences.

2.3. Consumer Choice and Consumer Utility

While it can be expected that companies acting on the profitability principle keeping costs low and revenues high, consumers act according to different rational principles. As described by Doebeli (1992), consumers choose between two poles: effort and cost minimization (cheap, fast, easy) and utility maximization (lust-oriented, hedonistic, searching for meaning). Paradoxically, they often oscillate between the polyvalent consumption options back and forth.

The multi-objective optimization introduced in Section 2.2.2 allows to solve optimization models of Section 2.2.1 toward a linear combination of multiple objectives. As a result of the liberalization of electricity markets, consumers can increase their satisfaction by choosing the retailing company of their choice. Thus, Shin and Managi (2017) conduct a study in Japan and find a positive impact of liberalization on the customers' satisfaction and that consumers are not only motivated by cost reduction. Kaenzig et al. (2013) conduct a similar study including 414 German electricity retail consumers. They conclude that apart from the price the most important attribute for most of the consumers is the electricity mix. Also, they state that consumers are willing to pay (WTP) a premium for green electricity. In this context, it has to be mentioned, that Denish and German citizens are paying the highest electricity retail prices of all EU countries in 2017, with the eco-tax on electricity as one of the critical drivers (Eurostat, 2019). Kubli et al. (2018) concludes that retailing companies can create real consumer value if they offer electricity mixes with a higher share of renewable, as long as the price remains below the WTP. According to Banfi et al. (2008), the consumer's WTP considers comfort benefits and cost-savings as well as the potential valuation of environmental benefits.

Concluding, financial objectives are not sufficient to motivate all consumers. Multiple objectives, as used by (Liu et al., 2017), describe consumers' utility function. In this work, the consumer's utility function and WTPs is composed of three objectives: cost and emission reduction and degree of local DER generation. It may be mentioned that three objectives are not sufficient to describe the manifoldness of all consumers and may be expanded in future scientific workings.

2.4. Game Theory in Energy Modeling

The use of optimization models allows calculating the monetary gain of ECs. As shown by Schwabeneder et al. (2019), aggregation provides most of the monetary value. Hence, ECs reduces the investment, maintenance, energy and grid costs compared to single-consumer, incentivized by EoS (Burger et al., 2017). Nevertheless, the question of how to allocate energy and monetary gains of ECs is not adequately addressed in most of the frameworks (Abada et al., 2017).

This fact motivates recent studies to develop energy sharing models. As a result of this, it has to be differentiated between operational and investment sharing problems. Examples of operational problems are Xiao et al. (2018) who uses reinforcement learning-based energy trading for MGs, while Chiş and Koivunen (2018) use coalitional game theory. Investment problems consider two time periods, modeled by two problems. While the investment problem includes the investment decision and costs, short-term operational problems focus on cash-flows. Wang and Huang (2017) propose a theoretical framework to study the joint investment and operation problem in MGs. As stated in Saad et al. (2012), some studies conclude, that game theory is expected to constitute a key analytical tool in the design of the future smart grid. Game theory is a formal mathematical framework allow to studing the complex interactions among independent rational players (Saad et al., 2012). Most works differentiate between cooperative and non-cooperative concepts (Wang et al., 2014). This work uses both concepts depending on the relationship between the players. Thus it may be appropriate to model the relationship of landlords and tenants by non-cooperative concepts, while community approaches may be considered with cooperative concepts.

2.4.1. Non-Cooperative Concepts

Non-cooperative games aim to study the outcome of games including players with conflicting interests. As stated in Saad et al. (2012) non-cooperative games can be grouped into two categories: static games and dynamic games. Static games are games where the information flows do not affect the actions of the players[1]. Most studies are dealing with dynamic games, where each player chooses her actions to optimize the individual utility function.

AlSkaif (2016) developed a distributed energy sharing framework for MGs based on a repeated game approach and showed that households achieve monthly cost saving of up to 68 %. An et al. (2016) models the MG as a multi-agent system, where agents (e.g., households) act like players in a cooperative game and employ a distributed algorithm based on the Nash Bargaining Solution (NBS). This allows allocating the costs of cooperative power management in a “fair” way. NBS is also used by Dehghanpour and Nehrir (2017) to find the solution of the bargaining game. Additionally, the problem of data privacy of different parties within the MG is addressed. Saad et al. (2012) provide a comprehensive account of the application of game theory in smart grid systems tailored to the interdisciplinary characteristics of these systems that integrate components from power systems, networking, communications, and control.

Interactions and energy exchanges are often modeled as controlled (Stadler et al., 2016) or autonomous operations (Wang et al., 2017). As suggested

[1] As pointed out in Saad et al. (2012) this setup can be seen as a one-shot game.

in Liu et al. (2017), a central entity like an operator or algorithm is needed for energy allocation and pricing. To understand the interactions between multiple participants in local energy markets, cooperative and non-cooperative game theory is regularly used (Mohsenian-Rad et al., 2010). As discussed above, many studies Mediwaththe et al. (2016), Mondal et al. (2017), and Wu et al. (2016) are using games (e.g., Stackelberg games) to model the interactions between consumers, prosumers and utility companies. Compared to the existing literature, this work develops and discusses different setups of the model, such as different types of ownership. Additionally, it elaborates on solutions for implementing game theoretical models practically.

As shown in Fan et al. (2016) and the non-cooperative and game theoretical decision-making problem of each player is formulated as a bi-level optimization problem. With this, the upper level represents the profit maximization of the player, and the lower level the energy market clearing. Bi-level models and complementary theory techniques are well-established frameworks to tackle electricity market problems (Ortner, 2017; Ruiz and Conejo, 2009). Bi-level optimization problems are a special kind of optimization problems which require every feasible upper-level solution to satisfy the optimality conditions of a lower-level optimization problem (Sinha and Deb, 2013).

This work uses non-cooperative concepts in the case that an EC consists of players with conflicting objectives. These concepts are applied if one member of the ECs generates electricity and sells it to another player. Finding an appropriate price is the output of a non-cooperative game.

2.4.2. Cooperative Concepts

On the contrary, cooperative games capture the situation, that players communicate with another and cooperate. Thus, cooperative games have been applied to allocate grid costs among customers (Junqueira et al., 2007) or planning of generation in a system of interconnected MGs (Wang and Huang, 2017). In an n-person cooperative game, the players can form $2^n - 1$ coalitions and negotiate the conditions of cooperation (Lippman and Rumelt, 2003).

Regarding ECs, cooperative game theory may be used to calculate investment and operation of DERs and ESSs, if owned by the community.

Nagarajan and Sošić (2008) formulate two essential questions answered by cooperative games: (i) How are the players in a coalition sharing the payoff? (ii) How to deal with the stability of coalitions. The literature provides many solution concepts for the first question (Lippman and Rumelt, 2003). Most prominent concepts are Shapley value (Shapley and Shubik, 1973), Nash bargaining solution (Nash, 1953), Nucleolus (Schmeidler, 1969) and the Vickrey (or English) auction (Hobbs et al., 2000). While the Vickrey solution is the natural result of price competition, Nash bargaining considers a bargaining process between the players. On the other hand, Shapley value is a utility measure of each player's position[2] in the game (Roth, 1978). Both the Nash bargaining solution (e.g., used by Wang and Huang (2017)) and the Shapley value (e.g., applied by Avrachenkov et al. (2015)) are widely applicable concepts for solving energy sharing and joint investment games, which also give the motivation of this work to investigate both concepts in the context of ECs.

A second question of Nagarajan and Sošić (2008) may be addressed by coalitional stability. If a coalition does not provide enough incentives for each player to stay in the coalition, it becomes unstable. The most prominent stability concept is the core of the game introduced by Gillies (1959). The core posses a stability property – if non-empty, no subset of players has an incentive to secede from the grand coalition[3] and form its coalition (Nagarajan and Sošić, 2008). Bachrach et al. (2009) exams the possibility of stabilizing a coalitional game by offering the player additional payments in order to discourage them from deviating.

In this work, the stability of ECs is a topic of interest. If coalitional stability is not given for ECs, mechanisms for stabilization are investigated.

[2]The term "position" sums up a player's endowment and the endowments of other players (Lippman and Rumelt, 2003).

[3]The grand coalition is the coalition which includes all players of the game.

2.5. Open-Source Modeling and Open Data

In recent years, open source models (OSMs) and open data (OD) became more relevant. While OSMs aim at providing the scientific community with validated methods, are OD free usable information and databases.

Currently, there are many OSMs in use in the energy research. The advantages of such models are the ability to share modeling approaches, to improve the quality and decrease adaption costs (Bazilian et al., 2012). Regardless of the specific type of OSM, Ajila and Wu (2007) show that open source software can generally meet high standards with little or no difference in quality relative to proprietary software. Thus, the scientific community more often decides not only to publish detailed technical articles, but the actual code of the models. This work aims to work partly on existing models and apply them to the research questions defined in Chapter 1.

The initiate openmod. attracted several energy modellers to their energy models (openmod., 2019). Several models with accessible source code and also input data used for publications can be found at online repositories. Dorfner (2016) presents a suite of OSMs for modeling local energy systems in his thesis. These models allow exploring the design space of energy infrastructure on an urban scale. Four case studies showed that the combined planning of the whole energy system can uncover still untapped potential synergies (Dorfner, 2016).

Besides own developments, this work uses the OSMs *urbs* (Dorfner, 2017b) and *rivus* (Dorfner, 2017a) and make improvements to the functionalities of the models. These improvements aim in increasing the models' performance, as well as including new capabilities to reflect reality more in detail. Other open souce programs used in this work are Python frameworks (e.g., Pyomo (Hart et al., 2017) and scikit-learn (Pedregosa et al., 2011)), the geographic information system QGIS (Team, 2018) and open source solvers (e.g., IPOPT (Wächter and Biegler, 2006)).

OD on the other side are freely available sets of data used without restrictions. Some of this data is available through open government initiatives, but increasingly it is coming from other institutions including non-profits, industry, transparency platforms, and research institutions (Bazilian et al., 2012). As an example, with the current discussion of the Open Data and Public Sector Information Directive, the European Commission aims at making the public sector and publicly funded data re-usable (European Commission, 2019a). The availability of OD allows to access validated data and reduces the effort of data collection. This thesis uses following OD: time series for solar radiation (MINES ParisTech / Transvalor, 2018), air temperature (ZAMG, 2012), wholesale electricity prices (EXAA, 2018; Electric Reliability Council of Texas Inc., 2017b) and costs stated in scientific publications (Lindberg et al., 2016; Loschan, 2017).

2.6. Contribution to Progress beyond State of the Art

This thesis intends to make three contributions to the literature on the topic of ECs. The contributions are in line with the research questions of Section 1.2. The first one is to calculate the value of large-scale ECs, i.e., a city district in terms of cost and emission reduction. Secondly, frameworks are proposed for allocating and pricing distributed generation and storage within an apartment building. Thirdly, this thesis presents a stabilization mechanism preventing ECs from breaking apart. Consequentially, the three following Chapters 3, 4 and 5 eleborate on the Research Questions 1 - 3. More in detail, Appendix A enlists technical assumptions and parameterization of the models used in the following chapters.

Chapter 3 proposes a framework for establishing an EC in a city district. The usage of different OSMs and a variety of scenarios help to identify how the most economic EC and, contrary, how a low carbon emission EC may be achieved. The main contributions of this chapter are:

- The proposition of a new method to quantify the benefits of ECs in city districts.
- The method describes a clustering algorithm based on the building structure of the city. Such a method may be of practical relevance for city planners as it allows reducing the complexity.
- The improvement of an established OSM with features such as economies-of-scale, input data clustering algorithms and Pareto optimization.
- Finally, as ECs might be interested in reducing the carbon emissions, different methods of emissions accounting are discussed based on the electricity market's conditions as well as the introduction of carbon taxes.

Chapter 4 of this work considers sharing concepts of DERs and ESSs for a small-scale EC. More in detail, it examines one apartment building. The main contributions of this chapter are:

- The proposition of a new algorithm for allocation and pricing of DERs in ECs (e.g., apartment houses). The algorithm may also be implemented for other community shared solar PV and battery projects.
- By solving the resulting games analytically, solutions for executing the proposed game-theoretical setup for a practical implementation are derived.
- The introduction of multiple consumer objectives (in addition to monetary motives) in a consumer utility function allows the representation of different consumer preferences in the model.
- Finally, multiple pricing mechanisms are compared to illustrate the welfare effects for the DER owner, consumers and the utility company.

Chapter 5, introduces methods for the joint investment and operation of DERs and ESSs within an small scale EC. Similar to Chapter 4, an apartment building is considered. The main contributions of this chapter are:

- Proposition of a novel analytical framework for ECs with a multi-energy system including electricity, heating and hot water provision.

- Development of new algorithms for allocating the value gained by the investment and operation of DERs and ESSs in a small-scale ECs (apartment houses) allowing a win-win situation for all participants.
- The chapter applies and compares two widely used methods of cooperative game theory, Shapley value, and Nash Bargaining within the EC framework.
- It proves that ECs often lack a stable design and introduce a stabilization mechanism based on rent costs for the PV area.

3. Cost and Emission Reduction provided by an Energy Community

This chapter aims to elaborate on Research Question 1. It bases on the paper *"Portfolio Optimization of Energy Communities to meet Reductions in Costs and Emissions"* (Fleischhacker et al., 2019b) published in "Energy - The International Journal"[1]. In the following, a large-scale EC covering a whole city district is considered. It is assumed that the EC owns the energy grids (e.g., electricity and district heating grid), DER and storages within the community's area. The assumption is in line with Walker (2008), where the ownership of EC projects might be: (i) 100 % community owned or (ii) developed under co-ownership arrangements with the private sector (e.g., community ownership of one turbine in a larger wind farm). For the sake of simplicity, this paper assumes the first case.

The work in this chapter aims to quantify the advantages of optimizing the technology portfolio of ECs regarding cost and carbon emission reduction. The EC is modeled as a multi-energy system with the restriction of satisfying needs for electricity and heat. Two verified open source models are coupled with the use of clustering algorithms. Furthermore, the open source models are expanded with three features: Pareto optimization, economies-of-scale, and time-dependent efficiency factors. As a result of this, existing and future building stock set-ups are taken into account, as well as the implementation of energy efficiency measures (lower heat demand and EV).

[1] The individual contribution of this thesis' author is enlisted in Appendix B.

The chapter is organized as follows. Section 3.1 introduces this work's contribution to the literature, by improving two open source models. Section 3.2 presents the project site and different scenarios. Section 3.3 presents the results, while Section 3.4 discusses the outcome of this chapter. Section 3.5 introduces all sets, variables and parameters used throughout this chapter.

3.1. Methods

The methods of this work base on two OSMs: "urbs" [2] Dorfner, 2017b and "rivus"[3] Dorfner, 2017a. The two models are chosen because they are well documented and allow the description of an EC in two dimensions, spatial and temporal. Dorfner (2016) developed both models and published them on the web-based Git version control repository GitHub under the terms of the GNU General Public License. In this work, the framework "HERO"[4] (an own development) is introduced, as a combination of both models "urbs" and "rivus". Figure 3.1 shows the setup and the interconnection of the model's components. The video provided in the supplementary materials of this work gives a brief introduction of the methods.

As input data, three different types of data sources are used:

1. time-series data, such as energy consumption (electricity, heat, cooling, etc.), solar radiation and the temperature depending on heat pump coefficient-of-performance (COP) as well as the energy system's emissions.
2. geographical data, such as building area or grid length and
3. technical (energy and emission conversion efficiency, technical limits, etc.) and economic parameters (investment, maintenance, and fuel costs).

[2] Latin term for city.
[3] Latin term for stream.
[4] Abbreviation of "Hybrid EneRgy Optimization".

To improve the performance and the interoperability of the models, de/-clustering algorithms are developed to meet the different requirements of the models.

The following sections describes aspects of the model. While Section 3.1.1 describes the clustering algorithms for varying the input data, introduces Section 3.1.2 improvements of the model "urbs" (such as the implementation of economies-of-scale and Pareto Optimization). Section 3.1.3 describes the method of modeling an EC, while Section 3.1.4 introduces a method to account emissions. Section 3.1.5 includes carbon taxes to the models' objective function. The video provided in the supplementary materials of this work gives a brief introduction of this work's methods.

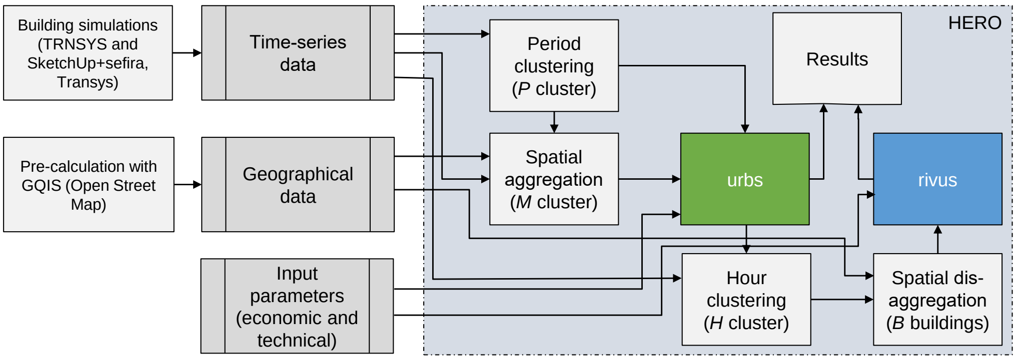

Figure 3.1.: Block diagram of the framework "HERO", developed in this work.

3.1.1. Applied data clustering and aggregation methods

As mentioned above, the two models put their focus differently: While "urbs" models processes (e.g. energy conversation including the operation of storages) in a high temporal resolution, "rivus" helps to plan the EC grid infrastructure on a disaggregated spatial layer. Consequently, both models have different requirements for the input data. This encourages this work to develop different clustering algorithms to benefit from each model's strength.

The input data is clustered to reduce the size of both models as well as the computation time of solving the optimization problems. Therefore the

K-Means clustering algorithm has been adopted for the "period clustering" to cluster the time-series data into R representative weeks (Section 3.1.1.2). Consequentially, another model uses "spatial aggregation" based on the method of different city blocks (Section 3.1.1.1). This allows the spatial aggregation of the compressed time-series data into M clusters.

The model "rivus" requires a higher reduction of the time-series data. The second time-series clustering method "hour clustering" selects the results of "urbs" to characteristic hours (Section 3.1.1.2). The "spatial disaggregation" method prepares the input data for "rivus" on a building level (Section 3.1.1.1). The model "rivus" bases on the theory of graphs and consists of edges and vertexes. Each edge of "rivus" (e.g., a grid connection between two houses) is represented by a binary variable.

In the following, the applied clustering algorithms are described in detail.

3.1.1.1. Aggregation and disaggregation of spatial data

A novel approach of this work is the assignment of urban areas to characteristic city blocks. This approach helps to reduce the complexity of planning the urban EC. The advantage of this approach is the fact that it requires less information about the area and it may be rather easy to be collected (e.g., by a standard GIS software). Characteristic blocks are modeled in detail, e.g., in terms of a dynamic heat load.

In this work, three types of buildings and blocks, significant for the Austrian housing situation within the tested case study[5], are defined:

Single-family housing block (E) is a city block of free-standing residential buildings. This building type is widespread in suburban or rural areas. Even though the buildings share one or more walls with another, it has direct access to a street or thoroughfare. Furthermore, it does not share heating facilities and hot water equipment with any other dwelling unit.

[5] For a further description of the case study see Section 3.2.

Apartment building block (B) is a city block of buildings with a high housing density. Apartment buildings are constructed around the border of the block, resulting in an enclosed area. Open space inside the block is used for collectively. Each building's apartments are self-contained housing units, whereby energy infrastructure could be shared (e.g., by a central heating plant) or not.

Large-panel system building or "Plattenbau" block (Z) is similar to apartment building block but consists of buildings constructed of large, prefabricated concrete slabs. In comparison, "Plattenbauten" are stand-alone buildings, resulting in limitations of energy sharing concepts.

In a first step, the city area is clustered in blocks, by using streets or another kind of obstacles (e.g., parks) as demarcation. In a second step, the blocks are assigned to the three predefined block-types. Figure 3.2 shows the result of this assignment as well as the block types. While E-type blocks consist of small stand-alone buildings, B-type blocks are rather enclosed entities consisting of large buildings covering the block's border. On the opposite, Z-blocks are identifiable as stand-alone buildings, but the area covered by buildings is much higher than those of single-family buildings.

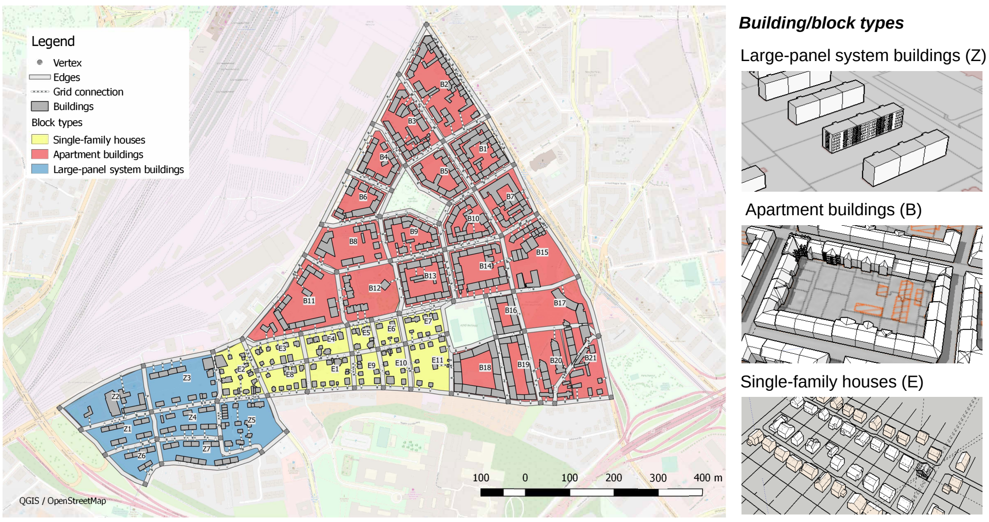

Figure 3.2.: Geographical location of all blocks in the area of Linz a city in Austria (left) and the detailed blocks (E), (B) and (Z) created in SketchUp (right). Source: (Zelger et al., 2018)

In a third step, the introduction of characteristic blocks of each type describes the remaining blocks. The assessment of the characteristic blocks bases on experts interviews (Kleboth and Granzow, 2016). Figure 3.2 shows all blocks and the characteristic blocks per type, namely B1, Z1, and E1. The energy demand (including electricity, heat and hot water and cooling demand) as well as the supply of renewable generation (solar radiation) of the characteristic blocks is used to describe the corresponding demand and supply characteristics. The description to the other blocks is based on two criteria, the building area A and the number of stories S. The energy demand is described as

$$d^i_{m,j} = d^i_{m,1} \frac{A^i_{m,j}}{A^i_{m,1}} \frac{S^i_{m,j}}{S^i_{m,1}}, \qquad (3.1)$$
$$i \in \{Heat, Elec, Cool\}\,,\ m \in \{E, Z, B\}\,,\ j \in \{2, 3, \ldots, N_m\}$$

with $d^i_{m,j}$ the electricity, heat and cooling demand of block type m and number j. $d^i_{m,1}$ is the demand of the characteristic block modeled by detailed building models (described in Zelger et al. (2018)).

By applying the “spatial aggregation”, the results is a four-node model (three for each block types plus one central slack node). The recapture of the full spatial information of the area, spatial disaggregation is applied to reverse the approach (3.1) and recalculate the energy demand of each block.

3.1.1.2. Clustering temporal data

Period clustering for urbs The K-Means clustering algorithm identifies P characteristic weeks. One weakness of this approach is that long-term (future) storage technologies such as hydrogen systems might not be integrated with adequate accuracy because of the lack of consecutive weeks.

As written in Bottou and Bengio Yoshua (1995), the K-Means method minimizes the quantization error function by using the Newton algorithm, i.e., a gradient-based optimization algorithm. In this work, the K-Means method is used to cluster time-dependent inputs:

- Demand vectors of heat (space heating and hot water demand), electricity (residential and commercial demand including the charging demand of electric vehicles) and cooling d_m^{Heat}, d_m^{Elec} and d_m^{Cool}
- Supply vectors of solar PV and solar thermal collectors (ST) q_m^{PV} and q_m^{ST} and
- Conversion efficiency of electricity to heat (COP) of heat pumps $\eta_m^{HP_{liq-water}}$ and $\eta_m^{HP_{water-water}}$.

All vectors have a length of T. Firstly, time vectors are standardized by applying the ℓ_2 norm. Standardization improves the convergence performance of the K-Means algorithm (Garreta, 2013). Secondly, the time vectors are reshaped into matrices

$$D_m^{Heat}, D_m^{Elec}, D_m^{Cool}, Q_m^{PV}, Q_m^{ST}, \Gamma_m^{HP_{liq-water}}, \Gamma_m^{HP_{water-water}} \in \mathbb{R}^{T_w \times W} \tag{3.2}$$

with T_w of timesteps within a week $w \in \{1, \ldots, W\}$ and include them in the K-Means input matrix

$$X = \begin{bmatrix} D_1^{Heat} & & D_M^{Heat} \\ \vdots & \ddots & \vdots \\ \Gamma_1^{HP_{water-water}} & & \Gamma_M^{HP_{water-water}} \end{bmatrix}. \tag{3.3}$$

This algorithm requires the number of clusters to be specified. In this work, $r \in \mathcal{R} = 4$ periods (therefore four representative weeks per year) are used.

The Python Package "scikit-learn" (Garreta, 2013; Pedregosa et al., 2011), more in detail, the method `kmeans++`, is used in this work. The K-Means algorithm divides a set of W samples X into P disjoint clusters C, each described by the mean of the samples in the cluster. The means of those clusters are commonly called the cluster "centroids"; note that they are not, in general, points from X, although they are in the same space.

Given enough time, K-means will always converge, however, this may be to a local minimum. As a result, the computation is done several times (1000 times in this approach), with different initializations of the centroids, with varying initializations. The random initialization leads to better results as shown in Arthur and Vassilvitskii (2007).

Because these centroids are neither in the dataset nor the right scale (as a result of the standardization), the Euclidean distance of each centroid to its nearest neighbor is calculated and used as the new cluster center. The corresponding length of the cluster indicates each cluster center's weight ϱ_p. In total, the sum of all weights is equal to 52 weeks per year.

To give an insight in the functionality of the clustering algorithm, Figure 3.3 shows the results of the period clustering from Section 3.3. For the sake of simplicity, only results of clustering d_{E1}^{Heat} and q_{E1}^{PV} are shown.

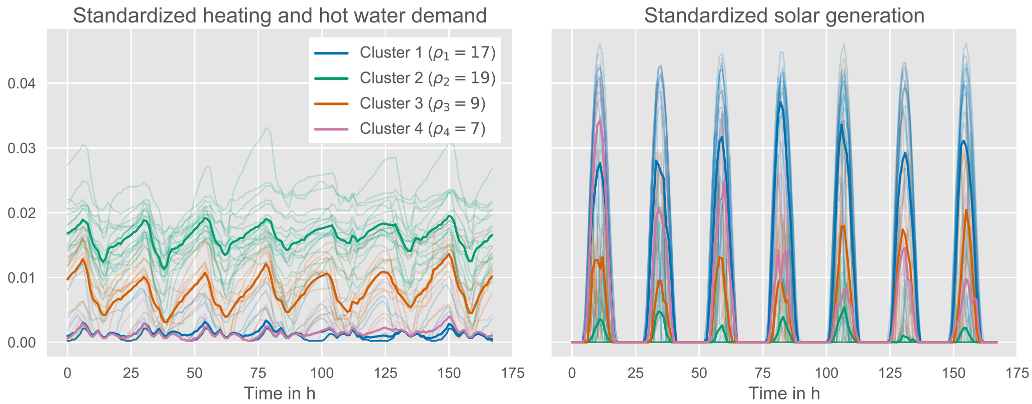

Figure 3.3.: Results for Linz (block E1) for heat and hot water demand and solar generation. While thin lines include the whole data set, the thick lines indicate the cluster centroids.

Hour clustering for "rivus" Similar to the approach presented before, hourly clustering is used to find representative hours in the dataset. Because of its characteristics, K-Means is not very suitable to cluster peaks or outliers of a dataset (Bottou and Bengio Yoshua, 1995). Therefore, an algorithm for both, peak detection and mean-value clustering has been developed:

(i) **Peak detection** identifies the annual peaks in the time series dataset. These parameters are essential for grid planning. Consequentially, all detected peaks from the dataset are excluded.

(ii) **K-Means** is applied to the reduced dataset (excluding the peaks). In contrast to period clustering (of Section 3.1.1.2), the clusters' size is one hour instead of a week.

The hour clustering algorithm to the results of "urbs". The model's results give insight into the optimal size and commitment of processes and storages. Consequentially, the data is used to model the required grid infrastructure. The grid infrastructure allows describing the distributed generation and sector-coupling[6].

In addition to the period clustering, Figure 3.4 shows the results of "urbs" as violin plot as well as cluster centers of the hourly clustering algorithm. Although Figure 3.4 includes results, it helps to increases the understanding of the algorithm. Hours of negative energy flows indicate an excess of distributed generation. The algorithm helps to identify the peaks of positive and negative load, as well as significant hours within the distribution.

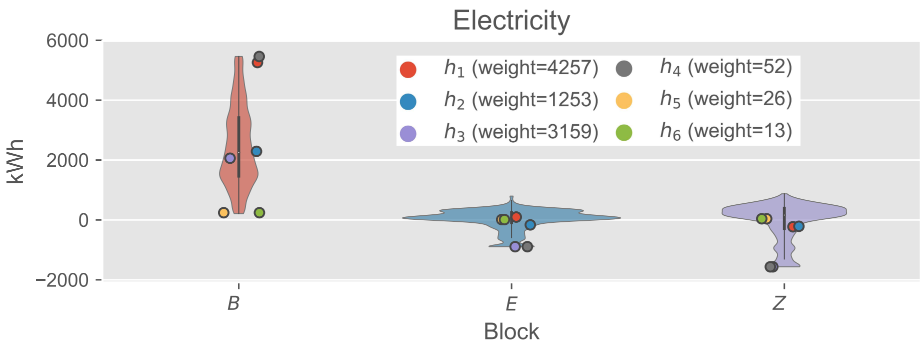

Figure 3.4.: Results of "urbs" (scenario "Status Quo" - minimum cost solution) of the electricity demand as violin plot and the corresponding "rivus" cluster center (including the weight) as points. The points h_4 - h_6 are the peaks of (i), while h_1 - h_3 are the centers of (ii).

3.1.2. Improvements of the open source model "urbs"

In this work, the OSM additional features are added to "urbs" to handle the needs of modeling ECs. Firstly, multiple periods (e.g., weeks) with the corresponding weights, are included. As the first improvement is a standard method, it will not be described in detail. Secondly, economies-of-scale (EoS) are included to capture the investment decision on a building level. Thirdly,

[6]E.g., a rise of the electrical peak load resulting from the electrification of the system

the time dependency of heat and solar generation is introduced. In a fourth step, the model's objective is changed to a Pareto Optimization with two objectives, costs and emissions.

3.1.2.1. Economies of Scale

Manfren et al. (2011) describe that optimization models have to be able to picture the EoS to describe the economics e.g. of DERs sufficiently. In accordance with the nomenclature introduced in Dorfner (2016) the process rules are expanded as follows: Total process capacity κ_{vp} (decision variable) of site $v \in V$ and process $p \in P$ consists of installed capacity K_{vp} (parameter) and new capacity $\hat{\kappa}_{vp}$ (decision variable), as

$$\kappa_{vp} = K_{vp} + \hat{\kappa}_{vp} \tag{3.4}$$

By the inclusion of binary decision variables s_{vp} the lower and upper restrictions are defined as

$$s_{vp}\underline{K}_{vp} - K_{vp} \leq \hat{\kappa}_{vp} \leq s_{vp}\bar{K}_{vp} - K_{vp} \tag{3.5}$$

Both parameters $\underline{K}_{vp}$ and $\bar{K}_{vp}$ are exogenous inputs and defined e.g. by spatial restrictions (such as roof area in the case of PV).

As EoS are significant for investments in the distribution grid as well, they are implemented as

$$s_{af}\underline{K}_{af} - K_{af} \leq \hat{\kappa}_{af} \leq s_{af}\bar{K}_{af} - K_{af} \tag{3.6}$$

with the corresponding index f referring to a transmission process to transfer a commodity along a distribution line a.

Finally, the investment costs of Dorfner (2016) are expanded by fixed investments costs

$$\zeta^{inv,fix} = \sum_{\substack{v \in V \\ p \in P}} N_{vp} s_{vp} \hat{\kappa}_{vp}^{inv,fix} + \sum_{\substack{a \in A \\ f \in F}} s_{af} \hat{\kappa}_{af}^{inv,fix} \tag{3.7}$$

including the binary decision variables. Parameter N_{vp} includes the number of processes to be purchased, e.g. in the case of PV the number of roofs (N_{vPV}= number of buildings at site v). For the following study, it is assumed that all distributed technologies are build on a building level.. The extension for storages is proceeded in the same way, but for the sake of simplicity it is not described in detail.

3.1.2.2. Time dependent conversion coefficients

Time dependent COP is added to "urbs" by expanding the output ratio r^{out}_{pct} by the dimension of time $t \in T$. To include generation time series of PV and ST, the efficiency is multiplied with the plants' nominal capacity κ_{vp}.

Coefficient-of-performance of heat pumps (air source and ground source)
The supply temperature is used to calculate the hourly COP. As introduced in Lindberg et al. (2016) the COP of process p[7] is described by a polynomial function

$$\eta^{i}_{pt} = k_0 - k_1(\Theta^{supply}pt - \Theta^{source}pt) + k_2(\Theta^{supply}pt - \Theta^{source}pt)^2 \qquad (3.8)$$

for both, domestic hot water (DHW) and space heating (SH) ($i \in \{\mathrm{DHW}, \mathrm{SH}\}$) separately. Θ^{source} describes the water or air temperature, while Θ^{supply} is different for DHW or SH. The temperature of DHW is assumed to be 55 °C and SH 50 °C/35 °C[8]. As it is not differentiated between DHW and SH in this work's model, the mean COP is calculated as

$$\eta_{pt} = (1 - share^{SH}_{p})\eta^{DHW}_{t} + share^{SH}_{p}\eta^{SH}_{t} \qquad (3.9)$$

with the $share^{SH}_{p} = 84\,\%$, a typical value for Austrian heat demand (Fischer and Madani, 2017).

[7] $p \in \{HP\ (air\text{-}water), HP\ (water\text{-}water)\}$

[8] As presented in Fischer and Madani (2017) for radiator heating in an old building stock (block type B) and floor heating for the case of a new building stock (E and Z).

Solar energy (ST and PV) Lindberg et al. (2016) describe the efficiency of the ST by a polynomial function. The framework requires the following inputs: the solar irradiation on the tilted surface, the temperature within the ST and the ambient temperature. Additionally, the solar PV collectors' efficiency is described by a function introduced in Huld et al. (2010). Huld et al. describe the collectors' efficiency as a function of the solar irradiation (the same as for ST), the modules temperature (calculated from the outdoor temperature) and a static power inverter's efficiency[9].

3.1.2.3. Pareto Optimization

Furthermore "urbs" is expanded by a Pareto Optimization to combine two opposing objectives: *costs* and *emissions*. In the following, the model's continuous variables are named $\mathbf{x}$ and binary variables $\mathbf{y}$, respectively. As introduced in Bérubé et al. (2009), Pareto Optimization dealing with two objectives may be formulated as

$$\begin{aligned} \min_{\mathbf{x},\mathbf{y}} \quad & f(\mathbf{x},\mathbf{y}) = (\mathit{costs}(\mathbf{x},\mathbf{y}), \mathit{emissions}(\mathbf{x},\mathbf{y})) \\ \text{subject to} \quad & \mathbf{x} \in \mathcal{X}, \mathbf{y} \in \mathcal{Y} \end{aligned}$$

with the feasible solution spaces $\mathcal{X}$ and $\mathcal{Y}$.

Both should be minimized by iterative use of the optimization model *"urbs"*. With this, a three-step approach is implemented basing on the ϵ-constraint method for bi-level combinatorial optimization problems[10]:

(I) The first step of the approach calculates the minimum cost solution without any restrictions concerning the emissions.

1. (II) Secondly, the objective is changed from costs to emissions. The result shows the solution in respect of minimal emissions.
2. (III) Finally, the model's objective and setup is changed back to (I), but including an upper limit of the emissions. The upper limit is a

[9] Assuming a constant power inverter's efficiency of 0.95 (Lindberg et al., 2016).

[10] See Bérubé et al. (2009) for detailed information of the characteristics of the ϵ-constraint method.

linear space between the emissions of (I) and (II) and is separated in enumerable steps.

The unit of objective of the objective function are monetary units (e.g. EUR) for (I), carbon emissions (e.g. t_{CO2}) for (II) and also monetary units for (III). Figure 3.5 shows the approach graphically. The vectors of the two different objective functions are $\mathbf{c}_{costs}^T$ and $\mathbf{c}_{emissions}^T$, respectively. Starting from point (I) (causing emissions $\overline{e}$), the Pareto Front is moving along (III) to (II) (causing emissions $\underline{e}$). The movement along (III) is a result of the ϵ-constraint in the form

$$emissions = \mathbf{c}_{emissions}^T \left[\mathbf{x}, \mathbf{y}\right]^T \leq \underline{e} + (\overline{e} - \underline{e})(1 - \alpha) \tag{3.11}$$

by the variation of the parameter α. In this work, a variation of α in 10 % steps is chosen.

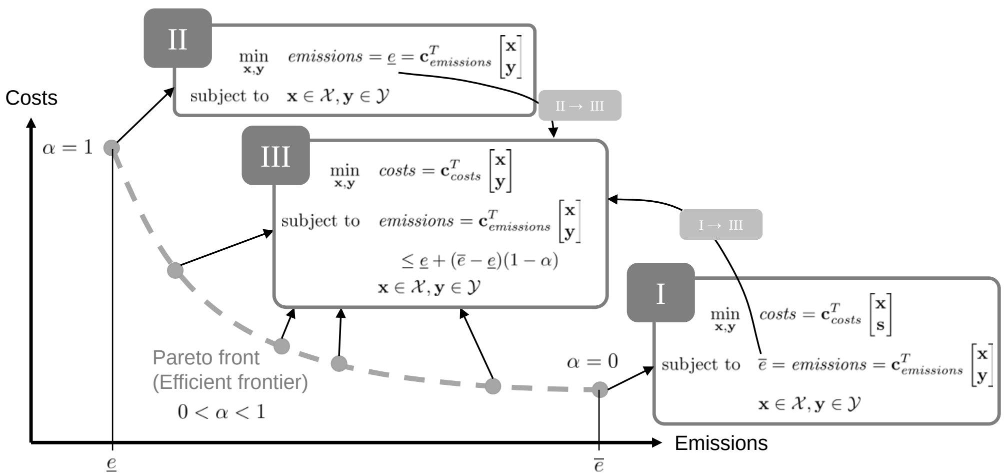

Figure 3.5.: The three-step approach of the Pareto Optimization applied in this work.

3.1.3. Modeling of Energy Communities

The big advantage of ECs is the fact that ECs can conduct joint investments. To capture this effect, EC are allowed to make investments of processes and storages on a building level (for all block types). Contrary, if there are no ECs, the investments of processes and storages are on a flat (B or Z blocks) or building (E blocks) level. So, ECs can exploit the EoS of processes and storages (modeled by binary decision variables in Section 3.1.2.1). The investment costs in the distribution grid are unchanged between those two cases.

3.1.4. Merit order based accounting of emissions

One of the objectives of ECs addresses emission reduction. So, EC may consider two types of emissions: (i) mean or (ii) marginal emissions. Both types of emissions reflect the current market conditions, but marginal emissions give information of one additional unit of energy fed into or consumed from the grid. The idea behind the comparison is that the ECs might be interested in substituting certain power plants (e.g., coal), as implied by the consideration of marginal emissions.

The mean emissions are calculated by using the total carbon emissions and the total amount of electricity generated for each time-step (hour). For the introduction of marginal emissions, the marginal generator has to be defined: The marginal generator is the unit selling the last bid and setting the price.

Figure 3.6 shows the result of the two types for two exemplary hours. The Emissions are based on the number of the German Bundestag (Deutscher Bundestag, 2007). While the upper part of the Figure shows the Central European merit order, the lower part shows the corresponding emissions of each power plant. So, the marginal generators are gas power plants (hour 1) and lignite power plants (hour 2). The merit order does reflect costs (and prices) but not the emissions: while the demand and electricity price for time step 1 is high, marginal and mean emissions are low and vice versa for time step 2. So, the marginal emissions at time step 1 are high compared to the mean emissions, as the lignite power plant sets the price.

In the following analysis, the Austrian merit order is used because of two aspects. Firstly, the Austrian electricity market[11] has a high share of RES, therefore gives an outlook how future merit orders may look like. So, the difference between mean and marginal emissions are significant. Secondly, Austrian consumers (and therefore ECs as well) have a high affinity to buy Austrian products. Section 3.3 shows the effects of considering either mean or marginal emissions by the planning of local energy infrastructure of an EC. If not stated otherwise, mean emissions are used.

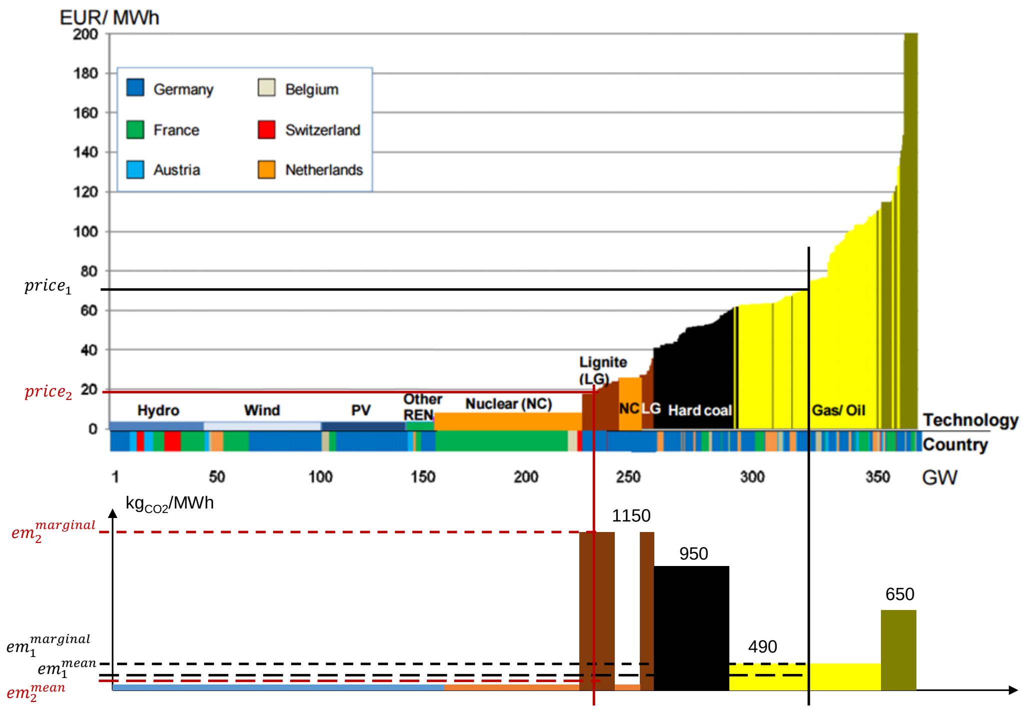

Figure 3.6.: Central European merit order (top) and the corresponding emissions (bottom). Own representation basing on IEA Coal Industry Advisory Board (2015) and Deutscher Bundestag (2007).

[11]Installed capacity according to the Austrian TSO Austrian Power Grid: Hydro 55.16 %, Wind 13.03 %, PV 4.73 %, Gas 20.48 %, Coal 2.74 % and Misc 3.86 % (APG, 2018).

3.1.5. Carbon Taxes

The European Commission proposes the introduction of carbon taxes as an effective policy measure for the reduction of carbon emissions (European Commission, 2018a). The introduction of carbon taxes effects the objective, as it increases the costs by

$$\zeta^{CarbonTax} = \sum_{t} \sum_{c \in \{Emission\}} \sum_{v \in V} \rho_{vct} C^{CarbonTax} \tag{3.12}$$

of all the emissions $\rho_{vEmissiont}$ and the parameter carbon tax $C^{CarbonTax}$.

3.2. Definition of the case study and scenarios

In the following, an EC at a site in the city of Linz, Austria is described, as well as the corresponding scenarios regarding the available energy infrastructure, energy demand, and generation. This site is chosen because data is publicly available and all three building types, typically for Austrian building stock, are present. The assumptions in regard of the economic (such as investment, maintenance and operational costs of processes, storages, and the grid) and technical (e.g., efficiency factors) parameters are listed in this work's Appendix C.

3.2.1. Project site and energy infrastructure

The method defined in Section 3.1 is applied, to a project site in Linz, more precisely the "Andreas-Hofer-Viertel"[12]. The existing buildings (as introduced in Figure 3.2 (Section 3.1)) are currently connected to the electricity and district heating grid (Linz AG, 2016). Consequentially, it is assumed in one scenario that a utility company provides electricity and heat demand (via the electricity and district heating grid). The name of this scenario is "Existing

[12]Geographical location: N 48°17′12.2", E 14°17′49.8"

Infrastructure". Also, the possibility that no generation and distribution system is available. This scenario is named "Green Field". In this case, the EC has to invest in the grid. The comparison of those scenarios helps to understand the "lock-in effect" given by existing energy infrastructure.

3.2.2. Energy demand and generation

Demand, generation, and efficiency data is described by measured and synthetic data from the year 2016[13]. To understand the effects of load development, two scenarios are introduced: The scenario "Status Quo" describe the current situation at the project site, while the second scenario, "Future", include a higher population density but also a higher energy efficiency standards[14] according to the current standard of legislation[15].

Also, the future availability of electric vehicles (EV) is addressed, by introducing one EV per two inhabitants Statistics Austria, 2018. It is assumed that the electric vehicles are charged at home (without discussing the issue of parking) The charging profiles originated from an Austrian EV Study E-Mobilitätsmodellregion VLOTTE Schuster et al., 2010. As the case study in this paper addresses an urban area, a daily demand of 4 kWh is assumed for this paper. So, the electricity demand increases more in blocks with a higher number of inhabitants (B and Z).

[13]Electricity profiles: Beausoleil-Morrison and Arndt, 2008, heat profiles: BGW, 2007, PV generation Huld et al., 2010 and ST generation Lindberg et al., 2016 and heat pump generation Lindberg et al., 2016, solar radiation time series MINES ParisTech / Transvalor, 2018 an temperature time series ZAMG, 2012. Retail electricity, gas and heat prices from the Austrian Regulation Authority E-Control, 2018. Further information regarding the building specific modeling may be found in Zelger et al., 2018.

[14]The implementation of energy efficiency measures allow a significant reduction of SH and DHW demand, especially for the B block type. Electricity demand (w/o any demand for heat pumps) depends on the number of inhabitants, whereas it is independent of building specific energy efficiency measures.

[15]Provincial Law of 5 May 1994, which enacts a building code for Upper Austria Land Oberösterreich, 1994.

3.3. Results and discussion

In this section, firstly the minimum costs solution of the EC of the case study is shown in Section 3.3.1. Secondly, Section 3.3.2 compares the minimum costs to the minimum carbon emissions solution. Consequentially, Section 3.3.3 calculates the entire Pareto Front and analyze it with respect to different methods of emissions accounting. The final results in Section 3.3.4 address the sensitivity of the minimum cost solution in the case of carbon taxes and compare it to the Pareto Front.

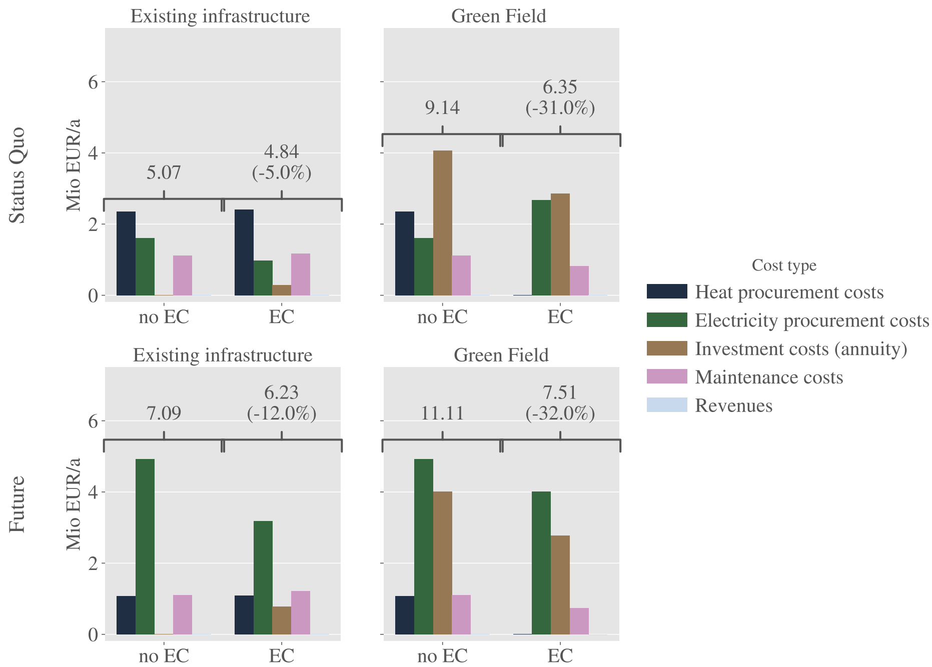

Figure 3.7.: Composition of the costs for the minimum costs solution.

3.3.1. The economic value of an energy community

In a first step, the economic value of an EC is discussed. Therefore, the cost minimal solution is calculated, also labeled solution (I) in Figure 3.5. Figure 3.7 shows the composition of annual total costs, for the cases without and with EC. Furthermore, it distinguishes between all the previously introduced scenarios.

The results show that the introduction of EC reduces the total costs by up to 32 %. The highest gains are achievable in the "Green Field" scenarios, therefore showing the lock-in effect of existing investments. In the "Green Field" scenario with an EC, the EC avoid investments in the heating grid. The EC exploits the EoS by investing in one grid only, the electricity grid. This work's method describes the EoS by two components, fixed and variable investment costs (Section 3.1.2.1). As stated in Table 4 the fixed investment costs of grids are very high. If the EC invests only in the electricity grid, the EC gains savings from not investing in district heating grids (reduced fixed investment costs). Additionally, to the savings from the EoS, the procurement costs of heat generated from electricity are lower than from district heating. In all cases, the revenues are minor because the distributed generation was almost entirely consumed locally.

For the following results, only the results for the EC are discussed.

3.3.2. Comparison of the minimum costs and minimum emissions

If the objective is switched to minimum emissions, shown as a transition from (I) to (II) in Figure 3.5, the solution changes drastically. Figure 3.8 shows the results for the grid deployment. It shows the results for the scenario "Status Quo/Existing Infrastructure" and the electricity grid changes strongly. The results show, that on the one hand, the grid capacity of the electricity grid gets increased massively (up to 600 %). On the other hand, the heat grid capacity stays constant or gets even reduced. The video provided in the supplementary material of this work shows the grid deployment of Figure 3.8 as a function of the Pareto Front.

Figure 3.9 shows the composition of the commodities used for electricity and heat provision (show in the first two sub-figures) and total emissions.

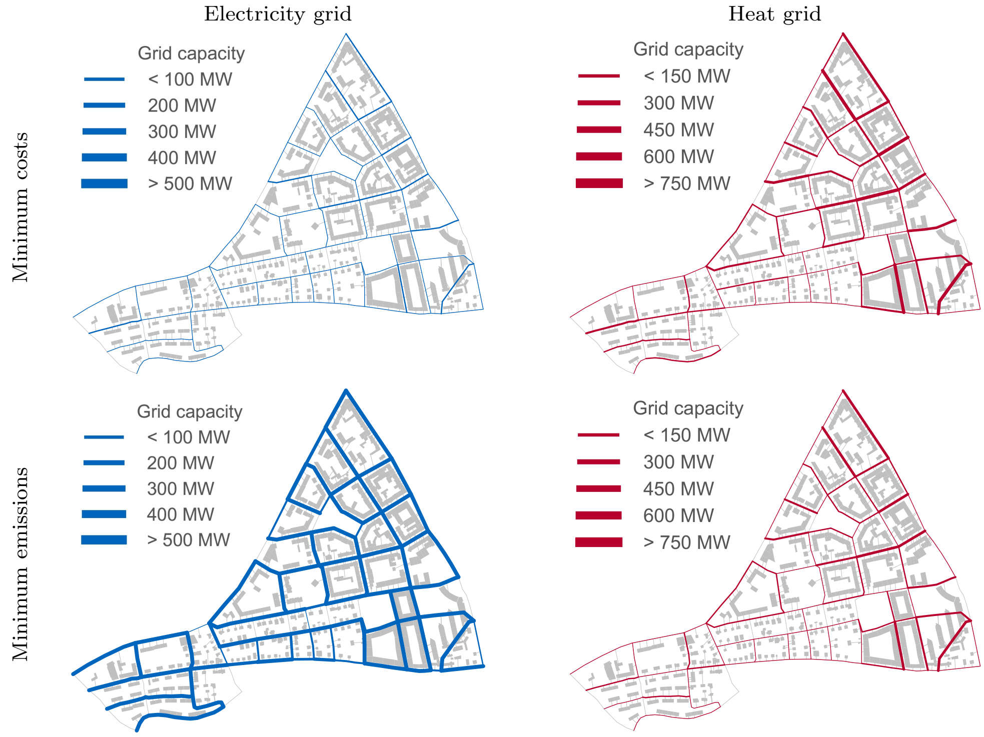

Figure 3.8.: Grid deployment for minimum costs and minimum emissions "Status Quo"/"Existing Infrastructure".

The results indicate that the emission reduction of 85 % is the result of PV installations and heat pumps. Such investments require investments in electricity grid infrastructure (see Figure 3.8 bottom/left) and processes (especially solar PV and heat pumps). As a result, the total costs increase by 598 %. For real-world installations, such an increase in costs would be hardly manageable.

Therefore, the following results will give more information about the transition towards a renewable energy community and quantify the trade-off between costs and emissions.

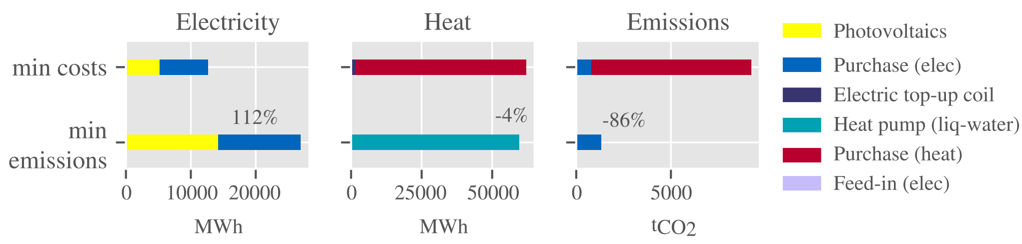

Figure 3.9.: Commodities created for minimum costs and minimum emissions solution.

3.3.3. Pareto Front and methods of emissions accounting

In the next step, the minimum costs and minimum emissions optimization are extended by the Pareto Optimization. Additionally, different methods of emission accounting are introduced, as introduced in Section 3.1.4

Figure 3.10 shows the Pareto Fronts, as well as two methods of emission accounting. The results vary highly between mean and marginal emissions (up to 389 %), although the sizing of the technologies is very similar in both emission scenarios. As shown in the previous results, the highest gains of emission reduction are achieved by electrifying the EC. By accounting emissions by the method of marginal emissions, the total annual emissions increases, although there are only minor changes in the optimal technology portfolio.

As stated in Section 3.3.1 and 3.3.2 the minimum costs solution in the case of "Existing Infrastructure" is the heat procurement via the heat grid. Contrary, the heat procurement in the "Green Field" scenario, is based on heat pumps. The results show that newly designed energy infrastructure under the aspect of cost reduction benefits regarding emission reduction, named ΔE. ΔE might be interpreted as the emissions savings potential of green-field infrastructure.

The results also show that the Pareto Front of "Existing Infrastructure" converges to the Pareto Front of "Green Field", but differs in costs by ΔC (the result of an existing electricity grid). ΔC may be interpreted as the monetary value of the existing infrastructure regarding the minimum emissions solution.

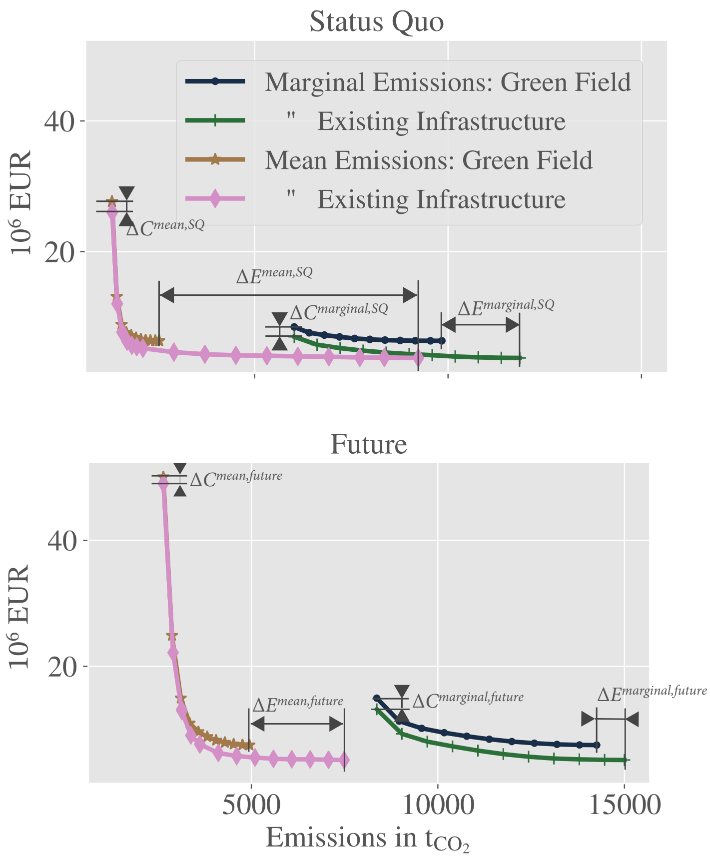

Figure 3.10.: Pareto Fronts with two methods of emissions accounting: mean and marginal emissions. Besides comparing the demand scenarios “Status Quo” and “Future”, it is also distinguished between “Green Field” and “Existing Infrastructure”.

3.3.4. Introduction of Carbon Taxes

For the final results, the impacts of carbon taxes on the minimum costs solution are investigated. In comparison to the Pareto Optimization, the emissions are not restricted up to the minimum emissions solution (quantity

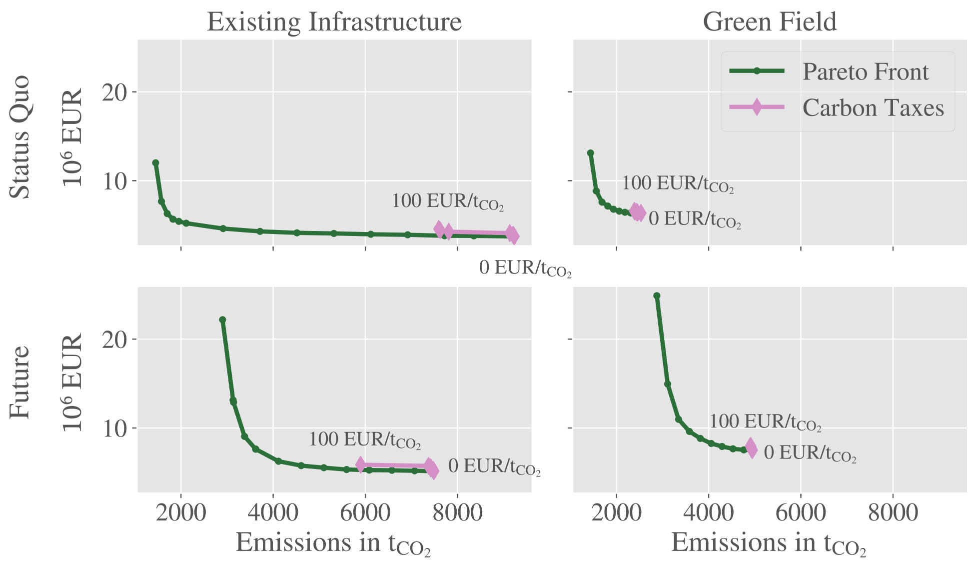

Figure 3.11.: Comparison of the Pareto Font with multiple minimum cost solutions with carbon taxes from 0 to 100 EUR/t_{CO_2}, ascending in 20 EUR/t_{CO_2} steps.

based reduction of emissions); instead, carbon taxes emissions increase the total costs (price based reduction of emissions).

Figure 3.11 shows the results for carbon taxes starting from from 0 to 100 EUR/t_{CO_2}[16] in 20 EUR/t_{CO_2} steps. Comparing "Existing Infrastructure" with the "Green Field", it shows that "Existing Infrastructure" is more sensitive to carbon taxes. On the other hand, carbon taxes up to 100 EUR/t_{CO_2} do not provide monetary incentives to change the technology portfolio for the "Green Field" significantly. Although, the carbon taxes $C^{CarbonTax}$ are increased up to 100 EUR/t_{CO_2}, it does not provide enough incentives to reduce the emissions to the level of the minimum emissions. As shown in Figure 3.9 most of the emissions are the result of heat procurement. A reduction in heat load characterizes the "Future" scenario. The Future, as well as the "Green Field" scenarios do have a low sensitivity to carbon taxes. The reason is that, the heat load is lower, and the infrastructure changed in favor of low-emission

[16]There is an ongoing discussion about the introduction and an appropriate level of carbon taxes. So, France plans to increase the carbon tax rate to 56EUR/tCO2 in 2020 and 100 EUR/tCO2 in 2030 (Zimmermannová et al., 2018).

technologies. So, compared to “Status Quo”, the emissions are lower, as the sensitivity to carbon taxes.

3.4. Résumé

To address the value of ECs regarding two objectives: costs and emissions, an energy system model based on two open-source optimization models has been developed. While the focus of the first sub-model is the optimal investment decisions on a high temporal level, the second sub-model address the optimal deployment of energy grids on a building level. Also, spatial and temporal clustering algorithms have been developed to increase the models’ interoperability and performance. This may make it easier for future users of the model (e.g., city planners) to apply the model. It may be concluded that the methods developed in this chapter allow urban planners to analyze city districts of interest towards sustainability and costs. The block-based method developed in this chapter allows future operators of the model to capture and include city districts with lower effort.

Furthermore, the lock-in effect of existing infrastructure is analyzed. It is significant, as carbon emissions are much higher for existing infrastructure than green-field investments. Also, existing infrastructure, e.g., heat grid, make ECs more vulnerable to carbon taxes. The conclusions of the scenarios, investigated in this paper, are that a transformation of the local energy system towards sustainability is possible. The local authorities have to be aware that the transformation has to initiated in time. Otherwise, externalities (e.g., carbon taxes) and reinvestment of high-emission infrastructure leads to sunk costs and/or high emissions.

As in this chapter it is assumed that all consumers at the project site join the EC, the situation, in reality, may depend on the willingness of the consumers to join such an EC. For the practical implementation to establish an EC, the “Green Field” scenario may be more suitable: In an urban development project, an appropriate framework may provide the incentives to inhabitants to join the EC and form a sustainable EC.

The following Chapter 4 continues by the introduction of energy sharing algorithms. Also it considers consumer preferences and choices, as identified by the literature as a requirement to increase social acceptance.

3.5. Nomenclature

Sets

$m \in \{E, Z, B\}$ . . . . . Block type
$i \in \{Heat, Elec, Cool\}$ Energy carrier
$j \in \{1, 2, \ldots, N_m\}$ . . . Block number
$t \in \mathcal{T} = \{1, \ldots, T\}$ . . Time-steps e.g. hours
$w \in \{1, \ldots, W\}$ . . . . Weeks of a year
$r \in \mathcal{R} = \{1, \ldots, R\}$ . . Periods of a year
$p \in P$ . . . . Process e.g. heat pump or solar photovoltaic
$v \in V$ . . . . Site or node
$f \in F$ . . . . Transmission process e.g. electricity
$a \in A$ . . . . Distribution line e.g. line from site v_1 to v_2

Decision variables

d and D . . . . Energy demand in MWh
q and Q . . . . Generation in MWh
η, *cop* and Γ . . . . . . Conversion efficiency in %
κ . . . . Process capacity in MW
$s \in \{0, 1\}$ . . . . Binary decision
ζ . . . . Costs in EUR
x . . . . All continuous decision variable of the optimization model
y . . . . All binary decision variables of the optimization model
$\overline{e}$ . . . . Emissions of minimum cost solution in t_{CO_2}
$\underline{e}$ . . . . Emissions of minimum emission solution in t_{CO_2}

Parameters

A . . . . Building area in m^2

S	Number of stories
K	Installed process capacity in MW
N	Total number of processes
$share$	Share of SH
Θ	Temperature in °C
$\alpha \in \{0, 1\}$	Adjusting factor for the Pareto front

4. Energy Allocation and Pricing Concepts in an Energy Community

Whereas the previous Chapter 3 comprehensively describes the value created by an energy community is described, this chapter presents allocation and pricing of DERs in a small-scale energy community, i.e. a single apartment house as an elaboration of Research Question 2. The content of this chapter bases on the paper *"Sharing solar PV and energy storage in apartment buildings"* (Fleischhacker et al., 2018). It is published in "IEEE Transactions on Smart Grid"[1]. The analysis of different models and cases helps to identify the best setup for real-life implementation: E.g., if a community-owned EC conducts the investment in DER, the requirements may be different from an external investor who seeks for profit maximization.

Additional to the technical restrictions, this chapter elaborates on the motivation of driving consumers and owners of DERs. While the consumers are described by multiple objectives such as cost and emission reduction and an increase of local generation, this work implies that owners are driven entirely by monetary motives. Two models, an EC welfare maximization model and a Stackelberg game, allows the investigation of different setups. While the first model describes a community approach, the second one formulates the relationship between landlord and tenants.

The chapter is organized as follows. In Section 4.1, two possible frameworks for sharing DERs, i.e., solar PV and energy storage in a small scale EC (single

[1] The individual contribution of this thesis' author is enlisted in Appendix B.

apartment house) are introduced. Section 4.2 presents the assumptions and parameterization of a numerical example from the Texan electricity market. The example considers an energy community which consists of four consumers for two representative days, with a high and low wholesale electricity price. Also, it introduces the The comprehensive results are shown in Section 4.3. It is shown how the electricity is allocated among the consumers as well as the price for a uniform or pay-as-bid auction. Consequentially, the results illustrate the welfare effects for the DER owner, the consumers and the utility company. Section 4.4 discusses this chapter. Section 4.5 introduces all sets, variables and parameters used throughout this chapter.

4.1. Methods

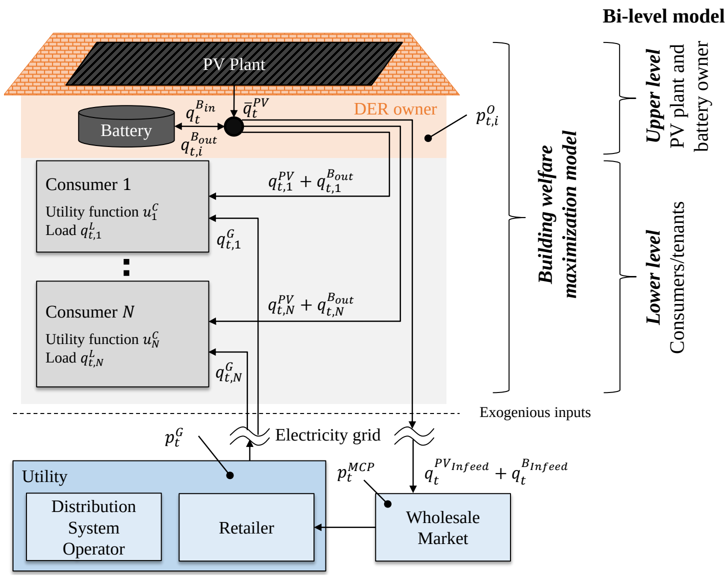

Figure 4.1.: Graphical representation of the EC in the building and interaction with utility/wholesale market. The left bracket shows the local welfare optimization model, while the right bracket shows the bi-level model.

This work considers the case of an EC in an apartment house. Multiple consumers live in the apartment building as tenants. The owner of the house also owns and operates the DER, consisting of solar PV and energy storage[2]. Fig. 4.1 shows the setup of this case study. The following section describes an optimization framework for sharing the generation of the DER among multiple consumers. The methods base on both, optimization and game theoretical models.

Firstly, a centralized welfare maximization framework for the whole EC, which considers conflicting consumer objectives such as costs and emissions reductions as well as the revenues from DERs is introduced. Secondly, a Mathematical Program with Equilibrium Constraints (MPEC) for DER pricing and resource allocation is formulated. This MPEC may be also interpred as a Stackelberg game. Within this game the owner of the DERs is the leader and the consumers are the followers. For clarification, the main assumptions of the models proposed in this work are as follows:

- The model addresses optimal allocation and pricing of generation by DER. As this is a question of short-term (operational) dispatch rather than long-term planning, investment decisions and corresponding costs are not part of the modeling framework.
- The model includes multiple consumer objectives, using weight factors to express consumer preferences for emissions reductions and locally produced electricity in monetary terms.
- The work assumes that the owner of the DERs is fully informed about the consumers' preferences, i.e. consumers' do not act strategically to influence the pricing and allocation of DERs.

4.1.1. Consumer utility function

According to Karjalainen (2011) it is challenging for consumers to compare electricity purchases across difference metrics, this work takes into account the consumers' individual objectives considering multiple criteria. The problem

[2]The DER owner could be all or a sub-set of the consumers or it could be a third party. Both approaches may be implemented practically, e.g., in Austria since the government recently adopted new legislation (see (Austrian Federal Chancellery, 2017)).

of multiple objectives is well studied in literature (Nwulu and Xia, 2015; Deghanpour et al., 2017; Marler and Arora, 2010). Marler and Arora describes that one solution of including multiple-objectives is to use the weighted sum method (Marler and Arora, 2010). It has to be considered that, for a priori articulation of preferences, the value of weight must be significant relative to other weights and relative to its corresponding objective function.

The introduction of weighting factors do not only help to address multiple objectives, but also allow to include individual consumer preferences. Consumers are interested in reducing the procurement costs for energy. Also, there may be a subset of consumers who are also interested in reducing emissions and increasing the share of generation by DER may be a consumer objective, respectively.

Therefore, weight factors w_i^E and w_i^{DER} for the consumer's value for emission reduction and local generation are introduced. The weight factors allow the consumers to express their preferences as a monetary value. All three objectives have different units, e.g. $[costs_i] = \$$, $[emissions_i] = \mathrm{kg_{CO2}}$ and $[der_i] = \mathrm{kWh}$. As stated in Fishburn and Triantaphyllou and Parlos multiple objectives or utilities may be summed in the single-dimensional case (e.g. USD) (Fishburn, 1967; Triantaphyllou and Parlos, 2010).

Hence, the consumer i's utility function,

$$u_i^C(q, p) = -costs_i(q, p) - w_i^E emissions_i(q) + w_i^{DER} der_i(q) \tag{4.1}$$

is the sum of three different objectives[3] The signs for costs and emissions are both negative because most consumers are interested in reducing those terms, while some consumers may also find an increase in generation by DER desirable (Peck, 2017; Wolitzky, 2015).

Procurement costs for electricity for consumer i depend on the costs for grid and distributed consumption,

$$costs_i(q, p) = \sum_{t \in \mathcal{T}} \left(p_{t,i}^G q_{t,i}^G + p_{t,i}^O \left(q_{t,i}^{PV} + q_{t,i}^{B_{out}} \right) \right). \tag{4.2}$$

[3] Karjalainen eleborates on additional objectives, such as energy saving or security-of-supply (Karjalainen, 2011). This may be included in future investigations.

The first term is the cost of electricity purchased from the local utility (with price $p^G_{t,i}$) and the second term the cost of generation by DER (with price $p^O_{t,i}$). The second objective of (4.1) concerns emissions reduction, defined as

$$emissions_i(q) = \sum_{t \in \mathcal{T}} e^G_t q^G_{t,i} \tag{4.3}$$

where e^G_t describes the grid's (or power market's) marginal emissions. As introduced in Chapter 3, marginal emissions are defined as the emissions of the price-setting power plant. So, any additional consumption results in an increase of marginal emissions. For an applied example see section 4.2. The third term in the objective function (4.1) defines the consumer's consumption of DER as

$$der_i(q) = \sum_{t \in \mathcal{T}} \left(q^{PV}_{t,i} + q^{B_{out}}_{t,i} \right). \tag{4.4}$$

Theorem 1 (Consumer willigness-to-pay). *The willingness-to-pay (WTP) for DER of consumer i, characterized by the utility function (4.1) is given as*

$$wtp_{t,i} = p^G_{t,i} + w^E_i e^G_t + w^{DER}_i \tag{4.5}$$

The WTP may also be interpreted as the marginal consumer utility.

Proof. The owner (leader in the Stackelberg game) maximizes revenues by selling electricity to consumers and the grid and sets the price for local generation $p^O_{t,i}$. As stated in (Liu et al., 2017, Definition 1), model (4.14) reaches the Stackelberg Equilibrium, if all players obtain the optimal solutions, including all consumers and the owner. Thereby, it is evident that the proposed framework reaches an Equilibrium as soon as the owner is able to find optimized $p^O_{t,i}$ and the consumers choose their consumption. As the owner is able to identify all consumers' demand curve, he is able to exercise market power. Therefore, optimal pricing, from the owner's perspective under the assumption of a discrimination auction, is equal to the consumer's WTP (4.5). Indicating the fact, that the market price p^{MCP}_t is lower than the utility rate $p^G_{t,i}$, it is favorable to sell electricity firstly to consumers, secondly stored in the battery and thirdly sell it to the grid. ■

4.1.2. Revenues for DER owner

In practice, potential owners of the DER include the building owner, an external company, or a group of residents. In model proposed in this work, the owner is entirely motivated by financial objectives, i.e. to maximize the operating revenues from the DER. Investment and fixed operational costs (e.g. maintenance and insurance) are omitted in this case. Consequentially, the owner's revenues are defined as

$$\begin{aligned} rev^O(q,p) = &\sum_{t\in\mathcal{T}}\sum_{i\in\mathcal{N}} p^O_{t,i}(q^{PV}_{t,i} + q^{B_{out}}_{t,i}) \\ &+ \sum_{t\in\mathcal{T}} p^{MCP}_t(q^{PV_{grid}}_t + q^{B_{grid}}_t) \end{aligned} \tag{4.6}$$

and consist of revenues from selling energy to the consumers within the EC or on the wholesale electricity market.

4.1.3. Welfare measures

It is expected that the introduction of an EC affects the business models of most of the participants in the electricity market. More general, it effects the distribution of the economic surplus between producers and consumers and between different types of producers and consumers (Hirth and Ueckerdt, 2013).

The introduction of welfare parameters allow to quantify the economic effects of local generation and energy sharing within the EC. In accordance with (Callan and Thomas, 2006) this work uses following welfare parameters: consumer surplus (CS), DER owner surplus (OS), and utility company surplus (US)[4] as:

$$CS(q,p) = \sum_{t\in\mathcal{T}}\sum_{i\in\mathcal{N}} \left(\left(wtp_{t,i} - p^O_{t,i}\right)\left(q^{PV}_{t,i} + q^{B_{out}}_{t,i}\right)\right), \tag{4.7}$$

[4]As this work does not consider the utility company's cost function, it is assumed that costs are equal to the energy procurements costs from the wholesale market. Costs related to investment and operation of the network are not considered (which is equivalent to assume that they are constant regardless of the level of DER generation in the EC).

$$OS(q,p) = rev^O(q,p) = (4.6) \text{ and} \tag{4.8}$$

$$US(q,p) = \sum_{t\in\mathcal{T}} \sum_{i\in\mathcal{N}} \left(\left(p^G_{t,i} - p^{MCP}_t\right) q^G_{t,i} \right). \tag{4.9}$$

Note, that consumers do have a utility by grid consumption (see (4.1)). The above-defined surplus address changes resulting from DER generation compared to exclusively grid consumption. We also define loss of economic efficiency in the case of scarcity (Callan and Thomas, 2006) as

$$Loss(q,p) = \sum_{t\in\mathcal{T}} \sum_{i\in\mathcal{N}} \left(\left(wtp_{t,i} - p^O_{t,i}\right) q^G_{t,i} \right). \tag{4.10}$$

Following this terminology, it is assumed that EC welfare (EW) that affects all parties within the building (i.e. consumers and DER owner) due to DER is

$$EW = CS + OS, \tag{4.11}$$

while the total welfare (TS) is defined as

$$TW = CS + OS + US. \tag{4.12}$$

4.1.4. Energy community welfare maximisation model

The first model maximizes the value of local generation using a local welfare optimization model as shown Fig. 4.1 (left). Each consumer $i \in \mathcal{N}$ is described the utility function u_i and load $q^L_{t,i}$. The DER owner is assumed to operate in a way to maximize the consumers' aggregated utility. Possible revenues from selling electricity to the grid are also included. Excess energy is remunerated with the wholesale market price, p^{MCP}_t, i.e. potential subsidy schemes, e.g., feed-in tariffs or tax credits are neglected in this work. As the objective function of this problem is the EC welfare ($\max BW$), it includes both the consumers' utility and the owner's revenues. The EC's welfare maximisation model is:

$$\max_{\substack{\left\{q^G_{t,i}, q^{PV}_{t,i}, q^{B_{out}}_{t,i}, \\ q^{B_{in}}_t, q^{B_{out}}_{t,i}, SOC_t\right\}}} \quad EW(q,p) = CS(q,p) + OS(q,p) \tag{4.13a}$$

$$\text{subject to} \quad q^{G}_{t,i} + q^{PV}_{t,i} + q^{B_{out}}_{t,i} = q^{L}_{t,i} \quad (\lambda^{L}_{t,i}) \tag{4.13b}$$

$$\sum_{t\in\mathcal{N}} q^{PV}_{t,i} + q^{PV_{grid}}_{t} + q^{B_{in}}_{t} + q^{PV_{curtail}}_{t} = \bar{q}^{PV}_{t} \quad (\lambda^{PV}_{t}) \tag{4.13c}$$

$$SOC_t = SOC_{t-1} + q^{B_{in}}_{t}\eta^{B} - \sum_{i\in\mathcal{N}} q^{B_{out}}_{t,i}/\eta^{B} - q^{B_{grid}}_{t} \quad \forall t \in \mathcal{T}\backslash\{0,T\} \tag{4.13d}$$

$$SOC_t = SOC^{init} \quad \forall t \in \{0,T\} \tag{4.13e}$$

$$0 \leq \sum_{i\in\mathcal{N}} q^{B_{out}}_{t,i} + q^{B_{grid}}_{t} \leq \bar{q}^{B} \tag{4.13f}$$

$$\sum_{i\in\mathcal{N}} q^{B_{out}}_{t,i} + q^{B_{grid}}_{t} \leq SOC_t \tag{4.13g}$$

$$0 \leq q^{B_{in}}_{t,i} \leq \bar{q}^{B} \tag{4.13h}$$

$$\underline{SOC} \leq SOC_t \leq S\bar{O}C \tag{4.13i}$$

$$q^{G}_{t,i}, q^{PV}_{t,i}, q^{B_{out}}_{t,i}, q^{B_{in}}_{t}, q^{B_{out}}_{t,i}, SOC_t \in \mathbb{R}^{+} \tag{4.13j}$$

where constraint (4.13b) ensures that generation and consumption are equal for all periods. PV generation is limited by its maximum hourly availability q^{PV}_{t} and can be either delivered to consumer i ($q^{PV}_{t,i}$), fed into the grid ($q^{PV_{grid}}_{t}$) or battery ($q^{B_{in}}_{t}$) or curtailed ($q^{PV_{curtail}}_{t}$), as dictated by (4.13c). Note that curtailment may be the optimal choice in periods where all (participating) consumers are entirely supplied with solar generated electricity, the battery is fully charged, and market prices are negative. Equations (4.13d)-(4.13i) describe the battery's integration into the framework, i.e. makes sure that the battery stays within its state of charge and power limits. Finally, (4.13j) ensures that all decision variables are limited to positive values.

The EW maxization model (4.13) dispatches DER in a way to maximize the EC welfare, considering the surpluses of both consumers and the DER owner. Also, the model finds the optimal energy allocation among the consumers. In reality, appropriate price signals are also necessary because of two reasons: (i) to find a financial settlement between consumers and DER owner, and (ii) to stimulate DER investments. Appropriate price signals help to determine the allocation of EW among consumers and the DER owner. To some extent, the range of the pricing scheme depends on marginal generation costs and grid procurement costs for the consumers. Consequentially, three pricing schemes are possible:

- $p^O_{t,i} = 0$: As the operating costs of renewable DERs are mainly given by investment costs (IC), one could also set the short-term DER price to zero. To ensure an economic viability of DERs, consumers would need to pay the IC up front or through annual payments based.
- $p^O_{t,i} = p^G_{t,i}$: From the consumer's point of view, the opportunity cost is given by the full retail rate for grid consumption. Settling DERs at this price level could be interpreted as a net-metering approach.
- $p^O_{t,i} = \lambda^{PV}_t$: As the dual variable of the solar PV balance, λ^{PV}_t represents the marginal value of PV generation to the local system, and this could also be used as a price signal. Dual variables are widely used in electricity market models to calculate prices (Ortner et al., 2017).

4.1.5. Bi-level model

The second model investigates the situation, that the DER owner takes advantage of the consumers' interest in DERs (described by the WTP) to increase its own profit. In this case, the question of optimal pricing from the DER owner's perspective leads to a non-cooperative game-theoretical model formulation. This section introduces a Mathematical Program with Equilibrium Constraints (MPEC) to calculate optimal pricing and energy flows of DERs. Fig. 4.1 (right bracket) shows the model's setup.

As introduced by Gabriel et al. an MPEC is an optimization model, whose constraints include other interrelated optimization or complementary problems (Gabriel et al., 2013). The MPEC in this work comprises two types of players:

- The DER owner runs the operation of the PV and battery. The DER owner determines the prices for locally generated electricity, $p^O_{t,i}$, to the consumers and sells to the grid with the objective to maximize as given by (4.6). Also, the DER owner is fully informed by the consumers WTP.

- The consumers decide if they buy electricity from the DER owner for a given price, or consume electricity from the grid to maximize their individual utility by (4.1).

The electric utility company[5] and the wholesale electricity market are exogenous entities in this framework. For the sake of simplicity, the utility rate for grid consumption p_t^G is assumed to be equal for all consumers in the EC.

In the literature, the general setup for this model is known as a Stackelberg game (Stackelberg, 2011). The leader (i.e. the DER owner) anticipates the reactions of the followers (i.e. the consumers in the EC) to the leader's decisions. The leader has a strategic advantage since it is assumed to know the consumers' demand curves. Therefore, model (4.13) may be reformulated as bi-level model:

$$\max_{\substack{\{p_{t,i}^O, p_{t,i}^U\} \\ \{q_{t,i}^G, q_{t,i}^{PV}, q_{t,i}^{B_{out}}\}}} \quad rev^O(q,p) \tag{4.14a}$$

$$\text{subject to} \quad (4.13c) - (4.13i)$$

$$p_{t,i}^O = p_t^U \tag{4.14b}$$

$$p_{t,i}^O, p_{t,i}^U, q_t^{B_{in}}, q_{t,i}^{B_{out}}, SOC_t \in \mathbb{R}^+ \tag{4.14c}$$

$$\max_{\{q_{t,i}^G, q_{t,i}^{PV}, q_{t,i}^{B_{out}}\}} \quad u_i^C(q,p) \tag{4.14d}$$

$$\text{s. t.} \quad (4.13b) \tag{4.14e}$$

$$q_{t,i}^G, q_{t,i}^{PV}, q_{t,i}^{B_{out}} \in \mathbb{R}^+ \tag{4.14f}$$

$$(\mu_{t,i}^{G_{min}}, \mu_{t,i}^{PV_{min}}, \mu_{t,i}^{B_{min}}).$$

The main difference to the EW maximization model (4.13) is the independent maximization of OS and CS in the upper and lower level problems, and the introduction of new decision variables for prices, $p_{t,i}^O$ and p_t^U. The upper-level problem maximizes the DER owner's revenue and includes the same constraints as in the EW model on solar PV generation and energy storage operation, i.e. constraints (4.13c)-(4.13i). This model considers the cases where the owner sells energy at different prices (discriminatory price auction)

[5] This work does not differentiate between retailer and distribution grid operator. For the sake of simplicity, those two companies are jointly labelled utility company.

or the same price (uniform price auction). The modeling framework is able to capture both auction systems, by activating or deactivating condition (4.14b).

Each consumer seeks to maximize his utility u_i from consuming electricity, under the restriction of satisfying his demand (4.13b). The corresponding lower-level problem (4.14d)-(4.14f) is linear and continuous. As described in (Gabriel et al., 2013) any MPEC can be formulated as a mathematical optimization problem constrained by a second optimization problem:

$$\min_{\substack{\{x\}\\ \{y,\lambda,\mu\}}} \quad f(x,y,\lambda,\mu) \tag{4.15a}$$
$$\text{s.t} \quad h(x,y,\lambda,\mu) = 0 \tag{4.15b}$$
$$g(x,y,\lambda,\mu) \leq 0 \tag{4.15c}$$
$$\min_{\{y,\lambda,\mu\}} \quad f^L(x,y) \tag{4.15d}$$
$$\text{s.t.} \quad h^L(x,y) = 0 \quad (\lambda) \tag{4.15e}$$
$$g^L(x,y) \leq 0 \quad (\mu) \tag{4.15f}$$

The MPEC exposed in this chapter is solved by reformulating the upper-level problem (4.14a)-(4.14c) as an equivalent optimization problem. Therefore, the KKT optimality conditions of the lower-level problem (4.14d)-(4.14f) is implemented in the first level, as:

$$\min_{\substack{\{x\}\\ \{y,\lambda,\mu\}}} \quad f(x,y,\lambda,\mu) \tag{4.16a}$$
$$\text{s.t} \quad h(x,y,\lambda,\mu) = 0 \tag{4.16b}$$
$$g(x,y,\lambda,\mu) \leq 0 \tag{4.16c}$$
$$\nabla_y f^L(x,y) + \lambda \nabla_y h^L(x,y) + \mu \nabla_y g^L(x,y) = 0 \tag{4.16d}$$
$$h^L(x,y) = 0 \tag{4.16e}$$
$$g^L(x,y) \leq 0 \ \perp \ \mu \geq 0 \tag{4.16f}$$

By introducing the Lagrangian as

$$\mathcal{L}\left(q^G_{t,i}, q^{PV}_{t,i}, q^{B_{out}}_{t,i}, \lambda^L_{t,i}, \mu^{G_{min}}_{t,i}, \mu^{PV_{min}}_{t,i}, \mu^{B_{min}}_{t,i}\right) \tag{4.17a}$$
$$= -\sum_{t\in\mathcal{T}} \tilde{p}^G_{t,i} q^G_{t,i} - \sum_{t\in\mathcal{T}} \tilde{p}^O_{t,i}(q^{PV}_{t,i} + q^{B_{out}}_{t,i}) \tag{4.17b}$$

$$- \lambda^{L}_{t,i} \left(q^{G}_{t,i} + q^{PV}_{t,i} + q^{B_{out}}_{t,i} - q^{L}_{t,i} \right) \tag{4.17c}$$
$$- \mu^{G_{min}}_{t,i} q^{G}_{t,i} - \mu^{PV_{min}}_{t,i} - \mu^{B_{min}}_{t,i} \tag{4.17d}$$

the lower levels optimization problem could be rewritten by its KKT conditions in the form

$$\partial \mathcal{L} / \partial q^{G}_{t,i} = \tilde{p}^{G}_{t,i} - \lambda^{L}_{t,i} - \mu^{G_{min}}_{t,i} = 0 \tag{4.18a}$$
$$\partial \mathcal{L} / \partial q_{t,i} = \tilde{p}^{O}_{t,i} - \lambda^{L}_{t,i} - \mu^{PV_{min}}_{t,i} = 0 \tag{4.18b}$$
$$\partial \mathcal{L} / \partial q^{B_{out}}_{t,i} = \tilde{p}^{O}_{t,i} - \lambda^{L}_{t,i} - \mu^{B_{min}}_{t,i} = 0 \tag{4.18c}$$
$$\partial \mathcal{L} / \partial \lambda^{L}_{t,i} = q^{G}_{t,i} + q^{PV}_{t,i} + q^{B_{out}}_{t,i} - q^{L}_{t,i} = 0 \tag{4.18d}$$
$$q^{G}_{t,i} \geq 0 \;\perp\; \mu^{G_{min}}_{t,i} \geq 0 \tag{4.18e}$$
$$q^{PV}_{t,i} \geq 0 \;\perp\; \mu^{PV_{min}}_{t,i} \geq 0 \tag{4.18f}$$
$$q^{B_{out}}_{t,i} \geq 0 \;\perp\; \mu^{B_{min}}_{t,i} \geq 0 \tag{4.18g}$$

As the 4.14 is nonlinear, because of the complementary conditions and a nonlinear objective function, linearization, as described in Gabriel et al. (2013) and Ruiz and Conejo (2009) is necessary. The MPEC model (4.14) two types of nonlinearities:

- the complementarity conditions and
- the term $p^{O}_{t,i}(q^{PV}_{t,i} + q^{B_{out}}_{t,i})$ (prices times quantity, both are decision variables) in the objective function.

Ruiz and Conejo (2009) propose to linearize complementarity conditions by the use of the well-known linear expressions. In this work, SOS1 constraints are used to formulate the complementary conditions (Hart et al., 2017). The strong duality condition and some of the KKT conditions allows the reformulation of the lower level's objective (similar to the problem formulated in Ruiz and Conejo (2009)). Ruiz and Conejo conclude that if a problem is convex, the objective functions of the primal and dual problems have the same value at the optimum. Thus the lower level's primal objective (4.14d) is equal to it's dual objective. $f^{L,Dual}_{i} = - \sum_{t \in \mathcal{T}} \lambda^{L}_{t,i} q^{L}_{t,i}$ Substituting those two equations allows the calculation of the upper level's non-linearity as a linear expression (4.19a).

The linearized problem[6] is

$$\max_{\substack{\{p^O_{t,i},p^U_{t,i},q^{B_{in}}_t,q^{B_{out}}_{t,i},\\ SOC_t,q^G_{t,i},q^{PV}_{t,i},q^{B_{out}}_{t,i},\\ \mu^{G_{min}}_{t,i},\mu^{PV_{min}}_{t,i},\mu^{B_{min}}_{t,i},\lambda^L_{t,i}\}}} \begin{cases} \sum_{t\in\mathcal{T}} \lambda^L_{t,i} q^L_{t,i} \\ -\sum_{t\in\mathcal{T}} p^G_{t,i} q^G_{t,i} \\ +w^{DER}_i \sum_{t\in\mathcal{T}} \left(q^{PV}_{t,i} + q^{B_{out}}_{t,i}\right) \\ +\sum_{t\in\mathcal{T}} p^{MCP}_t (q^{PV_{grid}}_t + q^{B_{grid}}_t) \end{cases} \tag{4.19a}$$

$$\text{subject to} \quad (4.13b) - (4.13i), (4.14b) - (4.14f)$$

$$p^G_{t,i} + w^E_i e^G_t - \lambda^L_{t,i} - \mu^{G_{min}}_{t,i} = 0 \tag{4.19b}$$

$$p^O_{t,i} + w^{DER} - \lambda^L_{t,i} - \mu^{PV_{min}}_{t,i} = 0 \tag{4.19c}$$

$$p^O_{t,i} + w^{DER} - \lambda^L_{t,i} - \mu^{B_{min}}_{t,i} = 0 \tag{4.19d}$$

$$q^G_{t,i} + w^E_i e^G_t \geq 0 \ \perp \ \mu^{G_{min}}_{t,i} \geq 0 \tag{4.19e}$$

$$q^{PV}_{t,i} \geq 0 \ \perp \ \mu^{PV_{min}}_{t,i} \geq 0 \tag{4.19f}$$

$$q^{B_{out}}_{t,i} \geq 0 \ \perp \ \mu^{B_{min}}_{t,i} \geq 0 \tag{4.19g}$$

$$\lambda^L_{t,i} \in \mathbb{R} \tag{4.19h}$$

As stated by Maskin (2000), an auction is efficient if, in the equilibrium, the winner is the consumer with the highest CS, i.e., if consumer i wins. The DER owner is aware of the consumers' CS, since w^E_i and w^{DER}_i are known to it. Therefore, the DER owner is able to calculate the consumers' WTP (4.5) and can charge them accordingly. Theorem 2 defines the equilibrium of (4.14) as the pricing scheme that maximizes the profit of the DER owner. In the case of a discriminatory auction system, this means that the price applied to consumer i is equal to the corresponding $wtp_{t,i}$. Therefore, the consumer with the highest $wtp_{t,i}$ pays the most for DER, followed by the consumer with the second highest valuation, etc. In return, energy will be dispatched according to this order as well.

Theorem 2 (Equilibrium of problem (4.14) under the assumption of a discriminatory based auction system)*. i.e., the DER profit-maximizing solution of* $p^O_{t,i}$ *applied to consumer* i *at time* t *is given by the consumer's* $wtp_{t,i}$.

Proof. The owner (leader in the Stackelberg game) maximizes revenues by selling electricity to consumers and the grid and sets the price for local

[6] For the sake of simplicity, complementary conditions are still written in their nonlinear form.

generation $p^O_{t,i}$. As stated in Liu et al. (2017) (Definition 1), model (4.14) reaches the Stackelberg Equilibrium, if all players obtain the optimal solutions, including all consumers and the owner. Thereby, it is evident that the proposed framework reaches an equilibrium as soon as the owner is able to find optimized $p^O_{t,i}$ and the consumers choose their consumption. As the owner is able to identify all consumers' demand curve, he is able to exercise market power. Therefore, optimal pricing, from the owner's perspective under the assumption of a discrimination auction, is equal to the consumer's WTP (4.5). Indicating the fact, that the $p^G_{t,i} > p^{MCP}_t$, it is favorable to sell electricity firstly to consumers, secondly store it in the battery and thirdly sell it to the grid. ■

Algorithm 1 Calculation of optimal pricing and revenues for uniform pricing (without battery).

procedure UniformPricing
  $j \leftarrow 0$ ▷ No consumer is supplied with PV energy.
  $\mathcal{N}' \leftarrow \{0\}$
  $p^O_{t,0} \leftarrow \infty$ ▷ Default pricing value for feed-in, only.
  $rev^O_{t,0} \leftarrow p^{MCP}_t \bar{q}^{PV}_t$ ▷ Valorization on wholesale markets, only.
  for all $j \in \mathcal{N}$ **do** ▷ Sorted descending by $p^O_{t,i}$.
    $\mathcal{N}' \leftarrow \mathcal{N}' \cup \{j\}$ ▷ Update set
    $p^O_{t,j} \leftarrow wtp_{t,j}$
    $q^{PV_{grid}}_{t,j} \leftarrow \bar{q}^{PV}_t - \sum_{k \in \{1,\ldots,j\}} q^L_{t,k}$
    ▷ Becomes negative if no surplus energy.
    if $q^{PV_{grid}}_{t,j} > 0$ **then** ▷ Feed-in
      $rev^O_{t,j} \leftarrow \sum_{k \in \mathcal{N}'} p^O_{t,j} q^L_{t,k} + p^{MCP}_t q^{PV_{grid}}_{t,j}$
    else ▷ No feed-in
      $rev^O_{t,j} \leftarrow \sum_{k \in \mathcal{N}' \setminus \{j\}} p^O_{t,j} q^L_{t,k} + p^O_{t,j}(q^L_{t,j} + q^{PV_{grid}}_{t,j})$
      ▷ In the case of $\sum_{k \in \mathcal{N}'} q^L_{t,k} \geq \bar{q}^{PV}_t$ consumer won't be fully supplied.
      break
    end if
  end for
  $i \leftarrow \text{argmax}\left(rev^O_{t,j}\right)$ ▷ Overwrite with optimal results.
  $p^U_t \leftarrow p^O_{t,i}$
  $rev^O_t \leftarrow rev^O_{t,i}$
  $q^{PV_{grid}}_t = \max(q^{PV_{grid}}_{t,i}, 0)$ ▷ Only positive values
  return $p^U_t, rev^O_t, q^{PV_{grid}}_t$
end procedure

The solution of model (4.14) for uniform auctions is more complex, e.g., see Borgs et al. (2005) and Maskin (2000). The problem is solvable by an algorithm. Algorithm 1 calculates the uniform prices p^U_t with the objective to maximize OS. The idea of this algorithm is to start with feeding all locally generated energy into the grid. Iteratively, the owner's revenues are updated by selling energy to the EC consumers, whereby the consumers are ranked in descending order by their WTP. In the end, the price level that gives the highest revenues to the DER owner will be returned and settled in (4.14b). Note that Algorithm 1 finds the optimal uniform price without the need of solving model (4.14).

4.2. Numerical example

To illustrate a potential application of the proposed models, the framework is applied to a numerical example for two illustrative days: one day with a high electricity price (high) and a low electricity price (low). The data of both days is from the ERCOT electricity market in Texas (Electric Reliability Council of Texas Inc., 2017b). Day-Ahead prices[7] are included as vector p_t^{MCP} for two illustrative days from July 2016:

- **Low price**: July 18th 2016, low (even negative) prices.
- **High price**: July 10th 2016, high prices at noon and afternoon.

Marginal emissions, included by the vector e_t^E. Since marginal emissions are not published this work assumes a relationship between Day-Ahead prices and marginal emissions. This approach assumes a static merit order dispatch[8] of the ERCOT market, under the assumption of a gas price of 3 \$/Mbtu from 2016 (Rhodes et al., 2017) as shown in Fig. 4.2. Fig. 4.2 also includes the Day-Ahead prices and corresponding marginal emissions for both days.

As desribed in Section 4.1 consumers are charcterized by their hourly demand vector $q_{t,i}^L$ and their individual weights for emissions reductions, w_i^E, and

[7] Load zone south with the label "HB_SOUTH".

[8] Hereby, nuclear and renewable generation are the marginal generation resources and set the price up to 10 \$/MWh, natural gas (NG) combined-cycle (CC) up to 23 \$/MWh, coal power plants up to 38 \$/MWh and NG other beyond 38 \$/MWh. It is assumed that nuclear and renewable generation do not cause any emissions, while gas CC, coal and peak power plants result in emissions of 440, 880 and 640 kg/MWh, respectively.

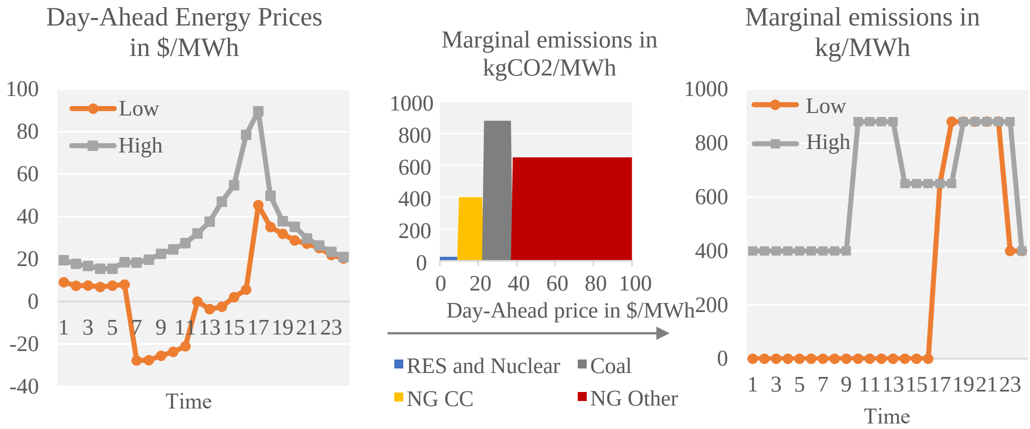

Figure 4.2.: Relationship between Day-Ahead prices $p_t^M CP$ (left) and marginal emissions e_t^G (right) as the result of a merit order relationship (middle).

distributed generation, w_i^{DER}. This work uses published demand data from NREL (Blair et al., 2014) of four Texan consumers $i \in \mathcal{N} = \{1, 2, 3, 4\}$, located in San Antonio and Corpus Christi for one selected day, i.e. July 1st 2016. The consumers' electric load includes electricity demand, heating (space heating and hot water), cooling (HVAC and fans), as well as interior and exterior lights and equipment. Two weight factor vectors are assumed to illustrate different consumer preferences: $w_i^E = [0, 7.5, 0, 10]$ ct/kg$_{CO2}$ and $w_i^{DER} = [0, 0, 5, 10]$ ct/kWh. Consumer 1 is interested in cost reduction, only, while consumers 2 and 3 are also interested in emission reduction or increased generation by DER, respectively. "Premium consumer" 4 is willing to pay for both emissions reduction and DER generation.

This work assumes that all four consumers have a supply contract with the same utility company. In regard of the utility rate $p_{t,i}^G$, paid by consumers for grid electricity[9]:

- **Flat tariff**: The generation charge is 0.059 $/kWh, while the delivery charge is 0.036 $/kWh. In total, $p_{t,i}^G = 0.095$ $/kWh. (Source: Southwestern Electric Power Company)

[9]Note that this work includes volumetric tariff components exclusively without fixed charges, as fixed components are usually small and based on a monthly or annual assessment. Also, electricity rates in Texas are low compared to most other U.S. states.

- **Real-time pricing (RTP)**: The generation charge consists of the Day-Ahead wholesale market price plus a generation markup of 0.013 \$/kWh (Source: Power Smart Pricing). The delivery charge is 0.036 \$/kWh[34]. In total, $p^G_{t,i} = p^{MCP}_t + 0.049\,\$/\text{kWh}$.

DER consists of a PV plant and battery system with an assumed roof area of 100 m^2. Consequentially, the PV system's installed capacity is 16.6 kWp. In regard of the solar generation, standardized time series data of ERCOT (Electric Reliability Council of Texas Inc., 2017a), is used. Consequentially, the generation profile of solar PV is $\bar{q}^{PV}_t = \eta^{PV}_t * 16.6\,\text{kWp}$ with the standardized generation η^{PV}_t. Storage capabilities are included by two Tesla Powerwalls with a nominal capacity of $SOC = 28\,\text{kWh}$, charging and discharging power of 14 kW and two-way efficiency of $\eta^B = 95\,\%$ (Tesla, 2017).

Both models ((4.13) and (4.14)) are implemented in the Python modeling framework Pyomo (Hart et al., 2017) and solved it with the solver Gurobi version 7.0.2 (Gurobi Optimization, 2018).

4.3. Results

In this section, the results of applying the Methods (4.1) to the Numerical Example (4.2) are shown. Firstly, the results show how the two models allocate and price energy among the consumers. Secondly, the results show the impact on social welfare followed by a sensitivity analysis regarding the size of the PV plant.

4.3.1. Resource allocation and pricing

The EW maximization model (4.13) and the bi-level model (4.14) with discriminatory prices give the same allocation of DERs. The composition of the load is shown in Fig. 4.3 (left). As consumer 4 always has the highest WTP for DER at any time (see Fig. 4.4), the model allocates energy mainly

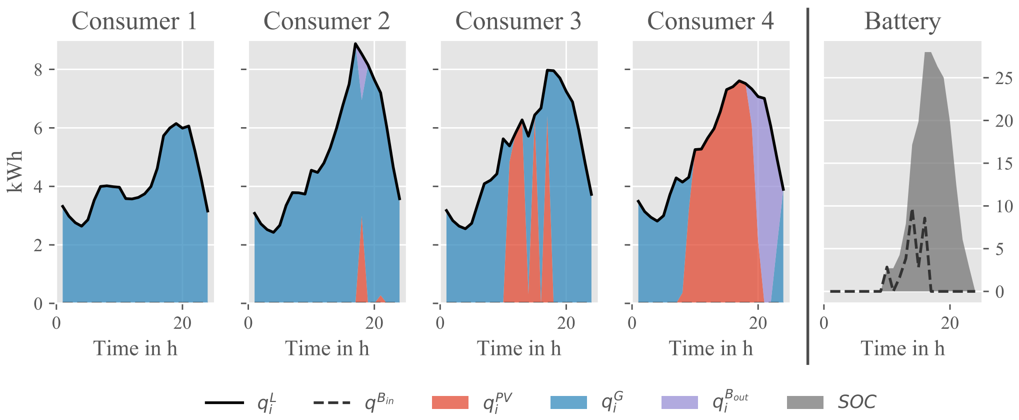

Figure 4.3.: Allocation of DER (left) and battery SOC as well as charging power (right) for the "low price" scenario. The battery's discharging power is shown in the left picture in purple (Flat tariff)

to consumer 4 . Consumer 2 and 3 do have different objectives in terms of emissions and DER. So, the energy allocation depends on the system's marginal emissions. The consumers' WTP changes over time, so $wtp_{t,i}$ is a function of e_t^G. Hence, consumer preferences concerning emissions are time-dependent, while preferences for DER remain constant. Fig. 4.3 shows that consumer 2 does not consume much DER. This is because the grid supply also has zero emissions during most of the hours (Fig. 4.2), making consumer 2 indifferent between grid and local generation.

The algorithm dispatches the battery to maximize EW, resulting in the battery schedule shown in Fig. 4.3 (right). As mentioned above, most of the electricity is sold to consumer 4, which has the highest WTP during the day.

Fig. 4.5 shows a comparison of the two different auction systems. Note that the dispatch of solar PV and the battery of the EW maximization model is equal to the bi-level model with discriminatory auctions. Under the bi-level model, PV generation and energy sold to consumer 4 are the same for both auction systems and all scenarios. The owner dispatches the solar PV and the battery in a way to maximize its revenues. Fig. 4.5 also shows the difference between Flat and RTP pricing. For instance, the DER owner sells energy

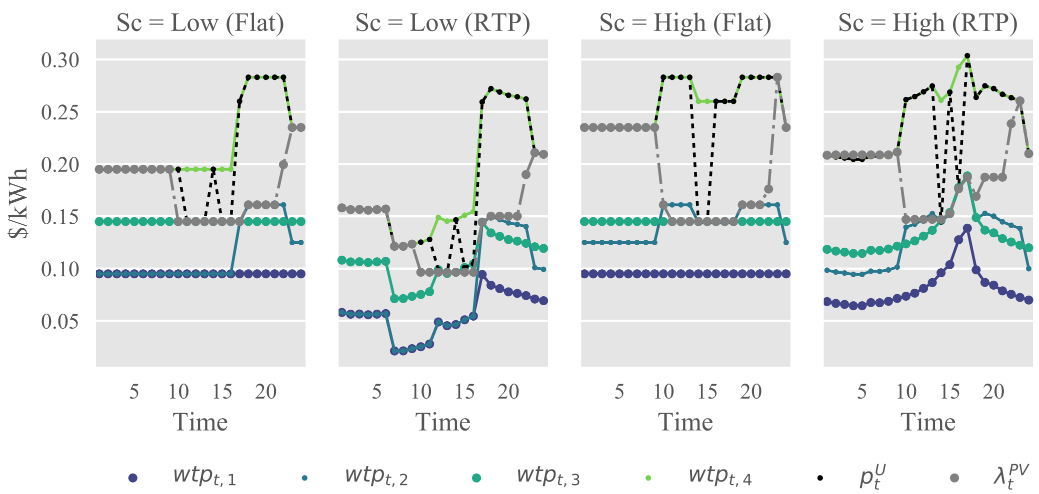

Figure 4.4.: $wtp_{t,i}$ (bi-level model, discriminatory price auctions), p_t^U (bi-level model, uniform price auctions) and λ_t^{PV} (EW max. model, dual variable) for all scenario combinations.

differently to consumer 2 and 3 depending on the pricing scheme. It is a result of a changed WTP. As stated in Theorem 1, the price of electricity consumption $p_{t,i}^G$ is an input of $wtp_{t,i}$. By adding a real-time based tariff instead of a flat rate, the volatility of $wtp_{t,i}$ increases as well and results in a change in the allocation of energy.

Fig. 4.5 also shows that the DER owner sells more energy to the grid and less energy to consumers 2 and 3 under the uniform auction scheme. The reason is that in this case the owner prefers to sell to the grid rather than reducing the price (and its revenues) for all consumers. The allocation of welfare for both models and auction systems are discussed in more detail in the next section.

Although the DER allocation is the same with model (4.13) and (4.14) with discriminatory price models, there are still differences in resulting prices. Fig. 4.4 shows the resulting prices of both models for fixed and RTP tariff schemes. For the EW max. model, two of the proposed pricing schemes are based on external assumptions. The third pricing scheme follows from the dual variable λ_t^{PV} of the PV balance, results in a price that is lower than the prices from the bi-level model. By focusing on the prices following from the the

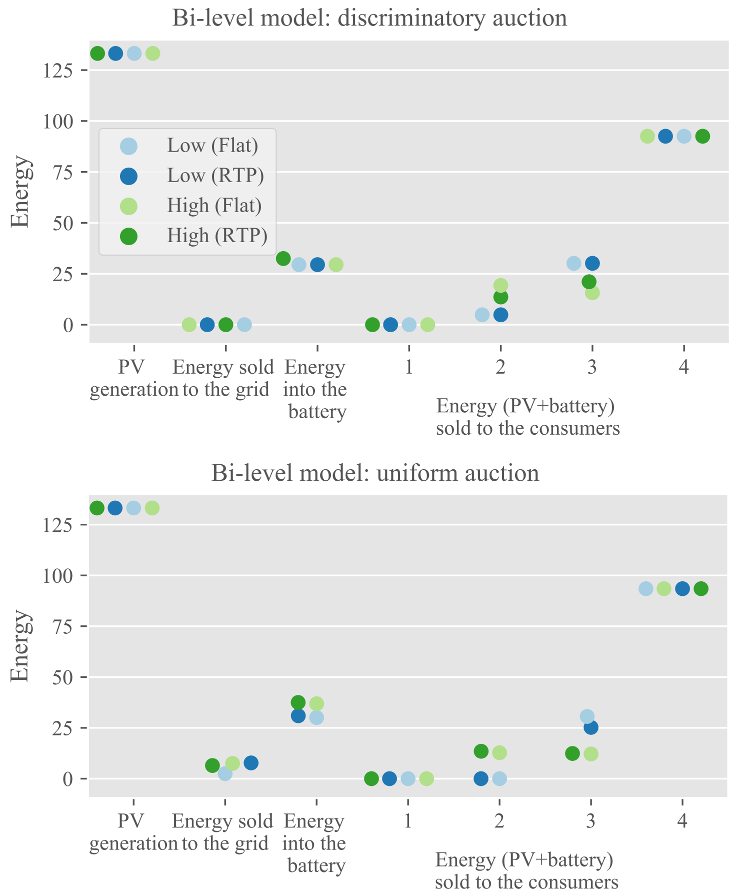

Figure 4.5.: PV generation sold to the grid, charged to the battery, and sold to consumers.

bi-level model, which finds optimal pricing from the owner's perspective, this work finds that the consumers are "captives" of the owners pricing scheme. As shown in Fig. 4.4, the prices of the discriminatory auctions are given by $wtp_{t,i}$, in accordance with Theorem 1. The uniform price under the bi-level model, p_t^U, on the other hand, varies between the different discriminatory price levels in order to maximize the owner's revenues taking into account that the prices of all consumers have to be the same. Fig. 4.4 illustrates why uniform price auctions are less profitable for the DER owner, since the prices are partly below the consumers' willingness to pay in this case. Therefore, the uniform auction results in a changed dispatch, as shown in Fig. 4.5.

4.3.2. Welfare allocation

The allocation of DER and pricing outcomes influence social welfare outcomes and the distribution of surplus between consumers and the DER owner. Table 4.1 shows the value of consumer electricity costs, emissions and welfare measures defined in section 4.1.3 for the two allocation models under both price scenarios, low and high.

Table 4.1.: Summary of welfare results in the "high price" (flat tariff) scenario. Relative changes to "No DER" are in brackets below the absolute values.

		EW maximization (4.13)			Bi-level model (4.14)	
	No DER	0	$p^G_{t,i}$	λ^{PV}_t	$wtp_{t,i}$	p^U_t
Total costs	44.9	32.8	44.9	52.7	63.4	61.1
in USD		(-27.0%)	0.0%)	(17.3%)	(41.1%)	(36.0%)
Total emissions	320.9	220.9	220.9	220.9	221.6	232.5
in kg_{CO2}		(-31.2%)	(-31.2%)	(-31.2%)	-31.0%)	(-27.5%)
Total DER gen.	0.0	127.5	127.5	127.5	127.5	118.4
in kWh	-	-	-	-	-	
OS in USD	0.0	0.0	12.1	19.9	30.6	28.1
CS in USD	0.0	30.6	18.4	10.7	0.0	1.6
US in USD	36.8	26.7	26.7	26.7	26.7	27.4
TW in USD	36.8	57.2	57.2	57.2	57.2	57.1
		(55.8%)	(55.8%)	(55.8%)	(55.8%)	(55.4%)
Loss in USD	33.8	15.3	15.3	15.3	15.3	16.0
		(-54.6%)	(-54.6%)	(-54.6%)	(-54.6%)	(-52.7%)

The EW maximizes the total welfare of the EC, but the welfare distribution depends on the pricing scheme. Naturally, using the pricing scheme $p^O_{t,i} = 0$ allocates all the EW from DER entirely to the consumers. In contrast, if $p^O_{t,i}$ is set equal to $p^G_{t,i}$ or λ^{PV}_t the welfare is shared among the consumers' and the DER owner, with the latter earning a higher surplus under the latter scheme, as summarized in Table 4.1.

The bi-level model, in contrast, aims at maximizing the owner's revenues or OS. Under the discriminatory pricing, the DER owner fully exploits the consumer's WTP for higher costs by setting prices accordingly, as the consumers are "captives" of the owner. Hence, all the surplus from DER goes to the DER owner, whereas the consumer utility, as the sum of costs, emissions, and DER, does not change compared to the case without DER ($CS = 0$).

Not surprisingly, Table 4.1 shows that the CS is marginally higher under uniform price auctions, while the owner's revenues are higher for discriminatory price auctions. As a result of uniform price auctions, total welfare losses increases by 1.9 % (high price scenario) compared to all the other cases with DER. As discussed previously, the welfare losses are the result of artificial scarcity (by selling to the market rather than to consumers), as the owner is willing to accept inefficiency in energy allocation in order to maximize it's revenues.

4.3.3. Sensitivity analysis regarding the solar power capacity

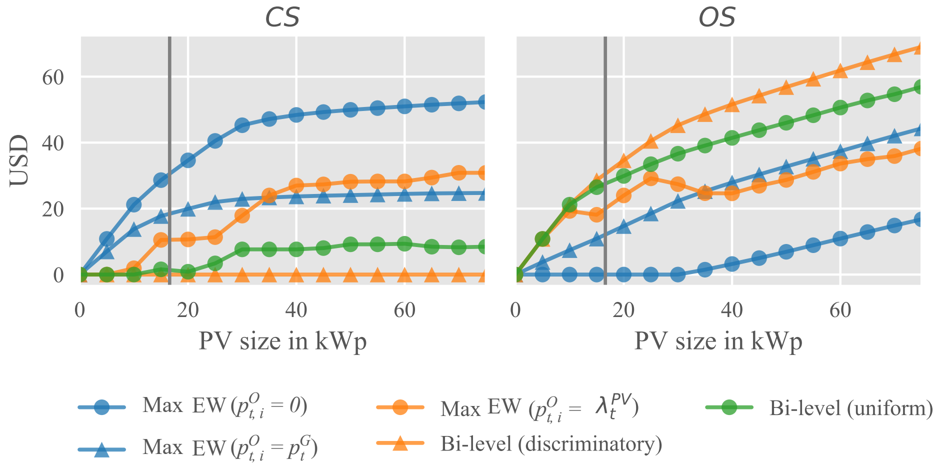

Figure 4.6.: Sensitivity analysis regarding the maximum PV plant size The vertical line shows the plant size of the previous investigation (16.6 kWp).

So far, the analysis has considered a fixed size of the PV/battery system. Fig. 4.6 shows the results of a sensitivity analysis regarding the PV plant size. The implemented pricing mechanism determines how EW is shared between consumers and the DER owner. The saturation effect in Fig. 4.6 occurs when there is a distinct switch from supplying DER to consumers to selling to the wholesale market. An interesting observation is that under the λ_t^{PV} pricing scheme for the EW model, the DER owner benefits the most up to an installed capacity of about 30 kWp, but there is a distinct switch towards a higher CS after exceeding the threshold. The explanation is that the dual variable λ_t^{PV}, which represents the marginal value of solar generation, is set by the consumers‘ WTP or the wholesale market. By increasing the PV plant size, this value is mostly defined by the market price p_t^{MCP}. In contrast, the $p_{t,i}^{O} = p_t^{G}$ pricing scheme results in increase CS and OS as a function of the solar PV size, although the growth rate is lower when PV capacity exceeds 30 kWp.

4.4. Résumé

To address the question of energy allocation and pricing of DER in an EC, two different models are developed. Additionally, consumer preferences are characterized by multiple objectives such as emissions reduction and on-site-generation in addition to cost. While the first model maximizes the total local welfare of the EC, the second model assumes that the DER owner acts strategically in a game theoretical (bi-level) model to increase its revenue. Both models (4.13) and (4.14) are efficient in the sense that consumers that place the highest value on DERs are served first, followed by the consumer with the second highest valuation, etc.

The results show that the optimization of EC welfare allocates energy identically to the bi-level model with a discriminatory price auction. The introduction of prices determine how the EC welfare from DERs is shared between the consumers and the DER owner. As multiple pricing schemes are presented, the situation, in reality, may depend on the affiliation between owner and consumers (e.g., ownership models). For practical implementation, both models are suitable: The EW maximization makes intuitive sense for a community shared battery and solar project, where owners may also be consumers.

As solar PV is a representative technology for renewable DERs and the battery as one for ESS, the proposed model may also be applied to other community energy systems. The following Chapter 5 extends the operational concept of this chapter by the investment perspective. Additionally, it includes multiple DER and ESS technologies, as well as considerations in terms of ECs stability.

4.5. Nomenclature

Sets

$t \in \mathcal{T} = \{1, \dots, T\}$	Time periods e.g. hours
$i \in \mathcal{N} = \{1, \dots, N\}$	Consumer

Decision variables

$p_{t,i}^{O}$	Price for solar PV and battery procurement applied to consumer i
p_{t}^{U}	Uniform price for solar PV and battery applied to all consumers
$q_{t,i}^{B_{in}}$	Power flow into the battery
$q_{t}^{PV_{grid}}$	Power feed (of solar PV generation) into the grid
$q_{t}^{B_{grid}}$	Power feed (of the battery) into the grid
$q_{t}^{PV_{curtail}}$	Power curtailment (of solar PV generation)
$q_{t,i}^{G}$	Power flow from grid to consumer i
$q_{t,i}^{PV}$	Power flow from solar PV plant to consumer i
$q_{t,i}^{B_{out}}$	Power flow from battery to consumer i
$\lambda_{t,i}^{L}, \lambda_{t,i}^{PV}$	Dual variables of supply = demand and limited solar PV generation constraint
$\mu_{t,i}^{G_{min}}, \mu_{t,i}^{PV_{min}}, \mu_{t,i}^{B_{min}}$	Dual variables of the inequality constraints
SOC_t	Battery state of charge
u_{i}^{C}	Utility of consumer i
$costs_i$	Electricity costs of consumer i
$emissions_i$	Emissions caused by the electricity consumption of consumer i
der_i	Electricity generated by distributed energy resources (DER) consumed by consumer i
rev^{O}	Revenues of DER owner

Parameters

e_t^G	Marginal grid emissions
$p_{t,i}^G$	Price of electricity from the grid
p_t^{MCP}	Wholesale market clearing price
$wtp_{t,i}$	Willingness-to-pay
$q_{t,i}^L$	Load of consumer i
$\bar{q}^B$	Maximum charging and discharging battery power
$\bar{q}_t^{PV}$	Electricity generation of PV plant
w_i^E	Individual weight for emissions of consumer i in $\$/kg_{CO_2}$
w_i^{DER}	Individual weight for DER of consumer i in $\$/kWh^{DER}$
$S\bar{O}C$	Maximum state of charge
$S\underline{O}C$	Minimum state of charge
SOC^{init}	Initial and end state of charge for period $\mathcal{T}$
η^B	Efficiency factor of the battery

Welfare measures

CS	Consumer surplus
OS	DER owner surplus
US	Utility company surplus
$Loss$	Loss of economic efficiency
EW	Energy community welfare
TW	Total welfare

5. Sharing of Value and Ensuring the Stability of Energy Communities

This chapter brings together the investment perspective of Chapter 3 and the individual point of view of each participant as introduced in Chapter 4. It bases on the paper *"On the Stability of Energy Communities from a Game Theoretical Point of View"* (Fleischhacker et al., 2019a), submitted to "IEEE Transactions on Smart Grid"[1]. The aim of this chapter is the introduction of the joint investment and operation of DERs and ESSs within an apartment building. Therefore, multiple games are formulated, basing on cooperative and non-cooperative game theory. The games are designed to reflect real-world situations, e.g., that consumers are either tenants or house-owners. The previous chapters assume that EC are stable, i.e., no member chooses to leave the EC. The following proves that a stable ECs are not always the case and introduce a stabilization mechanism based on rent costs for the PV area.

The chapter is organized as follows. In Section 5.1, methods for joint investment and operation of DERs and ESSs, the allocation of value and considerations on the stability of ECs are presented. Section 5.2 presents the assumptions and parameterization of a numerical example in Austria, while comprehensive results are shown in Section 5.3. Section 5.4 discusses this chapter. Section 5.5 on page 101 introduces all sets, variables and parameters used throughout this chapter.

[1]The individual contribution of this thesis' author is enlisted in Appendix B.

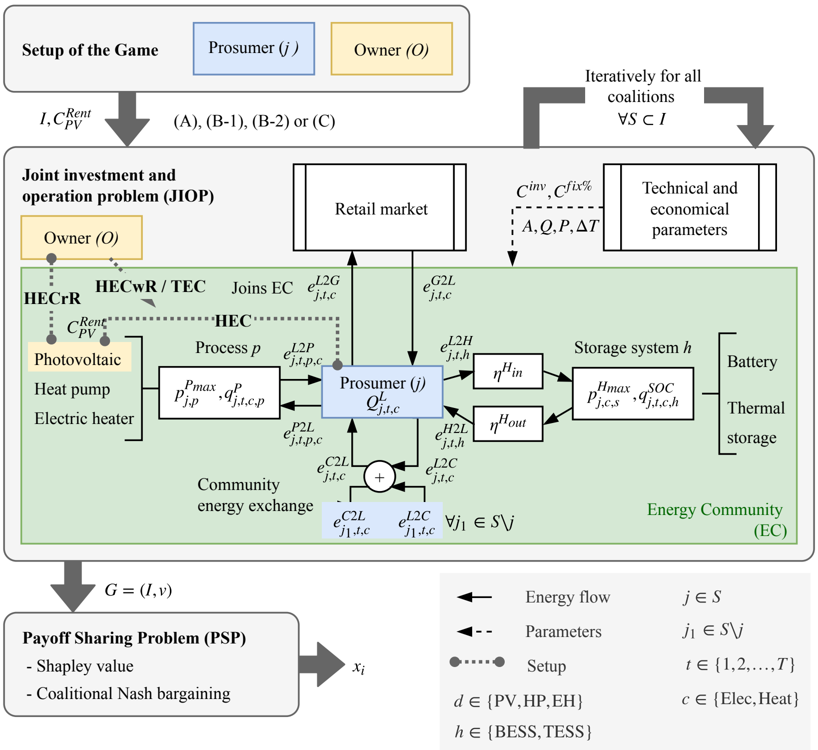

Figure 5.1.: Graphical representation of the methods of this paper, consisting of three blocks.

5.1. Methods

The purpose of the EC with the members $i \in I$ is to invest in joint generation and storage for electricity and heat and hot-water provision. In this case, the EC forms a coalition to share benefits, most importantly economic benefits, e.g., by the increase of self-consumption and economies-of-scale (EoS). It is assumed that there is an apartment house with two roles: consumers (Cs) and owners (Os). While Cs consume energy (e.g., for electricity and heat), Os own the house. There may also be mixed roles of i, e.g. Cs are also Os. On the other hand, there is an area suitable for community solar PV. The area could be either the rooftop (for rooftop mounted solar PV) or a green space (for ground-mounted). The area is either owned by the Os of the apartment building or a third party.

Fig. 5.1 shows the methodological setup of this paper. In a first step, the setup of the game is defined consisting of members $i \in I$, as well as rent costs for the PV system C_{PV}^{Rent}. In the second step, we use a joint investment and operation problem (JIOP) to compute the payoffs $v(S)$ of different coalitions S, e.g., three of four Cs form a coalition. Thirdly, the payoff sharing problem (PSP) to allocate the payoff among the players is solved by the Shapley value and the Coalitional Nash Bargaining methods. The approach bases on Theorem 1 of Wang and Huang (2016) proving that the decision variables of an EC may be split into joint planning and operational decisions (q, p, b) and a payoff sharing decision (x).

Section (5.1.1) describes the setups of different games, while Section (5.1.2) provides some background on concepts of the cooperative game theory relevant for this chapter. Section (5.1.3) describes the JIOP and (5.1.4) the PSP.

5.1.1. Setups of the Game

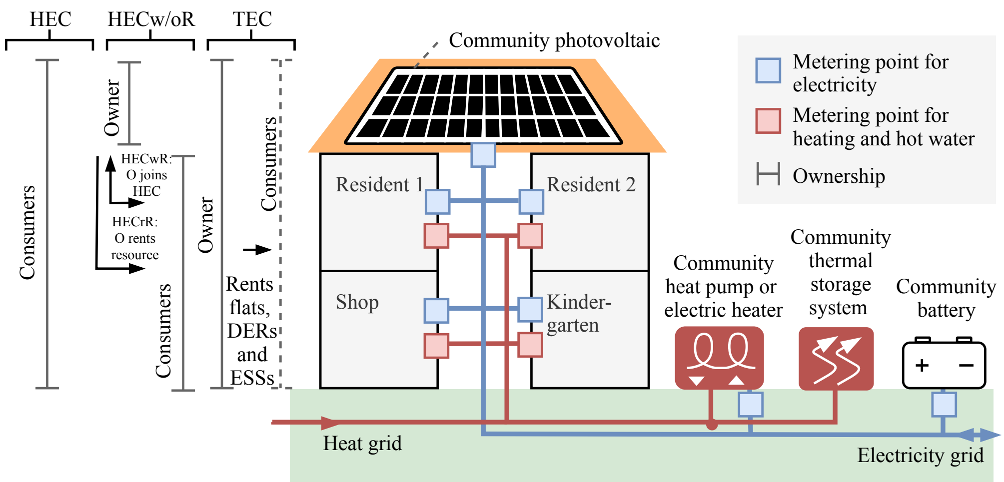

Figure 5.2.: Graphical representation of the setups of the game (5.1.1) and the use case of the energy community in Austria (5.2).

ECs may be available in different setups, as shown in Fig. 5.2. The left-hand side of Fig. 5.2 shows the setups of the game, while it also shows the energy flows from and to DERs and ESSs. The setups are formed around typical real-life relationships, with different rental and ownership contracts:

Homeowner Energy Community (HEC): Firstly, Cs share the ownership of the house. Thus, Cs live and own the house. In this case, the EC consists of $I = \{C\}$ and has the objective to reduce the total building energy costs. The rooftop may be shared between Cs, with or without rent costs.

HEC without resources (HECw/oR): The second setup elaborates on the case that the O as a third party owns the resource[2] suitable for community solar PV. While Cs may decide to invest in DERs (without PV) and ESSs, O has two options, joining the HEC or renting the resource:

- **HEC with Resource Owner (HECwR):** O may decide to invest in PV and sell the generation to Cs or the market. In this case, O joins the EC for, i.e., $I = \{C, O\}$.
- **HEC renting Resources (HECrR):** O may rent the rooftop to Cs, enabling them to invest in solar PV. In this case the EC $I = \{C\}$ is charged by O.

Tenant Energy Community (TEC): Thirdly, O may own the whole house, and Cs are tenants. If O invests in DER and ESS, energy costs of Cs are reduced. Thus, O joins the EC $I = \{C, O\}$.

On the one hand, setups HEC, HECwR and TEC are cooperative games. On the other hand, HECrR is a hybrid game, since O plays a non-cooperative game with the HEC $I = \{C\}$, playing a cooperative game between it's members Cs.

5.1.2. Cooperative Games

The problem of an EC is defined by the cooperative game theory as a coalitional game $Game = (I, v)$ with an exchangeable utility (i.e., side payments). Within the game, players $i \in I$ join a coalition $S \subset I$ creating a monetary

[2] Rooftop or any other area (e.g., a farmer's land).

payoff $v(S)$. If all players join the coalition I they form the Grand Coalition (GC).

If the core of a game (defined in Section 5.1.2.1) is non-empty, all coalitions, $\forall i \in I$ are incentivized to stay in the GC. In a game with an exchangeable utility, the value of the GC $v(I)$ can be divided among its members in any mutually agreeable fashion, and transferred from one party to the other via side payments: the question is how to allocate the total payoff among the parties (Lo Prete and Hobbs, 2016). Thus, this work uses two concepts of the cooperative game theory: the Shapley value (Section 5.1.2.2) and Coalitional Nash Bargaining (Section 5.1.2.3), to allocate

$$\sum_{i \in I} x_i = v(I). \tag{5.1}$$

For the sake of simplicity, the allocation methods are named Shapley and Nash, respectively. As a measure of coalitional stability, Section 5.1.2.4 introduces the Cost of Stability.

5.1.2.1. Core

Shapley defines the core as "a set of payoff configurations that leave no coalition in a position to improve the payoffs to all of its members" (Shapley and Shubik, 1973), and satisfies conditions of individual and group rationality. Individual rationality means the payoff of each player should be greater or equal to zero. Group rationality means that the sum of the total gains of all group members in coalition S should be positive that no coalition receives a payoff that is lower than the sum of each member's payoffs by acting alone. Finally, the sum of the gains of all players should equal the value of the grand coalition (Lo Prete and Hobbs, 2016).

The core is constituted by all allocations of the total value of the game $v(I)$ such that all coalitions S are incentivized to stay in the GC. The core is defined as:

$$(5.1) \tag{5.2a}$$

$$\forall S \subset I, \quad \sum_{i \in S} x_i(v) \geq v(S). \tag{5.2b}$$

The concept of the core has two disadvantages: (i) it is sometimes empty and (ii) if it is not empty, it contains an infinite range of allocations. As usually assumed in cooperative game theory, e.g., by Abada et al. (2017), it is considered that an EC is stable (or viable) if and only if the core is not empty.

5.1.2.2. Shapley Value

The Shapley value introduced in Shapley and Shubik (1973) is a widely used allocation rule. It satisfies three properties: symmetry, linearity, and Pareto-optimality. The detailed formulation of the Shapley value, where the allocation of each player of the game is calculated may be formulated as

$$x_i^{Shapley} = \sum_{i \in S \subset I} (v(S) - v(S/i)) \frac{(n-s)!(s-1)!}{n!} \tag{5.3}$$

with $v(S/i)$ as the payoff of the coalition without player i. The numbers s and n denotes the cardinal of S and I, respectively.

As stated in the introduction, the motivation for using Shapley is that the solution explicitly considers the power of each possible coalition in the game. The Shapley value is unique and not necessarily lies within the core. Lippman and Rumelt, 2003

5.1.2.3. Coalitional Nash Bargaining

Nash describes with the Nash Bargaining method how to share the payoff of a two-player game as the outcome of a negotiation process (Nash, 1953). The Nash bargaining solution is unique for bargaining games satisfying Pareto optimality, symmetry, scale independence, and independence of irrelevant alternatives (Avrachenkov et al., 2015). Compte and Jehiel (2008) expands the method by the Coalitional Nash Bargaining as a non-linear program

$$\max_{x_i^{Nash}} \quad \prod_{i \in I} \left(x_i^{Nash} - y_i\right) \tag{5.4a}$$

$$\text{subject to} \quad x_i^{Nash} \geq y_i \qquad \forall i \in I \tag{5.4b}$$

$$(5.2)$$

with the disagreement point y_i, being the outcome, if the players cannot agree. This work defines the $y_i = v(i)$ as the individual payoff of the player i, as the payoff of the game $S = \{i\}$. In comparison to Shapley, the coalition Nash Bargaining solution is formulated as an optimization problem including the core (5.2). Thus, it is ensured that if (5.4) is feasible, the solution is in the core. Furthermore, the Nash Bargaining solution is a very effective method to model interactions among negotiation processes, which fits very well to the games defined in Section 5.1.1.

5.1.2.4. Cost of Stability (CoS)

To measure the stability of a coalitional game's outcome, Bachrach et al. (2009) introduce a linear program in the form of

$$\min_{x_i, \Delta} \quad \Delta \tag{5.5a}$$

$$\text{subject to} \quad \sum_{i \in S} x_i \geq v(S) \tag{5.5b}$$

$$\sum_{i \in I} x_i = v(I) + \Delta \tag{5.5c}$$

$$x_i \geq 0 \qquad \forall i \in I \tag{5.5d}$$

to calculate the cost of stability Δ. Given a coalitional game $Game = (I, v)$, Δ is the smallest external payment needed to stabilize it. If $\Delta \leq 0$, the game has a core (stable EC), $\Delta > 0$ indicates that no core is available (unstable EC). As an example: If $Game_1$ has the outcome $\Delta_1 < 0$ and $Game_2$ the outcome $\Delta_2 < 0$ with $\Delta_1 < \Delta_2$, it can be concluded that both games are stable, but $Game_1$ has a higher stability than $Game_2$.

5.1.3. Joint Investment and Operation Problem (JIOP)

As shown in Fig. 5.1, the setup of the game defines the JIOP. The JIOP calculates the individual payoffs of all possible $2^n - 1$ coalitions S. The following analyzes, the JIOP minimizes the total costs of the EC, with optimal investment and optimal energy management for the EC. As shown in Fig. 5.1, the investment decisions include the investments and the operation of DERs (D), ESSs (H) and grid procurement (G) for the coalitions. Firstly, objectives of all players are defined, followed by a detailed calculation of the payoff for each setup.

5.1.3.1. Objectives of all Players

The Cs of a coalition S are interested in reducing the total costs. Thus their objective

$$\min_{q,p,b} \quad total\ costs^{C,wI}(S) =$$

$$\sum_{d} A_d \left(b^D C_d^{inv_{fix}} + \sum_{j} p_{j,d}^{D_{max}} C_d^{inv_{power}} \right) \tag{5.6a}$$

$$+ \sum_{s,c,j} A_s \left(p_{j,h}^{H_{max}} C_s^{inv_{power}} + q_{j,h}^{SOC_{max}} C_s^{inv_{cap}} \right) \tag{5.6b}$$

$$+ \sum_{c} p_{j,c}^{G_{max}} C_c^{fix_d} \tag{5.6c}$$

$$+ \sum_{j} p_{j,PV(I \setminus S)}^{D_{max}} C_{PV}^{Rent} \tag{5.6d}$$

$$+ \sum_{j,t,c} q_{j,t,c}^{G2L} C_{t,c}^{Retail} \tag{5.6e}$$

$$- \sum_{j,t,c} q_{j,t,c}^{L2G} C_{t,c}^{Market} \tag{5.6f}$$

consists of investment, maintenance and operation costs for DERs (5.6a), ESSs (5.6b), annual fixed grid costs (5.6c), rent costs for the PV area that is not the property of S (5.6d). We expresses different prices for energy procurement and revenues for selling at the wholesale market price via (5.6e) and (5.6f), respectively. The market design in Europe, especially in Austria, changed in the recent years. Nowadays it favours investment subsidies for DERs and ESSs over feed-in-premium or net-metering schemes. Note that the model may be easily adopted to handle other market designs (e.g., net metering). Equation (5.6f) reflects this situation by the introduction of a wholesale market based price $C_{t,c}^{Market}$. The decisions variables q describes energy flows, p installed capacities and b the binary variables for the investment decision.

Furthermore, the JIOP has technical constraints in the form

$$\sum_d q_{j,t,c,d}^{D2L} + \sum_h q_{j,t,c,h}^{H2L} + q_{j,t,c}^{G2L} + q_{j,t,c}^{C2L} \tag{5.7a}$$

$$= \sum_d q_{j,t,c,d}^{L2D} + \sum_h q_{j,t,c,h}^{L2H} + q_{j,t,c}^{L2G} + Q_{j,t,c}^{L} + q_{j,t,c}^{L2C}$$

$$q_{j,t,c}^{C2L} = q_{j,t,c}^{L2C} \tag{5.7b}$$

$$0 \leq q_{j,t,c}^{D2L} \leq \eta_{t,d}^{D_{out}} q_{j,t,c,d}^{D} \leq \eta_{t,d}^{D_{in}} q_{j,t,c,d}^{L2D} \tag{5.7c}$$

$$0 \leq q_{j,t,c,d}^{D} \leq p_{j,d}^{D_{max}} \Delta T \leq b_d M \tag{5.7d}$$

$$\sum_j p_{j,d}^{D_{max}} \leq P_d^{D_{max}} \qquad \forall d \in \{PV(S), PV(I \backslash S)\} \tag{5.7e}$$

$$q_{j,t-1,c,h}^{SOC} = q_{j,t,c,h}^{SOC} + q_{j,t,c,h}^{L2H} \eta_s^{H_{in}} - q_{j,t,c,h}^{H2L} / \eta_s^{H_{out}} \tag{5.7f}$$

$$q_{j,0,c,h}^{SOC} = q_{j,T,c,h}^{SOC} = 0 \tag{5.7g}$$

$$0 \leq q_{j,t,c,h}^{SOC} \leq q_{j,t-1,c,h}^{SOC_{max}} \tag{5.7h}$$

$$0 \leq p_{j,c,h}^{S_{max}} \leq b_h^H M \tag{5.7i}$$

$$0 \leq q_{j,t-1,c,h}^{L2H} \leq p_{j,h}^{H_{max}} \Delta T \tag{5.7j}$$

$$0 \leq q_{j,t-1,c,h}^{H2L} \leq p_{j,h}^{H_{max}} \Delta T \tag{5.7k}$$

$$0 \leq q_{j,t,c}^{G2L} \leq p_{j,c}^{G_{max}} \Delta T \tag{5.7l}$$

$$0 \leq q_{j,t,c}^{L2G} \leq p_{j,c}^{G_{max}} \Delta T \tag{5.7m}$$

with the energy balance within the EC (5.7a), the energy sharing equilibrium (5.7b), technical restrictions of the processes (5.7c)-(5.7e), of the storages (5.7f)-(5.7i) and the grid procurement (5.7j)-(5.7k) and infeed (5.7l)-(5.7m). (5.7e) introduces the limited resource for PV (reflected by a maximum installed capacity $P^{D_{max}}$) and differentiate between PV systems without rent costs

$PV(S)$ (owned by the coalition S) and PV systems with rent costs $PV(I\backslash S)$ (not owned by the coalition S).

As mentioned in Section 5.1.1, this work differentiates between three setups, having an impact on C_{PV}^{Rent}:

HEC If Cs own the roof C, all $S \neq I$ are affected by rent cost, also named internal payments (Section 5.1.4). For the GC ($S = I$), $P_{PV(I\backslash S)}^{D_{max}} = 0$ in (5.6d).

HECw/oR If O joins the EC at HECwR, $C_{PV}^{Rent} = 0$ but O gets a share of the payoff x_O. On the contrary, HECrR lets O acting strategically and charges the EC with $C_{PV}^{Rent} \geq 0$ (see external payment in Section 5.1.4) generating

$$revenues^{O,wI} = \sum_j p_{j,PV(I\backslash S)}^{D_{max}} C_{PV}^{Rent}. \tag{5.8}$$

TEC O owns the whole building, invests in DERs, and sells energy to Cs accordingly. This setup assumes no payments for the PV area in this case, $C_{PV}^{Rent} = 0, \ \forall S$.

As the core of the game may be empty, this work proposes to stabilize the EC by either internal or external payments based on the work of Meir et al. (2011). External payments affect all coalitions, as an external party is paid. Contrary, internal payments are transferred to players not part of the coalition. Consequentially, the GC is not affected by internal payments.

Theorem 3 (Stabilization of an EC by an internal payment)**.** *Given a coalitional game of an EC, Game* $= (I, v)$ *with an empty core, there is an internal payment within the EC* $\delta^{int} > 0$ *based on PV capacity stabilizing the EC.*

Proof. In the case the core is empty, there is

$$v(S) + v(I\backslash S) > v(I), \ \exists S \in I. \tag{5.9}$$

By introducing an internal payment for the PV capacity $p_{PV}^{D_{max}}$ not owned by the coalition S, the payoff of $\forall S \neq I$ changes to $v'(S) = v(S) - p_{PV}^{D_{max}}(S)\delta^{int}$. Consequentially,

$$\delta^{int} \geq \frac{v(S) + v(I \backslash S) - v(I)}{p_{PV}^{D_{max}}(I \backslash S) + p_{PV}^{D_{max}}(S)} \tag{5.10}$$

which defines the threshold necessary to stabilize game $Game = (I, v)$ by an internal payment. As (5.9) and $p_{PV}^{D_{max}} \geq 0$, $\delta^{int} \geq 0$. ■

Theorem 4 (Stabilization of an EC by an external payment)**.** *Given a coalitional game of an EC $G = (I, v)$ with an empty core, there is an external payment $\delta^{ext} > 0$ from the EC to an external (third) party based on PV capacity stabilizing the EC.*

Proof. The proof is similar to the proof of Theorem 3, with the difference that the external payment δ^{ext} effects $\forall S \subset I$ resulting in

$$\delta^{ext} \geq \frac{v(S) + v(I \backslash S) - v(I)}{p_{PV}^{D_{max}}(S) + p_{PV}^{D_{max}}(I \backslash S) - p_{PV}^{D_{max}}(I)}. \tag{5.11}$$

Note that $\delta^{ext} > \delta^{int}$, since $p_{PV}^{D_{max}}(I)$ is included in the denominator. ■

An internal payment reduces the payoff of all coalitions excluding the GC, while an external payment effects all coalitions. Therefore, and as shown in the proofs of Theorem 3 and 4, $\delta^{ext} > \delta^{int}$. While Theorem 3 is applied for setup HEC, Theorem 4 is applied for HECrR.

5.1.3.2. Payoff of a Homeowner Energy Community (HEC)

Firstly, the payoff of a coalition of Cs is defined as

$$v(S) = \sum_{i \in S} \Big(total\ costs^{C,w/oI}(S) - total\ costs^{C,wI}(S) \Big) \tag{5.12}$$

as the difference in total costs (without (w/oI) and with (wI) investments). In the case of w/oI, energy demand is satisfied by grid procurement. The results in Section 5.3 show results of different ownership assumptions, as well as the impact of C_{PV}^{Rent}.

5.1.3.3. Payoff of Homeowner Energy Community without Resources (HECw/oR)

For HECwR, the participation of O enables the EC to invest in PV, expressed as

$$p_{PV}^{D_{max}}(S) = \begin{cases} P_{PV}^{D_{max}} & O \in S \\ 0 & \text{otherwise} \end{cases} \tag{5.13}$$

with the calculation of $v(S)$ by (5.12).

Whereas for case HECrR, the O charges the EC $I = \{C\}$ with $C_{PV}^{Rent} \geq 0$, reducing the consumers' value. Two results for C_{PV}^{Rent}, both resulting from bi-level optimization models, are of particular interest:

- $C_{PV}^{Rent,min}$: As discussed above, the EC may not be stable without external payments. If O intends in stabilizing the EC in the long run, the C_{PV}^{Rent} the result of

$$\min_{\substack{\{c_{PV}^{Rent},x\} \\ \{b,q,p\}}} \quad c_{PV}^{Rent} \tag{5.14a}$$

$$\text{subject to} \quad (5.2) \tag{5.14b}$$

$$\min_{\{b,q,p\}} \quad (5.6) \text{ subject to } (5.7)$$

  If the EC is stable without C_{PV}^{Rent}, $revenues^{O,wI} = 0$.

- $C_{PV}^{Rent,max}$: If the intention of the owner is to maximize the revenues,

$$\max_{\substack{\{c_{PV}^{Rent},x\} \\ \{b,q,p\}}} \quad revenues^{O,wI}(c_{PV}^{Rent}) \tag{5.15a}$$

$$\text{subject to} \quad \min_{\{b,q,p\}} \quad (5.6) \text{ subject to } (5.7)$$

  may be applied. The bi-level optimization model ensures that c_{PV}^{Rent*} is chosen in a way so that the EC still invests into PV, but resulting in the highest revenues for the O. (5.15) is a Stackelberg game since the O has complete information of Cs decisions (Fleischhacker et al., 2018).

5.1.3.4. Payoff of Tenant Energy Community (TEC)

In this setup, O is the investor. If O is not part of the EC, no investments in DER or ESS are possible. Thus, the EC's payoff changes to

$$v(S) = \begin{cases} (5.12) & \text{if } O \in S \\ 0 & \text{else.} \end{cases} \tag{5.16}$$

with $C_{PV}^{Rent} = 0$. As O joins the EC, $revenues^{O,wI} = x_O$.

5.1.4. Payoff Sharing Problem (PSP)

The PSP derives the optimal allocation of payoff to incentivize cooperative planning for the EC. The algorithms (Shapley and Nash) use the result of the JIOP ($Game = (I, v)$) as input and calculate x_i. Note that v is the result of $2^n - 1$ JIOP runs. For allocation, either Shapley (5.3) or Nash (5.4) is used.

5.2. Definition of the Use Case

To illustrate a potential application of the proposed models, the framework is applied to a real use case in the municipality of Großschönau, Austria. It is considered that the EC consists of four consumers: one grocery store (shop), one kindergarten and two residential consumers (resident 1 and 2)[3] shown in Fig. 5.2. Table 5.1 shows the annual demand of all four consumers as well as

[3] This work uses measured data for the electricity and heat consumption (for space heating and hot water) with a 15 min time resolution. Electricity and heat profiles: measured from Großschönau in 15 min time interval from the year 2017 (Frantes, 2018). Other time series data: solar radiation (MINES ParisTech / Transvalor, 2018) and outdoor temperature (ZAMG, 2012). Models: solar PV (Huld et al., 2010) and heat pump (Lindberg et al., 2016).

the correlation coefficient as used in Wang and Huang (2016) of demand and solar PV generation, defined as

$$\rho_{X,Y} = \frac{\sum_t (X_t - \overline{X})(Y_t - \overline{Y})}{\sqrt{\sum_t (X_t - \overline{X})^2}\sqrt{\sum_t (Y_t - \overline{Y})^2} \tag{5.17}$$

with time series X and Y (dimension t) and mean values $\overline{X}$ and $\overline{Y}$, respectively. The data in Table 5.1 shows that shop has the highest consumption as well as the highest correlation of both demand types with solar PV, therefore the highest value for solar generation. On the contrary, both, resident 1 and 2 have a low annual demand as well as a low ρ.

Table 5.1.: Annual consumption of electricity and heat and correlation coefficients.

	$Q^L_{j,Elec}$ in kWh	$Q^L_{j,Heat}$ in kWh	$\rho_{Elec,PV}$	$\rho_{Heat,PV}$
Resident1	2,742	12,071	0.037	-0.065
Resident2	3,253	12,890	-0.031	-0.064
Kindergarten	3,393	61,190	0.330	-0.263
Shop	90,393	102,852	0.348	0.180

As shown in Fig. 5.1 and 5.2, the EC may choose to invest in DERs and ESSs or purchase from the electricity and heat grid[4]. As a result of limited PV, PV investments are restricted by a 150 m^2 (22.8 $\mathrm{kW_p}$).

The methods introduced in Section (5.1) are implemented in the Python modeling framework Pyomo (Hart et al., 2017) and solved it with the solvers Gurobi[5] version 8.0.1 (Gurobi Optimization, 2018) and IPOPT[6] version 3.11.1 (Wächter and Biegler, 2006), respectively.

[4]Electricity rate: $C^{Retail}_{t,Elec}$ = 15.92 ct/kWh (generation charge 5.99 ct/kWh, delivery charge 5.141 ct/kWh and taxes 4.78 ct/kWh); heat rate: $C^{Retail}_{t,Heat}$ = 7.2 ct/kWh (including generation, delivery and taxes). Data from (Frantes, 2018; E-Control, 2018). The market price for selling electricity to the grid is the wholesale price at the power exchange EXAAEXAA, 2018. As this work assumes an unidirectional high temperature heat grid, feed-in of thermal energy is not possible.

[5]Used for the problems JIOP (5.6)-(5.7) and CoS (5.5).

[6]Used for the PSP, Nash Bargaining solution (5.4).

5.3. Results

In this section, we firstly elaborate on unstable coalitions, followed by results for the HEC in Section 5.3.2, HECw/oR in Section 5.3.3 and a comparison and the results of TEC in 5.3.4.

5.3.1. Unstable Coalitions due to an Restricted PV Area

Considering setup HEC with a limited solar PV of 150 m^2, leads to a maximum capacity of 22.8 kW_p. Fig. 5.3 shows the payoff $v(S)$ of each coalition as well as the installed capacity of solar PV. Hereby two assumptions are shown: limited and unlimited area for solar PV.

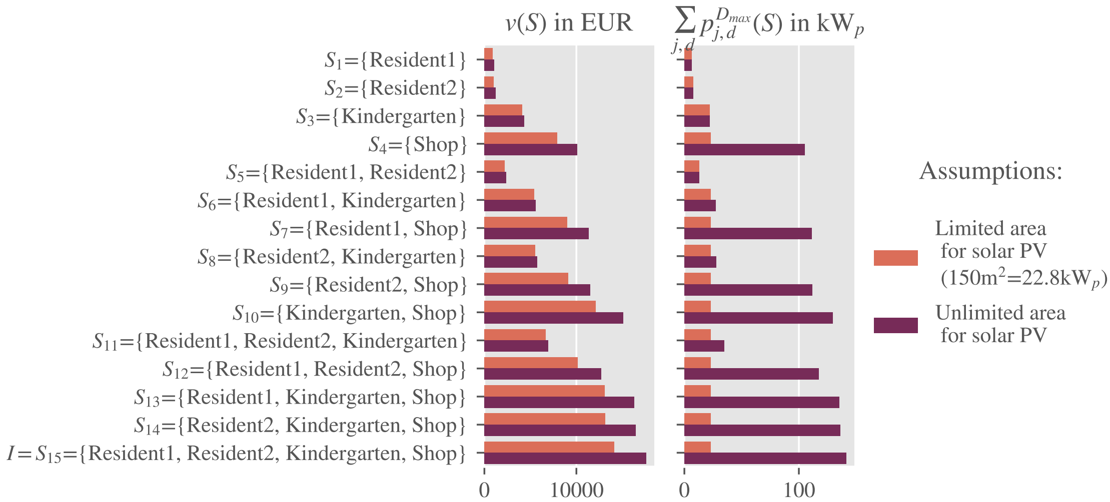

Figure 5.3.: Payoff of each coalition $S \subseteq I$, $v(S)$ and installed capacity in solar PV.

The game with limited area for solar PV has an empty core, shown by the following illustration: A joint investment by all consumers (I) result in a total payoff of 14 109 EUR. Alternatively, the investment can be carried out by coalition $S_4 \in$ {Shop} with a payoff of 7936 EUR or coalition $S_{11} \in$ {Resident1, Resident2, Kindergarten} with a payoff of 6685 EUR. Both coalitions use the total available area. The EC is unstable, as the payoff of the GC $v(I) = 14\,109\,\text{EUR}$ and $v(I) < v(S_4) + v(S_{11})$. Thus, for coalitions S_4 and S_{11} it is better to invest individually. The area for solar PV is a limited resource, and cannot be shared between two coalitions who want to fully utilize it. Under this assumptions, the coalition does not find a solution suitable for all members and the GC "breaks apart".

If the area is not restricted by an upper bound (e.g., in the case of a large greenfield for PV expansion close to the EC), the GC would invest into a capacity of $141.5\,\text{kW}_\text{p}$. In this case, the allocation algorithms Shapley and Nash could be applied. Tab. 5.2 shows the results of the allocation x_i. If the resource for solar PV is not limited, the core is not empty and x_i of both allocation methods is within the core.

Table 5.2.: Results for unstable (limited PV resource) and stable outcome.

	Limited resource for solar PV ($150\,\text{m}^2$)$^{(a)}$		Unlimited resource for solar PV$^{(b)}$	
x_i in EUR	Shapley	Nash	Shapley	Nash
Resident1	1017	-	1172$^{(*)}$	1183$^{(*)}$
Resident2	1133	-	1323$^{(*)}$	1346$^{(*)}$
Kindergarten	4165	-	4681$^{(*)}$	4664$^{(*)}$
Shop	7794	-	10430$^{(*)}$	10414$^{(*)}$

$^{(a)}$ Core empty. $^{(b)}$ Core not empty. $^{(*)}$ Within the core.

5.3.2. Results for a Homeowner Energy Community

Consequentially, an internal payment is introduced to stabilize the outcome in the case of a limited PV resource. It is assumed that the Cs share the PV area equally (25 % per C). In the case that the coalition S needs more PV area than owned by the coalition ($> s\ 0.25\ P_{PV}^{D_{max}}$), an internal rent is payed to $I \backslash S$. It is assumed that Cs hold equal shares of the PV area (25 % per C), which means that each C receives 25 % of the internal rent. Fig. 5.4 shows the allocation x_i to the Cs for both allocation methods, Shapley and Nash, as a function an internal payment $C_{PV}^{Rent} = \delta^{int}$. Note that for the interval $0 \leq C_{PV}^{Rent} \leq 37\,\text{EUR/kW}_\text{p}$ the core is empty and therefore EC becomes unstable. Hence, an internal payment, $\delta^{int} >= 37\,\text{EUR/kW}_\text{p}$, is required for a stable EC. As shown in Fig. 5.4 internal payments decrease the CoS until $C_{PV}^{Rent} \geq 150\,\mathrm{EUR/kW_p}$. Beyond this point, $\forall S \neq I$ stop to invest into PV and there is therefore no further stabilization of the EC.

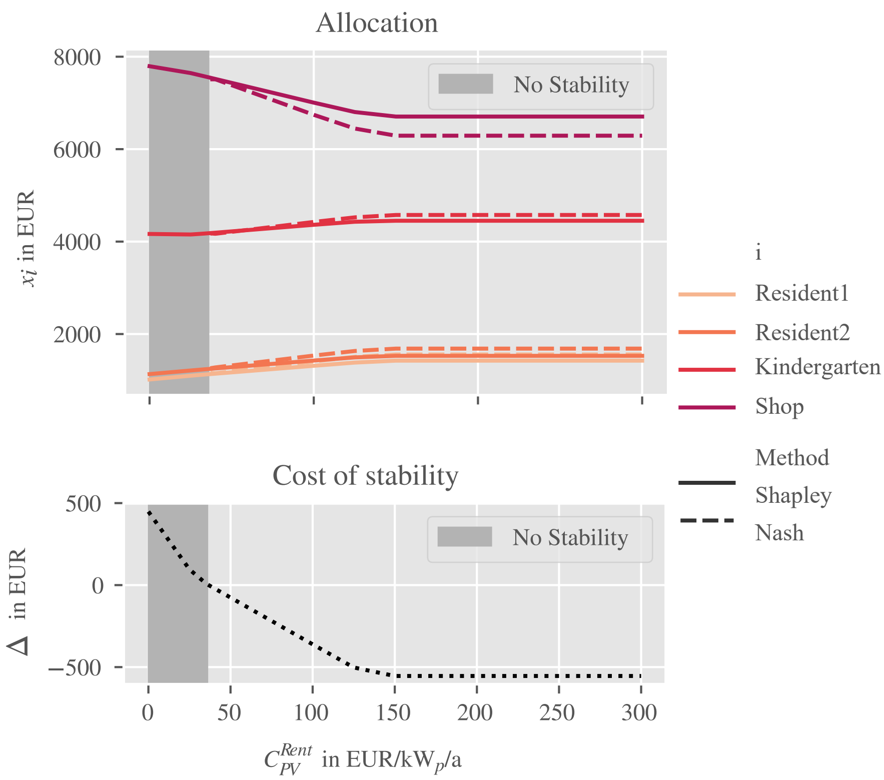

Figure 5.4.: Allocation x_i as function of C_{PV}^{Rent} (Shapley and Nash), with the PV area equally shared between all Cs (HEC).

5.3.3. Results for a Homeowner Energy Community without Resources

Fig. 5.5 (top) shows the allocation to Cs and O in the case O owns the PV resource. As the difference between Nash and Shapley is similar, Fig. 5.5 only shows the results for Nash. The straight line indicates the cooperative solution for HECwR (i.e., O joining the EC). In comparison to HEC, the solution for HECwR is stable without the need for additional payments. Note that HECwR is not affected by C_{PV}^{Rent}.

The dotted lines in Fig. 5.5 shows the allocation, if O is not joining the EC, and instead charging the EC with an external payment $C_{PV}^{Rent} = \delta^{ext}$. Revenues for O are highest at $C_{PV}^{Rent,max}$ and lowest for $C_{PV}^{Rent,min}$. $C_{PV}^{Rent,min} = 42\,\mathrm{EUR/kW_p}$ marks the minimum external payment ensuring a stable EC.

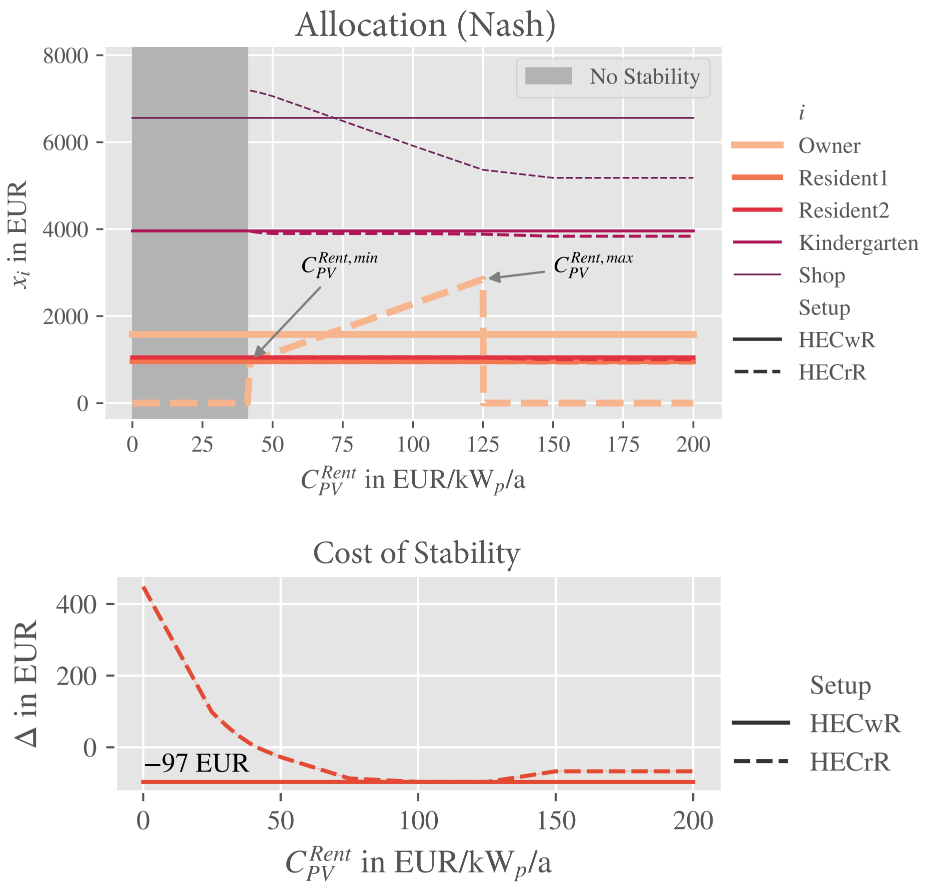

Figure 5.5.: Allocation with Nash (top) and CoS (bottom) for HECwR and HECrR.

Fig. 5.5 (bottom) shows the CoS. Since there exists a core, CoS does not change between the two allocation methods. Compared to HEC, minimum CoS is −97 EUR for HECwR and HECrR, although CoS for HECrR changes as a function of C_{PV}^{Rent}. Comparing Fig. 5.5 with Fig. 5.4 shows that $\Delta\,|_{HEC} \gg \Delta\,|_{HECw/oR}$. This results from the fact that internal payments stabilize the

EC by decreasing value of all coalitions excluding the GC, while external payments also affect the GC.

5.3.4. Comparison of all Setups

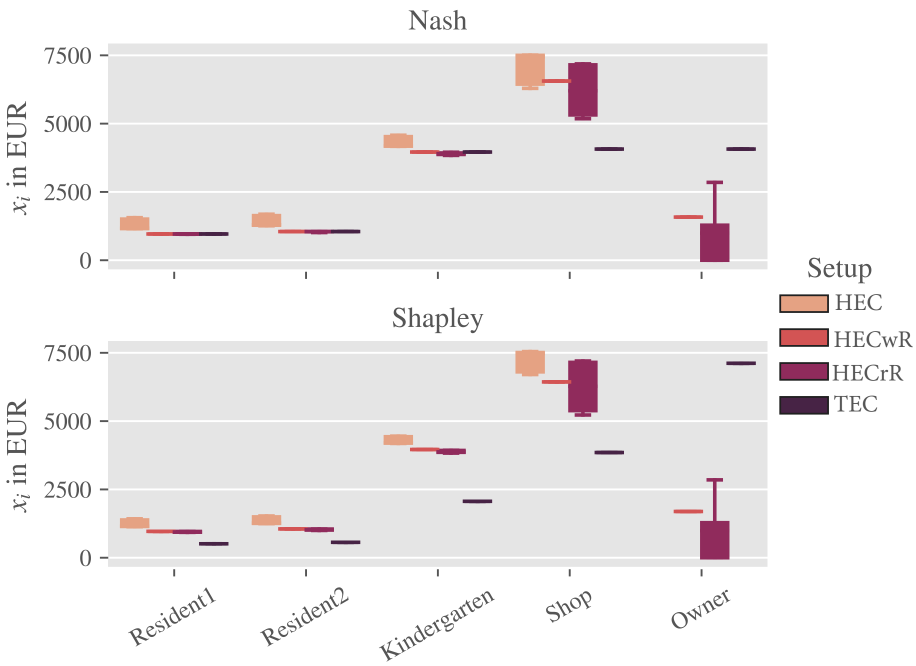

Figure 5.6.: Range of stable allocations for all setups with Shapley and Nash.

Fig. 5.6 shows the range of all stable allocations, therefore $\Delta_{TEC} \leq 0$. The results show that $x_i,\ i \in \{C\}$ is highest for HEC since Cs creates value by DER investment and consumption. The same is also valid for HECw/oR, with the difference, that O creates value by providing Cs with resources for solar PV. Interestingly, the results for the TEC differs significantly between Shapley and Nash. The reason is that O brings a high average marginal contribution to the EC (strong position for Shapley), but has a bad position for negotiation (bad position for Nash).

5.4. Résumé

This chapter investigates the optimal strategy for investment and operation of DERs and ESSs in ECs. To address the question of how to allocate the value of DERs and ESS, two methods from the cooperative game theory (Shapley value, and Coalitional Nash bargaining) are used. The two methods either rate the weighted average value added by each player to each coalition (Shapley) or shows the results of a bargaining process (Nash). Therefore, the solutions suggest a transparent and "fair" allocation to all players and help to decrease the negotiation effort necessary to found ECs.

It is also shown, that in dependence of the ECs' composition, it may lacks stability since the resources for solar PV are limited (e.g., by rooftop area). Consequentially, it introduces possibilities of stabilizing the coalitional game by charging the consumers with additional payments for PV capacity. The payments are designed in a way to discourage players from breaking up with the EC. The stabilization measures are based on the real-life relationship between tenants, house owners, and owners of resources for solar PV.

Firstly, the results of a quantitative example from Austria show that the EC is unstable due to a limited resource/area for solar PV. Secondly, it shows that internal (between the members of the EC) and external payments (from the EC to an external third party), provide incentives to stabilize the EC. Overall, the results demonstrate that the proposed model is suitable for practical implementation by solving the planning problem efficiently.

5.5. Nomenclature

Sets

$t \in \mathcal{T} = \{1, \dots, T\}$ . . Time periods e.g. hours
$i \in S \subset \mathcal{I}$ . . . . Coalitions S as a subset of the Grand Coalition I with $s = |S|$ and $n = |I|$
$d \in \{PV, HP, EH\}$ . . Set of DERs
$h \in \{BESS, TESS\}$. Set of ESSs
$c \in \{Elec, Heat\}$ . . . Set of energy commodities

Decision variables

q . . . . Energy flow (in kWh/15min)
b . . . . Binary investment decision variable: if d or s is installed [0,1]
p . . . . Continuous investment decision variable: installed power (in kW)
$q^{SOC_{max}}$ . . . . Continuous investment decision variable: installed storage capacity (in kWh)
$v(S)$ . . . . Payoff of coalition S (in EUR)
x_i . . . . Allocation of $v(S)$ to i (in EUR)
y_i . . . . Disagreement point, opportunity for i if the coalition breaks apart (in EUR).
Δ . . . . Cost of stability (in EUR)
δ^{int} . . . . Internal stabilization payment (in EUR/$\mathrm{kW_p}$)
δ^{ext} . . . . External stabilization payment (in EUR/$\mathrm{kW_p}$)

Parameters

A . . . . Annuity factor
$C^{inv_{fix}}$ . . . . Fixed investment costs related with b (in EUR)
$C^{inv_{power}}$ . . . . Investment costs related in power, i.e. p (in EUR/kW)

$C^{inv_{cap}}$	Investment costs related in storage capacity, i.e. $q^{SOC_{max}}$ (in EUR/kWh)
C^{Retail}	Costs for grid procurement (in EUR/kWh)
C^{Market}	Costs for selling to the wholesale market (in EUR/kWh)
C_{PV}^{Rent}	Rent costs for PV, price for the resource
P_{PV}^{Dmax}	Maximum PV capacity due to limited rooftop area

6. Discussion and Synthesis of Results

6.1. Findings referring to the Research Questions

The previous chapters show different modelling approaches as well as comprehensive results for ECs. This is in-line with this thesis' objective in response of the research questions formulated in Chapter 1. In this regard, this chapter follows up with detailed key findings. Beginning with Research Question 1

What is the value in respect of emission and cost reductions, if energy communities are implemented on a large scale?

this work, and Chapter 3 in particular, finds that ECs can reduce the costs as well as emissions. Not surprisingly, solutions for minimum costs and minimum carbon emissions are contrary to each other. Therefore, information about the relationship between costs and emissions (e.g., by a Pareto Front) helps to quantify the optimal technical portfolio as a function of both objectives. This information provides stakeholders (such as the local government) with information about the capabilities and restrictions of the local energy system. In addition, it helps the stakeholders to formulate and quantify feasible emission reduction targets. The results of Chapter 3 show that emission reduction is mainly the result of electrification, although the use of one single energy carrier increases the risk of ECs. Such risks may concern security-of-supply or the vulnerability to price shocks. The expectations are that ECs are implemented for existing buildings and infrastructure, i.e., existing grid infrastructure. With this, the findings of this thesis are that a transformation of the local energy system towards sustainability is possible. Nevertheless, local authorities have to be aware that the transformation has to initiated in time. Otherwise, externalities (e.g., carbon taxes) and reinvestment of high-emission infrastructure lead to sunk costs and/or high emissions.

Further, in regard of Research Question 2

If an energy community is implemented, how should the energy be shared and priced between the members of the community?

Chapter 4 finds efficient allocation and pricing algorithms. The algorithms are designed in a way to include the consumers' perspective. Thus, in a first step, consumer preferences have to be characterized by multiple objectives such as emission reductions and on-site-generation in addition to cost. Only in this way, an algorithm allows to picture and maximize the welfare of ECs. The algorithms developed in this work are efficient in the sense that the consumers that place the highest value on DERs are served first, followed by the consumer with the second highest valuation, etc. Secondly, it has to be defined how ECs are organized and which player owns the assets for generation and storage (DERs and ESSs). If ECs and the assets are community owned, welfare optimization models answer how the energy should be allocated. Appropriate value allocation algorithms are developed in Chapter 4. On the contrary, if the assets are owned by an external investor, who is seeking for revenue maximization, non-cooperative game theoretical models give insights on how the welfare is allocated. If the consumers' true preferences are revealed, the economics of DERs as well as the owner's surplus may be increased.

Finally, regarding Research Question 3

If an energy community is implemented, how to share the value and how to provide incentives that the members stay within the community?

this work finds that it depends on the organization of the EC. Chapter 5 considers three possible configurations of ECs, starting from community-owned to investor-owned assets. This thesis finds that ECs generate value, but the setup defines how the value is shared between its members. Algorithms based on the cooperative game theory suggest a “fair” and transparent allocation to all members and help to decrease the negotiation effort necessary for the founding and operation of ECs. All allocation methods have in common that they are not applicable if ECs are not stable and is breaking apart. This work identifies limited resources (e.g., limited roof area for solar PV) as the factor causing instability. Appropriate pricing of limited resources, e.g., by the introduction of internal (between the ECs’ members) and external payments (to a third party), stabilize ECs and discourages the players from breaking up with the EC. Real-life implementations of ECs have to consider stability issues of ECs since it is one key design element.

6.2. Synthesis of the Results

6.2.1. Strengths, Weaknesses, Opportunities and Threats Analysis

The following provides a synthesis of this thesis’ studies. The studies show that ECs can unlock the resources of renewable generation (e.g., rooftops for solar PV) and flexibility (e.g., storages). Both components are necessary for a successful transformation of the energy system towards sustainability. However, where there is light, there is also shade, and thus in the following, a “Strengths, Weaknesses Opportunities and Threats” (SWOT) Analysis gives insights in four dimensions. SWOT may be understood as a 2x2 matrix and differentiate between the internal and external factors ECs face (Hill and Westbrook, 1997). Strengths and weaknesses are internal factors (i.e., by the members of the EC), while opportunities and threats are external factors (e.g., by markets or regulation). Furthermore, the SWOT analysis differentiates between helpful (strengths and opportunities) and harmful factors (weaknesses and threats).

Table 6.1.: SWOT analysis of ECs.

	Helpful	**Harmful**
Internal	**Strengths**	**Weaknesses**
	- Reduction in costs and emissions - Economies-of-Scale for local investments - Participants may express the preferences - Generation of local value and businesses - Raise awareness	- Involvement of many participants necessary - Energy communities could not be formed - Limited experience - Development of new processes - Consumer participation - Access to resources
External	**Opportunities**	**Threats**
	- Cost reduction (DERs and ESSs) increases the economic efficiency - New technologies such as EV may trigger the development (e.g., charging in the city) - New partnerships - Resilience	- Legal restrictions and framework - Market design (including new process) and grid tariff - Access to resources - Information and Communications Technology (ICT)

Table 6.1 shows the comprehensive results of the SWOT analysis. Firstly, the implementation of ECs have to be beneficial to all members of the EC. As this thesis shows, ECs provide benefits to the participants, e.g, reduction in costs and emissions and the exploitation of Economies-of-Scale. Additionally, consumers are able to express their preferences, which cannot be entirely satisfied by the current market design. An example is that ECs make local generation accessible, which may not be the case otherwise. Consumer participation and acceptance is another key element. Hereby, the thesis shows that it is possible to involve the consumer twofold: joint investment or an operational involvement. The first one is an one-time task, although periodically involvements may be necessary, e.g., selling or purchasing shares or reinvestment. On the contrary, forwarding preferences for operational strategies requires a continuous involvement, but could be automatized (e.g., submission via a mobile application). Consequentially, ECs generate value to it's participants and establish new local businesses. By raising the awareness of energy generation and consumption, ECs offer also an educational approach.

ECs face weaknesses, even resulting in a complete inability to act or to be formed. Most prominent examples are involving a high number of participants or that participants have opposing expectations and objectives. Also, if ECs are organized voluntarily, the lack of a contractual framework or sanctions increases the risk for the EC. As the experience on ECs is limited at this time, it is not entirely clear how processes (e.g., clearing) have to be organized or how to integrate technical solutions (e.g., data exchange). The lack of consumer participation may be a significant weakness of ECs. This means, that the business model of ECs counts on the fact that consumers are either investing in DERs or ESSs or consuming energy of those assets. If consumers cannot be motivated or persuaded to join the EC, it may never exceed the planning phase.

There exist opportunities for ECs. As it is expected that investment costs for DERs and ESSs are further decreasing (Jean et al., 2015; Mundada et al., 2016), it may also be expected, that the economic efficiency of ECs may increase. Energy transition does not only mean that it changes the way how energy is generated but also changes the way how energy is used. E.g., the implementation of new technologies, such as EVs, requires new ways of generating, distributing and using energy. The most prominent example is the utilization of EVs in cities. As parking slots are scattered throughout the neighborhood and maybe not used by the same consumer, ECs may be an appropriate way to enable innovative charging processes. Consequentially, the implementation of new technologies may push the necessity of realizing ECs. As ECs are composed of different market participants, they also form new partnerships, different from current relationships. E.g., this means the introduction of new players (e.g., technology providers) or the reorganization of processes. So, consumers may be involved further in the currently top-down organized process of energy generation and distribution. Depending on the design of the EC, it may also help to increase resilience[1] of the community.

[1]Resilience is often used in the literature. Sharifi and Yamagata (2016) identified, 196 planning and design criteria for energy resilience and categorized them into five themes: "infrastructure", "resources", "land use, urban geometry and morphology", "governance" and "socio-demographic aspects and human behavior".

The last category of the SWOT analysis addresses the threats. As they are considered external to the EC, they are manifold. Most prominent are legal and regulatory restrictions. So, in most European countries[2] currently it is not possible to form and operate an EC. Consequentially, an appropriate market design (including new process), as well as a beneficial grid tariff, is necessary. DERs still depend on natural resources, such as space appropriate for PV installations. If access to those resources is not possible, the capabilities of energy generation are limited and so are the advantages of an EC.

Table 6.3.: Overcome harmful factors of ECs.

	Internal	**External**
Local members	- Encouragement of the local community - Communication to potential members - Emergence of opinion leaders	
Regulation and policy		- Ensure a long-term perspective - Ensuring an environment to develop viable business models
Retailers, contractors and technology providers	- Develop new processes for ECs - Exploit existing channels to communicate with potential members	- Access resources - Adopt the portfolio by products for ECs - Contractual relationship - Deploy ICT
Grid operators and metering companies	- Develop new processes for ECs (e.g., clearing) - Deploy access to smart meter data	

[2]Lettner et al. (2018) provides an overview of legal feasibility of different PV prosumers models in the European Union.

Nevertheless it is expected that it is possible to overcome harmful factors of ECs. In accordance with the players and actors defined in Chapter 1, the following elaborates on the individual contribution of each player. Table 6.3 considers four types of players:

- Local members of the EC (consumers, prosumers and real estate owners),
- Regulation and policy,
- Retailers, contractors, ESCOs, aggregators and technology providers and
- Grid operators and metering companies (most important the DSO).

Local members of the EC are very relevant in overcoming the EC's internal weaknesses. Most important is the encouragement of other or potential members of the community. With this, well-functioning communication channels have to be established and maintained. The emergence of opinion leaders may be necessary for initiating ECs and keeping it stable. As shown by this thesis, a stable design is a key element of ECs.

Another key design elements are regulatory and policy frameworks which define the environment of ECs. Thus they have an impact on the external factors threatening ECs. If well designed, a long-term perspective of ECs is ensured, and viable business models may be developed.

The following type of players, retailing companies, contractors and technology providers have an impact on both, internal and external factors of ECs. By the implementation of new processes, they may help in enabling the administration and operation of ECs. If these players are present at the markets, they have existing channels to potential members of ECs. In this respect, the funding of ECs may be supported. The development of products represents a logical consequence. As these players know how to deploy infrastructure projects necessary for ECs, they may tap existing resources (e.g., rooftops for solar PV). Other inputs of the players also include providing ECs with contractual relationships and ICT.

Since in most of the European countries DSOs or metering companies are responsible for metering and clearing (JRC, 2019), they are essential players in helping the development of processes for EC. In this regard, their responsibility may include to give access to metered data and conduct the clearing.

6.2.2. System Perspective

While the SWOT analysis allows studying ECs in detail, it is also necessary to discuss the impact of ECs' on the energy system. The term "energy system" in this regard includes all relevant participants (e.g., other consumers, grid operators, generators, policy, energy markets) except the EC. The impacts of ECs on the system are manifold: As stated in Chapter 1 and quantified in Chapter 3 to 5 of this thesis, ECs provide the opportunity to push the energy transition and reduce greenhouse gases. Therefore, the most significant advantage from a system's perspective is that ECs trigger investments in DERs and ESSs. Subsequently, Farfan and Breyer (2017) discussed the impacts of penetration of DERs on the current infrastructure. It is expected that a large share of existing capacities is vulnerable of becoming stranded assets.

As shown in Anatolitis and Welisch (2017), the transformation of the energy system becomes more efficient (e.g., auctions for wind power). Efficient expansion of renewable generation also requires efficient exploitation of (renewable) resources. As shown in Chapter 3 to 5 of this thesis, ECs are a promising way to increase the transformation's efficiency. Thus, the work shows exemplarily for solar PV, that the most efficient resources (e.g., large rooftops with a southern orientation) are exploited firstly, followed by the second most efficient, etc. In this way, ECs may help to transform the energy system and to achieve the goals of sustainability with lower transformation costs. As stated previously, this also requires an appropriate market design.

ECs allow, by the implementation of DERs and ESSs, to increase the share of local self-consumption. This is not only a result of trading with members of the ECs but also by the Economies of Scale (EoS). More in detail, if a person invests in DERs for individual use, the size would be smaller compared to the case if she can sell energy to members of the community. Grid utilization may be reduced by the implementation of ECs, although it depends on the tariff design. Nevertheless, as shown in this thesis and stated by Mengelkamp et al. (2018), the availability of grid infrastructure is an "enabler" for ECs, since it allows the interconnection of its members. Nowadays some business models for ECs (including those investigated in this thesis) base on the fact that the grid fee for consuming local generation is lower than for grid consumption. This fact and the costs-by-cause principle may play an essential role in designing future tariffs from a system's perspective. Additionally, the implementation of ECs increases the system's flexibility, if the frameworks and markets are designed in a way to encourage that. As consumers are involved in the organization of the EC, it also helps to increase the energy transition's public acceptance and activates the utilization of local resources. The last relevant point from a system's perspective is the transformation towards a sharing society (including goods and services). As a result of this work, ECs approaches may be a possibility of integrating sharing in the energy sector.

7. Conclusions and Outlook

The decentralization and democratization of generating and storing energy provide an opportunity for energy communities. This thesis contributes to this topic by providing three modeling cases. As the cases are different in respect to research questions and scope, tailor-made algorithms and methods have been developed. Different actors relevant to energy communities may make use of this work's methods and findings. The method developed in the first case allows urban planners to analyze city districts of interest in terms of sustainability and costs. As there exist different setups for energy communities, the other two modeling cases formulate algorithms to share energy and investment costs as well as providing feasible clearing algorithms. While the algorithms of the second case are basing on the non-cooperative relationship between asset owner and consumer the third modeling case considers cooperative approaches. As all clearing algorithms base on game-theoretical considerations, they suggest a "fair" allocation based on the members' objectives and contribute to the community. The beneficiaries of these algorithms are potential members of energy communities, such as consumers, investors, property owners, utility companies and platform providers.

Following general conclusions can be drawn from the results of the studies: Energy communities, if properly designed, can lower costs and emissions. However, the organization of an energy community may be non-trivial since it requires involving different players with different objectives. Therefore, individual perspectives have to be taken into account to provide incentives for the potential participants to enter and stay in the community. This decision is driven by multiple objectives (e.g., emission reduction), but dominated by economics. Therefore, the algorithms developed in this work are designed in a way to satisfy the consumers' utility. Nevertheless, the results of the case studies show that the future design of energy communities (e.g., the implementation of European guidelines (European Commission, 2017a; European Commission, 2017b), planned for 2021) is a crucial parameter. At this moment, it should be kept in mind, that the involvement of consumers is a central element of the energy transition and that they are willing to contribute without possessing expert-knowledge in this area. The definition of the market rules should recognize this and provide scalable and liberal guidelines.

The studies of in this work comprehensively use optimization approaches to tackle the research questions. This approaches may lack plausibility since most real-life decisions are not only driven by the objectives identified in this work. Additionally, assets are not available in any arbitrary size as suggested by the results of this thesis. Another limitation is the assumption of a perfect forecast. This is an inherent presumption concerning all cases investigated in this thesis and may be of relevance for the implementation of energy communities. Another limitation is the choice of the consumers, and their load profiles used in the studies. Since they only represent a subset of the population, different compositions and types of consumers may affect the results of this analysis.

Besides revealing insights into the topic of energy communities, this thesis may also formulate future directions of research. Firstly, future research may extend new technologies, such as hydrogen generation and storages as well as the fact of technological learning curves. Secondly, the effects of uncertainty, e.g., in terms of future demand for DERs and market prices, require attention. One setback of some methods developed in this thesis is that the problems are computationally hard and the effort raises with the size of energy communities. Therefore, future research may focus on increasing the performance of the models to allow practical implementations of the models. Another research topic may investigates the consumer engagement. Since the functionalities of energy communities have to be communicated to the consumers, a more intuitive understanding, of methods developed in this thesis, may be required. As the focus of this thesis is to consider urban areas, the situation for rural regions may be discussed separately. Other directions of futures research may focus on the perspective of other market participants, especially the utility company or the optimal composition of energy communities.

8. References

Books

AlSkaif, Tarek (2016). “Energy Sharing in Smart Grids: A Game Theory Approach”. Dissertation. Barcelona, Spain: Universitat Politècnica de Catalunya (cit. on p. 20).

Beausoleil-Morrison, Ian and Ulli Arndt (2008). *An experimental and simulation-based investigation of the performance of small-scale fuel cell and combustion-based cogeneration devices serving residential buildings: Final report of Annex 42 of the International Energy Agency's Energy Conservation in Buildings and Community Systems Programme*. [Ottawa: IEA Energy Conservation in Buildings & Community Systems Programme. ISBN: 978-0-662-47924-6 (cit. on p. 43).

Ben-Tal, Aharon (1980). “Characterization of Pareto and Lexicographic Optimal Solutions”. In: *Multiple Criteria Decision Making Theory and Application*. Ed. by Günter Fandel and Tomas Gal. Red. by M. Beckmann and H. P. Künzi. Vol. 177. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 1–11. ISBN: 978-3-540-09963-5. DOI: 10.1007/978-3-642-48782-8_1. URL: http://link.springer.com/10.1007/978-3-642-48782-8_1 (visited on 01/25/2019) (cit. on p. 17).

Callan, S. and J. Thomas (2006). *Environmental Economics and Management: Theory, Policy and Applications*. Cengage Learning. ISBN: 978-0-324-32067-1. URL: https://books.google.at/books?id=ANWPlfqX0yQC (cit. on pp. 60, 61).

Dorfner, Johannes (2016). *Open Source Modelling and Optimisation of Energy Infrastructure at Urban Scale*. Dissertation, München, Technische Universität München, 2016 (cit. on pp. 23, 28, 36).

Gabriel, Steven A., A. Conejo, D. Fuller, Hobbs B., and Ruiz C. (2013). *Complementarity modeling in energy markets*. New York, NY: Springer New York and Imprint: Springer. ISBN: 978-1-4419-6123-5 (cit. on pp. 63, 65, 66).

Garreta, Raúl (2013). *Learning scikit-learn: Machine learning in Python : experience the benefits of machine learning techniques by applying them to real-world problems using Python and the open source scikit-learn library*. Community experience distilled. Birmingham, UK: Packt Pub. ISBN: 978-1-78328-193-0 (cit. on p. 33).

Geidl, Martin (2007). "Integrated Modeling and Optimization of Multi-Carrier Energy Systems". Dissertation. ETH Zurich (cit. on pp. 15, 17).

Gillies, D. B. (1959). "Solutions to general non-zero-sum games". In: *Contributions to the Theory of Games*. Vol. IV. 40 vols. Princeton: Princeton University Press, pp. 47–85. ISBN: 978-1-4008-8216-8 (cit. on p. 22).

Gómez, Tomás, Carlos Mateo, Álvaro Sánchez, Pablo Frías, and Rafael Cossent (2013). "Reference Network Models: A Computational Tool for Planning and Designing Large-Scale Smart Electricity Distribution Grids". In: *High Performance Computing in Power and Energy Systems*. Ed. by Siddhartha Kumar Khaitan and Anshul Gupta. Power Systems. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 247–279. ISBN: 978-3-642-32683-7. DOI: 10.1007/978-3-642-32683-7_9. URL: https://doi.org/10.1007/978-3-642-32683-7_9 (visited on 01/18/2019) (cit. on p. 16).

Hart, William E., Carl D. Laird, Jean-Paul Watson, David L. Woodruff, Gabriel A. Hackebeil, Bethany L. Nicholson, and John D. Siirola (2017). *Pyomo – Optimization Modeling in Python*. 2nd ed. 2017. SpringerLink : Bücher. Cham: Springer. ISBN: 978-3-319-58821-6 (cit. on pp. 23, 66, 71, 94).

Loschan, Christoph (2017). "Marktanalyse von Skaleneffekten dezentraler Erzeugungstechnologien mit Regressionsanalyse". Bachelor Thesis. TU Wien (cit. on pp. 15, 24, 145).

Mühlecker, D. (2016). "Betriebswirtschaftlich optimale Wärme- und Stromversorgung eines Stadtentwicklungsgebietes". Master Thesis. TU Wien. URL: https://repositum.tuwien.ac.at/obvutwhs/content/titleinfo/1375199 (cit. on p. 145).

OECD/IEA (2018). *World Energy Outlook 2018*. OCLC: 1078911525. ISBN: 978-92-64-06452-2 (cit. on p. 1).

Ortner, André (2017). *Electricity balancing markets in Europe: fundamental modeling approaches and case studies assuming perfect competition*. Wien: Wien. URL: https://resolver.obvsg.at/urn:nbn:at:at-ubtuw:1-102213 (visited on 01/23/2019) (cit. on p. 21).

Peck, James (2017). *Econ 501.02 - Intermediate Microeconomic Theory: Preferences and Utility Functions*. URL: http://www.econ.ohio-state.edu/jpeck/Econ501aL3.pdf (cit. on p. 58).

Rhodes, Joshua D., Michael E. Webber, Thomas Deetjen, and Todd Davidson (2017). *Are solar and wind really killing coal, nuclear and grid reliability?* URL: https://theconversation.com/are-solar-and-wind-really-killing-coal-nuclear-and-grid-reliability-76741 (cit. on p. 69).

Shapley, Lloyd S and Martin Shubik (1973). "Game Theory in Economics: Characteristic function, core, and stable set". In: *Volume 6 of Game Theory in Economics*. R-904/6-NSF. Rand Corporation (cit. on pp. 22, 85, 86).

Sinha, Ankur and Kalyanmoy Deb (2013). "Bilevel Multi-Objective Optimization and Decision Making". In: *Metaheuristics for Bi-level Optimization*. Ed. by El-Ghazali Talbi. Vol. 482. Studies in Computational Intelligence. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 247–284. ISBN: 978-3-642-37837-9. DOI: 10.1007/978-3-642-37838-6 (cit. on p. 21).

Stackelberg, Heinrich von (2011). *Market Structure and Equilibrium*. Berlin, Heidelberg: Springer Berlin Heidelberg. ISBN: 978-3-642-12585-0. DOI: 10.1007/978-3-642-12586-7 (cit. on p. 64).

Triantaphyllou, Evangelos and Panos M. Parlos (2010). *Multi-criteria decision making methods: A comparative study*. Vol. v. 44. Applied optimization. Dordrecht: Kluwer Academic Publishers. ISBN: 978-1-4757-3157-6 (cit. on p. 58).

Voll, Philip (2014). *Automated optimization-based synthesis of distributed energy supply systems*. 1. Aufl. Vol. 1. Aachener Beiträge zur Technischen Thermodynamik. Aachen: Mainz. ISBN: 978-3-86130-474-6 (cit. on p. 17).

Wolitzky, Alexander (2015). *14.121 Microeconomic Theory I: Lecture 8: Expected Utility Theory*. MIT (cit. on p. 58).

Journal Articles

Abada, Ibrahim, Andreas Ehrenmann, and Xavier Lambin (2017). “On the viability of energy communities”. In: *Cambridge Working Paper in Economics* (cit. on pp. 19, 86).

Ajila, Samuel A. and Di Wu (2007). “Empirical study of the effects of open source adoption on software development economics”. In: *Journal of Systems and Software* 80.9, pp. 1517–1529. ISSN: 0164-1212. DOI: https://doi.org/10.1016/j.jss.2007.01.011. URL: http://www.sciencedirect.com/science/article/pii/S0164121207000076 (cit. on p. 23).

Alanne, Kari and Arto Saari (2006). “Distributed energy generation and sustainable development”. In: *Renewable and Sustainable Energy Reviews* 10.6, pp. 539–558. ISSN: 13640321. DOI: 10.1016/j.rser.2004.11.004. URL: https://linkinghub.elsevier.com/retrieve/pii/S1364032105000043 (visited on 01/30/2019) (cit. on p. 3).

An, Lu, Jie Duan, Yuan Zhang, Mo-Yuen Chow, and Alexandra Duel-Hallen (2016). “Distributed Multi-Step Power Scheduling and Cost Allocation for Cooperative Microgrids”. In: *arXiv:1611.08770 [cs]*. arXiv: 1611.08770. URL: http://arxiv.org/abs/1611.08770 (visited on 01/24/2019) (cit. on p. 20).

Anatolitis, Vasilios and Marijke Welisch (2017). “Putting renewable energy auctions into action – An agent-based model of onshore wind power auctions in Germany”. In: *Energy Policy* 110, pp. 394–402. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2017.08.024. URL: http://www.sciencedirect.com/science/article/pii/S0301421517305189 (visited on 04/10/2019) (cit. on p. 110).

Avrachenkov, Konstantin, Jocelyne Elias, Fabio Martignon, Giovanni Neglia, and Leon Petrosyan (2015). “Cooperative network design: A Nash bargaining solution approach”. In: *Computer Networks* 83, pp. 265–279. ISSN: 13891286. DOI: 10.1016/j.comnet.2015.03.017 (cit. on pp. 22, 87).

Banfi, Silvia, Mehdi Farsi, Massimo Filippini, and Martin Jakob (2008). “Willingness to pay for energy-saving measures in residential buildings”. In: *Energy Economics* 30.2, pp. 503–516. ISSN: 01409883. DOI: 10.1016/j.eneco.2006.06.001 (cit. on p. 19).

Bazilian, Morgan, Andrew Rice, Juliana Rotich, Mark Howells, Joseph DeCarolis, Stuart Macmillan, Cameron Brooks, Florian Bauer, and Michael Liebreich (2012). “Open source software and crowdsourcing for energy analysis”. In: *Energy Policy*. Special Section: Fuel Poverty Comes of Age: Commemorating 21 Years of Research and Policy 49, pp. 149–153. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2012.06.032. URL: http://www.sciencedirect.com/science/article/pii/S0301421512005423 (visited on 04/03/2019) (cit. on pp. 23, 24).

Bertsch, Joachim, Christian Growitsch, Stefan Lorenczik, and Stephan Nagl (2012). “Flexibility Options in European Electricity Markets in High RES-Escenarios—Study on Behalf of the International Energy Agency”. In: *Cologne, Germany: Energiewirtschaftliches Institut an Der Universität Zu Köln (EWI)* (cit. on p. 2).

Bérubé, Jean-François, Michel Gendreau, and Jean-Yves Potvin (2009). “An exact -constraint method for bi-objective combinatorial optimization problems: Application to the Traveling Salesman Problem with Profits”. In: *European Journal of Operational Research* 194.1, pp. 39–50. ISSN: 03772217. DOI: 10.1016/j.ejor.2007.12.014 (cit. on p. 38).

Bottou, Léon and Bengio Yoshua (1995). “Convergence Properties of the K-Means Algorithms”. In: *Advances in Neural Information Processing Systems* 7, pp. 585–592 (cit. on pp. 32, 34).

Burger, Scott, Jose Pablo Chaves-Ávila, Carlos Batlle, and Ignacio J. Pérez-Arriaga (2017). “A review of the value of aggregators in electricity systems”. In: *Renewable and Sustainable Energy Reviews* 77, pp. 395–405. ISSN: 1364-0321. DOI: 10.1016/j.rser.2017.04.014. URL: http://www.sciencedirect.com/science/article/pii/S1364032117305191 (visited on 02/11/2019) (cit. on p. 19).

Chiş, A. and V. Koivunen (2018). “Coalitional game based cost optimization of energy portfolio in smart grid communities”. In: *IEEE Transactions on Smart Grid*, pp. 1–1. ISSN: 1949-3053. DOI: 10.1109/TSG.2017.2784902 (cit. on p. 19).

Christensen, Laurits R. and William H. Greene (1976). “Economies of Scale in U.S. Electric Power Generation”. In: *Journal of Political Economy* 84.4, pp. 655–676. ISSN: 0022-3808. DOI: 10.1086/260470. URL: https://www.journals.uchicago.edu/doi/abs/10.1086/260470 (visited on 01/30/2019) (cit. on p. 3).

Compte, O and P Jehiel (2008). "The Coalitional Nash Bargaining Solution". In: *Econometrica* 78.5, pp. 1593–1623. URL: http://www.jstor.org/stable/40928967 (cit. on p. 87).

Connolly, D., H. Lund, B. V. Mathiesen, and M. Leahy (2010). "A review of computer tools for analysing the integration of renewable energy into various energy systems". In: *Applied Energy* 87.4, pp. 1059–1082. ISSN: 0306-2619. DOI: 10.1016/j.apenergy.2009.09.026. URL: http://www.sciencedirect.com/science/article/pii/S0306261909004188 (visited on 02/20/2019) (cit. on pp. 14, 15).

Costa, Antonio and Alberto Fichera (2014). "A mixed-integer linear programming (MILP) model for the evaluation of CHP system in the context of hospital structures". In: *Applied Thermal Engineering*. Special Issue: MICROGEN III: Promoting the transition to high efficiency distributed energy systems 71.2, pp. 921–929. ISSN: 1359-4311. DOI: 10.1016/j.applthermaleng.2014.02.051. URL: http://www.sciencedirect.com/science/article/pii/S1359431114001434 (visited on 03/26/2019) (cit. on p. 4).

Creutzig, Felix, Peter Agoston, Jan Christoph Goldschmidt, Gunnar Luderer, Gregory Nemet, and Robert C. Pietzcker (2017). "The underestimated potential of solar energy to mitigate climate change". In: *Nature Energy* 2.9, p. 17140. ISSN: 2058-7546. DOI: 10.1038/nenergy.2017.140. URL: https://www.nature.com/articles/nenergy2017140 (visited on 02/04/2019) (cit. on p. 2).

Dehghanpour, Kaveh, Christopher Colson, and Hashem Nehrir (2017). "A Survey on Smart Agent-Based Microgrids for Resilient/Self-Healing Grids". In: *Energies* 10.5, p. 620. ISSN: 1996-1073. DOI: 10.3390/en10050620 (cit. on p. 58).

Dehghanpour, Kaveh and Hashem Nehrir (2017). "Real-Time Multiobjective Microgrid Power Management Using Distributed Optimization in an Agent-Based Bargaining Framework". In: *IEEE Transactions on Smart Grid*, p. 1. ISSN: 1949-3053. DOI: 10.1109/TSG.2017.2708686 (cit. on p. 20).

Després, Jacques, Nouredine Hadjsaid, Patrick Criqui, and Isabelle Noirot (2015). "Modelling the impacts of variable renewable sources on the power sector: Reconsidering the typology of energy modelling tools". In: *Energy* 80, pp. 486–495. ISSN: 0360-5442. DOI: 10.1016/j.energy.2014.12.

005. URL: http://www.sciencedirect.com/science/article/pii/S0360544214013620 (visited on 04/02/2019) (cit. on p. 14).

Espe, Eunice, Vidyasagar Potdar, and Elizabeth Chang (2018). "Prosumer Communities and Relationships in Smart Grids: A Literature Review, Evolution and Future Directions". In: *Energies* 11.10, p. 2528. ISSN: 1996-1073. DOI: 10.3390/en11102528. URL: http://www.mdpi.com/1996-1073/11/10/2528 (visited on 02/11/2019) (cit. on p. 3).

Farfan, Javier and Christian Breyer (2017). "Structural changes of global power generation capacity towards sustainability and the risk of stranded investments supported by a sustainability indicator". In: *Journal of Cleaner Production* 141, pp. 370–384. ISSN: 0959-6526. DOI: 10.1016/j.jclepro.2016.09.068. URL: http://www.sciencedirect.com/science/article/pii/S0959652616314093 (visited on 04/10/2019) (cit. on p. 110).

Fichera, Alberto, Mattia Frasca, and Rosaria Volpe (2017). "Complex networks for the integration of distributed energy systems in urban areas". In: *Applied Energy* 193, pp. 336–345. ISSN: 0306-2619. DOI: 10.1016/j.apenergy.2017.02.065 (cit. on p. 16).

Fischer, David and Hatef Madani (2017). "On heat pumps in smart grids: A review". In: *Renewable and Sustainable Energy Reviews* 70, pp. 342–357. ISSN: 13640321. DOI: 10.1016/j.rser.2016.11.182 (cit. on p. 37).

Fishburn, Peter C. (1967). "Additive utilities with finite sets: Applications in the management sciences". In: *Naval Research Logistics Quarterly* 14.1, pp. 1–13. ISSN: 00281441. DOI: 10.1002/nav.3800140102 (cit. on p. 58).

Fleischhacker, Andreas, Hans Auer, Georg Lettner, and Audun Botterud (2018). "Sharing solar PV and energy storage in apartment buildings: resource allocation and pricing". In: *IEEE Transactions on Smart Grid*, pp. 1–1. ISSN: 1949-3053, 1949-3061. DOI: 10.1109/TSG.2018.2844877. URL: https://ieeexplore.ieee.org/document/8374974/ (visited on 09/19/2018) (cit. on pp. 9, 55, 92, 142–144).

Fleischhacker, Andreas, Carlo Corinaldesi, Georg Lettner, and Audun Botterud (2019a). "On the Stability of Energy Communities from a Game Theoretical Point of View". In: *IEEE Transactions on Smart Grid* submitted (under review) (cit. on pp. 9, 81, 142–144).

Fleischhacker, Andreas, Georg Lettner, Daniel Schwabeneder, and Hans Auer (2019b). "Portfolio Optimization of Energy Communities to meet

Reductions in Costs and Emissions". In: *Energy*. DOI: 10.1016/j.energy.2019.02.104 (cit. on pp. 8, 27, 142–144).

Fonseca, Jimeno A., Thuy-An Nguyen, Arno Schlueter, and Francois Marechal (2016). "City Energy Analyst (CEA): Integrated framework for analysis and optimization of building energy systems in neighborhoods and city districts". In: *Energy and Buildings* 113, pp. 202–226. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2015.11.055. URL: http://www.sciencedirect.com/science/article/pii/S0378778815304199 (visited on 12/27/2018) (cit. on p. 17).

Good, N. and P. Mancarella (2019). "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, pp. 503–513. ISSN: 1949-3053. DOI: 10.1109/TSG.2017.2745559 (cit. on p. 13).

Gui, Emi Minghui and Iain MacGill (2018). "Typology of future clean energy communities: An exploratory structure, opportunities, and challenges". In: *Energy Research & Social Science* 35, pp. 94–107. ISSN: 22146296. DOI: 10.1016/j.erss.2017.10.019. URL: https://linkinghub.elsevier.com/retrieve/pii/S221462961730347X (visited on 02/14/2019) (cit. on pp. 3, 4).

Hill, Terry and Roy Westbrook (1997). "SWOT analysis: It's time for a product recall". In: *Long Range Planning* 30.1, pp. 46–52. ISSN: 0024-6301. DOI: 10.1016/S0024-6301(96)00095-7. URL: http://www.sciencedirect.com/science/article/pii/S0024630196000957 (visited on 02/26/2019) (cit. on p. 105).

Hirth, Lion and Falko Ueckerdt (2013). "Redistribution effects of energy and climate policy: The electricity market". In: *Energy Policy* 62, pp. 934–947. ISSN: 03014215. DOI: 10.1016/j.enpol.2013.07.055. URL: https://linkinghub.elsevier.com/retrieve/pii/S0301421513006988 (visited on 01/28/2019) (cit. on p. 60).

Hobbs, Benjamin F., Michael H. Rothkopf, Laurel C. Hyde, and Richard P. O'Neill (2000). "Evaluation of a Truthful Revelation Auction in the Context of Energy Markets with Nonconcave Benefits". In: *Journal of Regulatory Economics* 18.1, pp. 5–32. ISSN: 1573-0468. DOI: 10.1023/A:1008151712010. URL: https://doi.org/10.1023/A:1008151712010 (visited on 02/13/2019) (cit. on p. 22).

Hossain, Eklas, Ersan Kabalci, Ramazan Bayindir, and Ronald Perez (2014). "Microgrid testbeds around the world: State of art". In: *Energy Conversion and Management* 86, pp. 132–153. ISSN: 0196-8904. DOI: 10.1016/j.enconman.2014.05.012. URL: http://www.sciencedirect.com/science/article/pii/S0196890414004233 (visited on 02/05/2019) (cit. on p. 4).

Huang, Zishuo, Hang Yu, Zhenwei Peng, and Mei Zhao (2015). "Methods and tools for community energy planning: A review". In: *Renewable and Sustainable Energy Reviews* 42, pp. 1335–1348. ISSN: 1364-0321. DOI: 10.1016/j.rser.2014.11.042. URL: http://www.sciencedirect.com/science/article/pii/S1364032114009733 (visited on 02/19/2019) (cit. on p. 14).

Huld, Thomas, Ralph Gottschalg, Hans Georg Beyer, and Marko Topič (2010). "Mapping the performance of PV modules, effects of module type and data averaging". In: *Solar Energy* 84.2, pp. 324–338. DOI: 10.1016/j.solener.2009.12.002 (cit. on pp. 38, 43, 93).

Iqbal, M., M. Azam, M. Naeem, A. S. Khwaja, and A. Anpalagan (2014). "Optimization classification, algorithms and tools for renewable energy: A review". In: *Renewable and Sustainable Energy Reviews* 39, pp. 640–654. ISSN: 1364-0321. DOI: 10.1016/j.rser.2014.07.120. URL: http://www.sciencedirect.com/science/article/pii/S1364032114005723 (visited on 02/20/2019) (cit. on p. 15).

Jean, Joel, Patrick R. Brown, Robert L. Jaffe, Tonio Buonassisi, and Vladimir Bulović (2015). "Pathways for solar photovoltaics". In: *Energy & Environmental Science* 8.4, pp. 1200–1219. DOI: 10.1039/C4EE04073B. URL: https://pubs.rsc.org/en/content/articlelanding/2015/ee/c4ee04073b (visited on 02/28/2019) (cit. on p. 107).

Junqueira, M., L. C. da Costa, L. A. Barroso, G. C. Oliveira, L. M. Thome, and M. V. Pereira (2007). "An Aumann-Shapley Approach to Allocate Transmission Service Cost Among Network Users in Electricity Markets". In: *IEEE Transactions on Power Systems* 22.4, pp. 1532–1546. ISSN: 0885-8950. DOI: 10.1109/TPWRS.2007.907133 (cit. on p. 21).

Kaenzig, Josef, Stefanie Lena Heinzle, and Rolf Wüstenhagen (2013). "Whatever the customer wants, the customer gets? Exploring the gap between consumer preferences and default electricity products in Germany". In: *Energy Policy* 53, pp. 311–322. ISSN: 0301-4215. DOI: 10.1016/j.enpol.

2012.10.061. URL: http://www.sciencedirect.com/science/article/pii/S0301421512009469 (visited on 01/17/2019) (cit. on p. 18).

Karjalainen, Sami (2011). "Consumer preferences for feedback on household electricity consumption". In: *Energy and Buildings* 43.2, pp. 458–467. ISSN: 03787788. DOI: 10.1016/j.enbuild.2010.10.010 (cit. on pp. 57, 58).

Kondziella, Hendrik and Thomas Bruckner (2016). "Flexibility requirements of renewable energy based electricity systems – a review of research results and methodologies". In: *Renewable and Sustainable Energy Reviews* 53, pp. 10–22. ISSN: 1364-0321. DOI: 10.1016/j.rser.2015.07.199. URL: http://www.sciencedirect.com/science/article/pii/S1364032115008643 (visited on 03/26/2019) (cit. on p. 2).

Kubli, Merla, Moritz Loock, and Rolf Wüstenhagen (2018). "The flexible prosumer: Measuring the willingness to co-create distributed flexibility". In: *Energy Policy* 114, pp. 540–548. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2017.12.044. URL: http://www.sciencedirect.com/science/article/pii/S0301421517308704 (visited on 04/02/2019) (cit. on p. 18).

Lechtenböhmer, Stefan, Lars J. Nilsson, Max Åhman, and Clemens Schneider (2016). "Decarbonising the energy intensive basic materials industry through electrification – Implications for future EU electricity demand". In: *Energy* 115, pp. 1623–1631. ISSN: 03605442. DOI: 10.1016/j.energy.2016.07.110. URL: https://linkinghub.elsevier.com/retrieve/pii/S0360544216310295 (visited on 02/04/2019) (cit. on p. 2).

Li, J., X. Ma, C. Liu, and K. P. Schneider (2014). "Distribution System Restoration With Microgrids Using Spanning Tree Search". In: *IEEE Transactions on Power Systems* 29.6, pp. 3021–3029. ISSN: 0885-8950. DOI: 10.1109/TPWRS.2014.2312424 (cit. on p. 4).

Lindberg, Karen Byskov, Gerard Doorman, David Fischer, Magnus Korpås, Astrid Ånestad, and Igor Sartori (2016). "Methodology for optimal energy system design of Zero Energy Buildings using mixed-integer linear programming". In: *Energy and Buildings* 127, pp. 194–205. ISSN: 03787788. DOI: 10.1016/j.enbuild.2016.05.039 (cit. on pp. 24, 37, 38, 43, 93, 145, 146).

Lippman, Steven A. and Richard P. Rumelt (2003). “A bargaining perspective on resource advantage”. In: *Strategic Management Journal* 24.11, pp. 1069–1086. ISSN: 0143-2095, 1097-0266. DOI: 10.1002/smj.345. URL: http://doi.wiley.com/10.1002/smj.345 (visited on 01/08/2019) (cit. on pp. 21, 22, 86).

Liu, Nian, Xinghuo Yu, Cheng Wang, and Jinjian Wang (2017). “Energy Sharing Management for Microgrids With PV Prosumers: A Stackelberg Game Approach”. In: *IEEE Trans. Ind. Inf.* 13.3, pp. 1088–1098. DOI: 10.1109/TII.2017.2654302 (cit. on pp. 19, 21, 59, 68).

Lo Prete, Chiara and Benjamin F. Hobbs (2016). “A cooperative game theoretic analysis of incentives for microgrids in regulated electricity markets”. In: *Applied Energy* 169, pp. 524–541. ISSN: 03062619. DOI: 10.1016/j.apenergy.2016.01.099. URL: https://linkinghub.elsevier.com/retrieve/pii/S0306261916300873 (visited on 10/19/2018) (cit. on p. 85).

Ma, Tengfei, Junyong Wu, Liangliang Hao, Wei-Jen Lee, Huaguang Yan, and Dezhi Li (2018). “The optimal structure planning and energy management strategies of smart multi energy systems”. In: *Energy* 160, pp. 122–141. ISSN: 0360-5442. DOI: 10.1016/j.energy.2018.06.198. URL: http://www.sciencedirect.com/science/article/pii/S0360544218312635 (visited on 12/27/2018) (cit. on pp. 13, 16).

Mancarella, Pierluigi (2014). “MES (multi-energy systems): An overview of concepts and evaluation models”. In: *Energy* 65, pp. 1–17. ISSN: 0360-5442. DOI: 10.1016/j.energy.2013.10.041. URL: http://www.sciencedirect.com/science/article/pii/S0360544213008931 (cit. on pp. 13, 14).

Manfren, Massimiliano, Paola Caputo, and Gaia Costa (2011). “Paradigm shift in urban energy systems through distributed generation: Methods and models”. In: *Applied Energy* 88.4, pp. 1032–1048. ISSN: 0306-2619. DOI: 10.1016/j.apenergy.2010.10.018 (cit. on p. 36).

Marler, R. Timothy and Jasbir S. Arora (2010). “The weighted sum method for multi-objective optimization: new insights”. In: *Structural and Multidisciplinary Optimization* 41.6, pp. 853–862. ISSN: 1615-147X. DOI: 10.1007/s00158-009-0460-7 (cit. on p. 58).

Martinez-Mares, A. and C. R. Fuerte-Esquivel (2013). “A Robust Optimization Approach for the Interdependency Analysis of Integrated Energy Systems Considering Wind Power Uncertainty". In: *IEEE Transactions on Power Systems* 28.4, pp. 3964–3976. ISSN: 0885-8950. DOI: 10.1109/TPWRS.2013.2263256 (cit. on p. 13).

Maskin, Eric S. (2000). "Auctions, development, and privatization: Efficient auctions with liquidity-constrained buyers". In: *European Economic Review* 44.4, pp. 667–681. ISSN: 00142921. DOI: 10.1016/S0014-2921(00)00057-X (cit. on pp. 67, 68).

McKenna, Russell, Erik Merkel, and Wolf Fichtner (2017). "Energy autonomy in residential buildings: A techno-economic model-based analysis of the scale effects". In: *Applied Energy* 189, pp. 800–815. ISSN: 0306-2619. DOI: 10.1016/j.apenergy.2016.03.062. URL: http://www.sciencedirect.com/science/article/pii/S0306261916303828 (cit. on p. 16).

Mediwaththe, Chathurika P., Edward R. Stephens, David B. Smith, and Anirban Mahanti (2016). "A Dynamic Game for Electricity Load Management in Neighborhood Area Networks". In: *IEEE Transactions on Smart Grid* 7.3, pp. 1329–1336. ISSN: 1949-3053. DOI: 10.1109/TSG.2015.2438892 (cit. on p. 21).

Mehleri, Eugenia D., Haralambos Sarimveis, Nikolaos C. Markatos, and Lazaros G. Papageorgiou (2012). "A mathematical programming approach for optimal design of distributed energy systems at the neighbourhood level". In: *Integration and Energy System Engineering, European Symposium on Computer-Aided Process Engineering 2011* 44.1, pp. 96–104. ISSN: 0360-5442. DOI: 10.1016/j.energy.2012.02.009. URL: http://www.sciencedirect.com/science/article/pii/S036054421200103X (cit. on p. 16).

Mendes, Gonçalo, Christos Ioakimidis, and Paulo Ferrão (2011). "On the planning and analysis of Integrated Community Energy Systems: A review and survey of available tools". In: *Renewable and Sustainable Energy Reviews* 15.9, pp. 4836–4854. ISSN: 1364-0321. DOI: 10.1016/j.rser.2011.07.067. URL: http://www.sciencedirect.com/science/article/pii/S1364032111003121 (visited on 02/20/2019) (cit. on p. 14).

Mengelkamp, Esther, Johannes Gärttner, Kerstin Rock, Scott Kessler, Lawrence Orsini, and Christof Weinhardt (2018). "Designing microgrid energy markets: A case study: The Brooklyn Microgrid". In: *Applied Energy* 210, pp. 870–880. ISSN: 0306-2619. DOI: 10.1016/j.apenergy.2017.06.

054. URL: http://www.sciencedirect.com/science/article/pii/S030626191730805X (visited on 04/08/2019) (cit. on p. 111).

Mohsenian-Rad, A. H., Wong, V. W. S., J. Jatskevich, R. Schober, and A. Leon-Garcia (2010). "Autonomous Demand-Side Management Based on Game-Theoretic Energy Consumption Scheduling for the Future Smart Grid". In: *IEEE Transactions on Smart Grid* 1.3, pp. 320–331. ISSN: 1949-3053. DOI: 10.1109/TSG.2010.2089069 (cit. on p. 21).

Molyneaux, A., G. Leyland, and D. Favrat (2010). "Environomic multi-objective optimisation of a district heating network considering centralized and decentralized heat pumps". In: *ECOS 2008* 35.2, pp. 751–758. ISSN: 0360-5442. DOI: 10.1016/j.energy.2009.09.028. URL: http://www.sciencedirect.com/science/article/pii/S0360544209004216 (cit. on p. 17).

Mondal, Ayan, Sudip Misra, and Mohammad S. Obaidat (2017). "Distributed Home Energy Management System With Storage in Smart Grid Using Game Theory". In: *IEEE Systems Journal* 11.3, pp. 1857–1866. ISSN: 1932-8184. DOI: 10.1109/JSYST.2015.2421941 (cit. on p. 21).

Morvaj, Boran, Ralph Evins, and Jan Carmeliet (2016). "Optimization framework for distributed energy systems with integrated electrical grid constraints". In: *Applied Energy* 171, pp. 296–313. ISSN: 0306-2619. DOI: 10.1016/j.apenergy.2016.03.090. URL: http://www.sciencedirect.com/science/article/pii/S0306261916304159 (cit. on p. 17).

Mundada, Aishwarya S., Kunal K. Shah, and J. M. Pearce (2016). "Levelized cost of electricity for solar photovoltaic, battery and cogen hybrid systems". In: *Renewable and Sustainable Energy Reviews* 57, pp. 692–703. ISSN: 1364-0321. DOI: 10.1016/j.rser.2015.12.084. URL: http://www.sciencedirect.com/science/article/pii/S1364032115014677 (visited on 02/28/2019) (cit. on p. 107).

Nagarajan, Mahesh and Greys Sošić (2008). "Game-theoretic analysis of cooperation among supply chain agents: Review and extensions". In: *European Journal of Operational Research* 187.3, pp. 719–745. ISSN: 0377-2217. DOI: 10.1016/j.ejor.2006.05.045. URL: http://www.sciencedirect.com/science/article/pii/S0377221706007806 (visited on 01/08/2019) (cit. on p. 22).

Nash, John (1953). "Two-Person Cooperative Games". In: *Econometrica* 21.1, pp. 128–140. ISSN: 0012-9682. DOI: 10.2307/1906951. URL: https:

//www.jstor.org/stable/1906951 (visited on 10/19/2018) (cit. on pp. 22, 86).

Nazar, Mehrdad Setayesh and Mahmood R. Haghifam (2009). "Multiobjective electric distribution system expansion planning using hybrid energy hub concept". In: *Electric Power Systems Research* 79.6, pp. 899–911. ISSN: 0378-7796. DOI: 10.1016/j.epsr.2008.12.002. URL: http://www.sciencedirect.com/science/article/pii/S0378779608003180 (cit. on p. 15).

Nwulu, Nnamdi I. and Xiaohua Xia (2015). "Multi-objective dynamic economic emission dispatch of electric power generation integrated with game theory based demand response programs". In: *Energy Conversion and Management* 89, pp. 963–974. ISSN: 01968904. DOI: 10.1016/j.enconman.2014.11.001 (cit. on p. 58).

Orehounig, Kristina, Ralph Evins, and Viktor Dorer (2015). "Integration of decentralized energy systems in neighbourhoods using the energy hub approach". In: *Applied Energy* 154, pp. 277–289. ISSN: 0306-2619. DOI: 10.1016/j.apenergy.2015.04.114. URL: http://www.sciencedirect.com/science/article/pii/S0306261915005772 (cit. on p. 16).

Ortner, A., C. Graf, and D. Huppmann (2017). "Modeling competitive equilibrium prices for energy and balancing capacity in electricity markets involving non-convexities". In: *Working paper* (cit. on p. 63).

Pedregosa, F. et al. (2011). "Scikit-learn: Machine Learning in Python". In: *Journal of Machine Learning Research* 12, pp. 2825–2830 (cit. on pp. 23, 33).

Pepermans, G., J. Driesen, D. Haeseldonckx, R. Belmans, and W. D'haeseleer (2005). "Distributed generation: definition, benefits and issues". In: *Energy Policy* 33.6, pp. 787–798. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2003.10.004. URL: http://www.sciencedirect.com/science/article/pii/S0301421503003069 (visited on 01/30/2019) (cit. on pp. 2, 3).

Reinhart, Christoph F. and Carlos Cerezo Davila (2016). "Urban building energy modeling – A review of a nascent field". In: *Building and Environment* 97, pp. 196–202. ISSN: 0360-1323. DOI: 10.1016/j.buildenv.2015.12.001. URL: http://www.sciencedirect.com/science/article/pii/S0360132315003248 (visited on 04/02/2019) (cit. on p. 14).

Roth, Alvin E. (1978). "The Nash Solution and the Utility of Bargaining". In: *Econometrica* 46.3, pp. 587–594. ISSN: 0012-9682. DOI: 10.2307/1914234.

URL: https://www.jstor.org/stable/1914234 (visited on 01/14/2019) (cit. on p. 22).

Ruiz, C. and A. J. Conejo (2009). "Pool Strategy of a Producer With Endogenous Formation of Locational Marginal Prices". In: *IEEE Transactions on Power Systems* 24.4, pp. 1855–1866. ISSN: 0885-8950. DOI: 10.1109/TPWRS.2009.2030378 (cit. on pp. 21, 66).

Saad, W., Z. Han, H. V. Poor, and T. Basar (2012). "Game-Theoretic Methods for the Smart Grid: An Overview of Microgrid Systems, Demand-Side Management, and Smart Grid Communications". In: *IEEE Signal Processing Magazine* 29.5, pp. 86–105. ISSN: 1053-5888. DOI: 10.1109/MSP.2012.2186410 (cit. on pp. 19, 20).

Sameti, Mohammad and Fariborz Haghighat (2017). "Optimization approaches in district heating and cooling thermal network". In: *Energy and Buildings* 140, pp. 121–130. ISSN: 03787788. DOI: 10.1016/j.enbuild.2017.01.062 (cit. on p. 16).

Schmeidler, David (1969). "Competitive Equilibria in Markets with a Continuum of Traders and Incomplete Preferences". In: *Econometrica* 37.4, pp. 578–585. URL: https://ideas.repec.org/a/ecm/emetrp/v37y1969i4p578-85.html (cit. on p. 22).

Schoor, Tineke van der and Bert Scholtens (2015). "Power to the people: Local community initiatives and the transition to sustainable energy". In: *Renewable and Sustainable Energy Reviews* 43, pp. 666–675. ISSN: 1364-0321. DOI: 10.1016/j.rser.2014.10.089. URL: http://www.sciencedirect.com/science/article/pii/S1364032114009149 (visited on 01/30/2019) (cit. on p. 2).

Sharifi, Ayyoob and Yoshiki Yamagata (2016). "Principles and criteria for assessing urban energy resilience: A literature review". In: *Renewable and Sustainable Energy Reviews* 60, pp. 1654–1677. ISSN: 1364-0321. DOI: 10.1016/j.rser.2016.03.028. URL: http://www.sciencedirect.com/science/article/pii/S136403211600263X (visited on 02/28/2019) (cit. on p. 107).

Shin, Kong Joo and Shunsuke Managi (2017). "Liberalization of a retail electricity market: Consumer satisfaction and household switching behavior in Japan". In: *Energy Policy* 110, pp. 675–685. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2017.07.048. URL: http://www.sciencedirect.com/

science/article/pii/S0301421517304792 (visited on 01/30/2019) (cit. on p. 18).

Stadler, M., M. Groissböck, G. Cardoso, and C. Marnay (2014). "Optimizing Distributed Energy Resources and building retrofits with the strategic DER-CAModel". In: *Applied Energy* 132, pp. 557–567. ISSN: 0306-2619. DOI: 10.1016/j.apenergy.2014.07.041. URL: http://www.sciencedirect.com/science/article/pii/S0306261914007235 (cit. on p. 17).

Stadler, Michael, Gonçalo Cardoso, Salman Mashayekh, Thibault Forget, Nicholas DeForest, Ankit Agarwal, and Anna Schönbein (2016). "Value streams in microgrids: A literature review". In: *Applied Energy* 162, pp. 980–989. ISSN: 03062619. DOI: 10.1016/j.apenergy.2015.10.081 (cit. on pp. 15, 20).

Wächter, Andreas and Lorenz T. Biegler (2006). "On the implementation of an interior-point filter line-search algorithm for large-scale nonlinear programming". In: *Mathematical Programming* 106.1, pp. 25–57. ISSN: 0025-5610, 1436-4646. DOI: 10.1007/s10107-004-0559-y. URL: http://link.springer.com/10.1007/s10107-004-0559-y (visited on 12/20/2018) (cit. on pp. 23, 94).

Walker, Gordon (2008). "What are the barriers and incentives for community-owned means of energy production and use?" In: *Energy Policy* 36.12, pp. 4401–4405. ISSN: 03014215. DOI: 10.1016/j.enpol.2008.09.032 (cit. on p. 27).

Wang, Cong, Siir Kilkis, Johan Tjernström, Jerker Nyblom, and Ivo Martinac (2017). "Multi-objective Optimization and Parametric Analysis of Energy System Designs for the Albano University Campus in Stockholm". In: *Procedia Engineering*. International High-Performance Built Environment Conference – A Sustainable Built Environment Conference 2016 Series (SBE16), iHBE 2016 180, pp. 621–630. ISSN: 1877-7058. DOI: 10.1016/j.proeng.2017.04.221. URL: http://www.sciencedirect.com/science/article/pii/S1877705817317289 (visited on 12/27/2018) (cit. on pp. 17, 20).

Wang, H. and J. Huang (2016). "Cooperative Planning of Renewable Generations for Interconnected Microgrids". In: *IEEE Transactions on Smart Grid* 7.5, pp. 2486–2496. ISSN: 1949-3053. DOI: 10.1109/TSG.2016.2552642 (cit. on pp. 83, 94).

Wang, H. and J. Huang (2017). "Joint Investment and Operation of Microgrid". In: *IEEE Transactions on Smart Grid* 8.2, pp. 833–845. ISSN: 1949-3053. DOI: 10.1109/TSG.2015.2501818 (cit. on pp. 19, 21, 22).

Wang, Y., W. Saad, Z. Han, H. V. Poor, and T. Başar (2014). "A Game-Theoretic Approach to Energy Trading in the Smart Grid". In: *IEEE Transactions on Smart Grid* 5.3, pp. 1439–1450. ISSN: 1949-3053. DOI: 10.1109/TSG.2013.2284664 (cit. on p. 20).

Weber, C. and N. Shah (2011). "Optimisation based design of a district energy system for an eco-town in the United Kingdom". In: *Energy* 36.2, pp. 1292–1308. ISSN: 0360-5442. DOI: 10.1016/j.energy.2010.11.014. URL: http://www.sciencedirect.com/science/article/pii/S0360544210006407 (cit. on p. 15).

Widl, Edmund, Tobias Jacobs, Daniel Schwabeneder, Sebastien Nicolas, Daniele Basciotti, Sawsan Henein, Tae-Gil Noh, Olatz Terreros, Anett Schuelke, and Hans Auer (2018). "Studying the potential of multi-carrier energy distribution grids: A holistic approach". In: *Energy* 153, pp. 519–529. ISSN: 0360-5442. DOI: 10.1016/j.energy.2018.04.047. URL: http://www.sciencedirect.com/science/article/pii/S0360544218306510 (visited on 12/27/2018) (cit. on p. 13).

Wu, Xiaohua, Xiaosong Hu, Xiaofeng Yin, and Scott Moura (2016). "Stochastic Optimal Energy Management of Smart Home with PEV Energy Storage". In: *IEEE Transactions on Smart Grid*, p. 1. ISSN: 1949-3053. DOI: 10.1109/TSG.2016.2606442 (cit. on p. 21).

Xiao, Liang, Xingyu Xiao, Canhuang Dai, Mugen Pengy, Lichun Wang, and H. Vincent Poor (2018). "Reinforcement Learning-based Energy Trading for Microgrids". In: *arXiv:1801.06285 [cs]*. arXiv: 1801.06285. URL: http://arxiv.org/abs/1801.06285 (visited on 11/30/2018) (cit. on p. 19).

Zhang, Zhaohui, Ruilong Deng, Tao Yuan, and S. Joe Qin (2016). "Bi-level Demand Response Game with Information Sharing among Consumers**The work is supported in part by Alberta Innovates Technology Futures (AITF) postdoctoral fellowship". In: *IFAC-PapersOnLine* 49.7, pp. 663–668. ISSN: 24058963. DOI: 10.1016/j.ifacol.2016.07.252 (cit. on p. 17).

Zimmermannová, Jarmila, Miroslav Hájek, and Ladislav Rozenský (2018). "Carbon taxation in the European countries". In: URL: https://www.

researchgate.net/publication/322315012_Carbon_taxation_in_the_European_countries (cit. on p. 49).

Other sources

Adam, M., P. Wirth, and R. Radosavljevic (2014). *Verbundprojekt: Standardisierung und Normung von multifunktionalen PVT Solarkollektoren (PVT–Norm): Teilvorhaben: PVT–Systemanwendungen und Simulationen.* E2 – Erneuerbare Energien und Energieeffizienz (cit. on p. 145).

APG (2018). *Installed Power Plant Capacity.* URL: https://www.apg.at/en/markt/Markttransparenz/erzeugung/installierte-leistung (visited on 05/01/2019) (cit. on p. 41).

Arthur, David and Sergei Vassilvitskii (2007). "K-means++: The Advantages of Careful Seeding". In: *Proceedings of the Eighteenth Annual ACM-SIAM Symposium on Discrete Algorithms.* SODA '07. Philadelphia, PA, USA: Society for Industrial and Applied Mathematics, pp. 1027–1035. ISBN: 978-0-89871-624-5. URL: http://dl.acm.org/citation.cfm?id=1283383.1283494 (cit. on p. 33).

Austrian Federal Chancellery (2017). *Federal Act Providing New Rules for the Organisation of the Electricity Sector: ElWOG 2010* (cit. on p. 57).

Bachrach, Yoram, Edith Elkind, Reshef Meir, Dmitrii Pasechnik, Michael Zuckerman, Jörg Rothe, and Jeffrey S. Rosenschein (2009). "The Cost of Stability in Coalitional Games". In: *Algorithmic Game Theory.* Second International Symposium, SAGT 2009. Ed. by Marios Mavronicolas and Vicky G. Papadopoulou. Lecture Notes in Computer Science. Springer Berlin Heidelberg, pp. 122–134. ISBN: 978-3-642-04645-2 (cit. on pp. 22, 87).

BGW (2007). *Praxisinformation P 2007/13 Gastransport / Betriebswirtschaft: Abwicklung von Standardlastprofilen.* Berlin (cit. on p. 43).

Biermayr, Peter, Christa Di\s sauer, Manuela Eberl, Monika Enigl, Hubert Fechner, Kurt Leonhartsberger, Florian Maringer, Stefan Moidl, Christoph Schmidl, Christoph Strasser, Werner Weiss, Patrik Wonisch, and Elisabeth Wopienka (2017). *Innovative Energietechnologien in Österreich Markten-*

twicklung 2016: Biomasse, Photovoltaik, Solarthermie, Wärmepumpen und Windkraft. Vienna: BMVIT (cit. on p. 2).

Blair, N., A. Dobos, J. Freeman, T. Neises, M. Wagner, T. Ferguson, P. Gilman, and S. Janzou (2014). *System Advisor Model, SAM 2014.1.14: General Description: NREL/TP-6A20-61019*. National Renewable Energy Laboratory. URL: http://www.nrel.gov/docs/fy14osti/61019.pdf (cit. on p. 70).

Borgs, Christian, Jennifer Chayes, Nicole Immorlica, Mohammad Mahdian, and Amin Saberi, eds. (2005). *Multi-unit Auctions with Budget-constrained Bidders*. URL: https://www.microsoft.com/en-us/research/publication/multi-unit-auctions-budget-constrained-bidders/ (cit. on p. 68).

Casrai (2019). *CRediT*. URL: https://casrai.org/credit/ (visited on 01/02/2019) (cit. on p. 143).

Deutscher Bundestag (2007). "CO2-Bilanzen verschiedener Energieträger im Vergleich". Berlin (cit. on pp. 40, 41).

Doebeli, H.P. (1992). *Die Orientierung - Konsum 2000*. Von der Schweizerischen Volksbank (cit. on p. 18).

Dorfner, Johannes (2017a). *rivus: A mixed integer linear optimisation model for energy infrastructure networks*. URL: https://github.com/tum-ens/rivus (visited on 01/05/2017) (cit. on pp. 23, 28).

Dorfner, Johannes (2017b). *urbs: A linear optimisation model for distributed energy systems*. URL: https://github.com/ojdo/urbs (visited on 01/05/2017) (cit. on pp. 23, 28).

E-Control (2018). *Price composition*. E-Control Austria. URL: https://www.e-control.at/konsumenten/strom/strompreis/preiszusammensetzung (visited on 12/20/2018) (cit. on pp. 43, 94).

EEA (2017). *Energy and climate change*. URL: https://www.eea.europa.eu/signals/signals-2017/articles/energy-and-climate-change (visited on 01/30/2019) (cit. on p. 1).

Electric Reliability Council of Texas Inc. (2017a). *Generation: Solar Power Production - Hourly Averaged Actual and Forecasted Values*. URL: http://www.ercot.com/gridinfo/generation (visited on 07/27/2017) (cit. on p. 71).

Electric Reliability Council of Texas Inc. (2017b). *Market Conditions: Day-Ahead Market*. URL: http://www.ercot.com (visited on 07/27/2017) (cit. on pp. 24, 69).

European Commission (2017a). *Directive of the European Parliament and of the Council: on common rules for the internal market in electricity (recast)*. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52016PC0864R(01) (visited on 01/10/2018) (cit. on pp. 3, 114).

European Commission (2017b). *Regulation of the European Parliament and of the Council: on the internal market for electricity (recast)*. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52016PC0861 (visited on 01/10/2018) (cit. on pp. 3, 114).

European Commission (2018a). *A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*. Brussels. URL: https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_en.pdf (visited on 01/23/2019) (cit. on p. 42).

European Commission (2018b). *In-Depth Analysis in Support of the Commission Communication COM(2018) 773*. COM(2018) 773. Brussels, p. 393. URL: https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en.pdf (visited on 01/23/2019) (cit. on pp. 1, 13).

European Commission (2019a). *Digital Single Market - Open data*. Digital Single Market - European Commission. URL: https://ec.europa.eu/digital-single-market/en/open-data (visited on 04/03/2019) (cit. on p. 24).

European Commission (2019b). *Press release - Clean Energy for All Europeans: Commission welcomes European Parliament's adoption of new electricity market design proposals*. URL: http://europa.eu/rapid/press-release_IP-19-1836_en.htm (visited on 04/16/2019) (cit. on p. 3).

Eurostat (2019). *Electricity prices by type of user - EUR per kWh*. URL: https://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&language=en&pcode=ten00117&plugin=1 (visited on 04/02/2019) (cit. on p. 18).

EXAA (2018). *Spotmarkt GreyPower AT : EXAA Energy Exchange Austria.* URL: `https://www.exaa.at/de/marktdaten/handelsergebnisse/GreyPower-AT` (visited on 12/20/2018) (cit. on pp. 24, 94).

Fan, Ying, Dimitrios Papadaskalopoulos, and Goran Strbac (2016). "A game theoretic modeling framework for decentralized transmission planning". In: *2016 Power Systems Computation Conference (PSCC).* IEEE, pp. 1–7. ISBN: 978-88-941051-2-4. DOI: `10.1109/PSCC.2016.7540990` (cit. on p. 21).

Frantes, Bettina (2018). *Sonnenplatz Großschönau.* URL: `http://www.sonnenplatz.at/page.asp/-/Home` (visited on 12/20/2018) (cit. on pp. 93, 94).

Fraunhofer ISE (2019). *Photovoltaics Report*, p. 47 (cit. on p. 2).

Gurobi Optimization, LLC (2018). *Gurobi Optimizer Reference Manual.* Gurobi Optimization, LLC. URL: `http://www.gurobi.com` (cit. on pp. 71, 94).

Hiesl, Albert (2018). "Kostenentwicklung dezentraler Batteriespeicher - Evolution oder Revolution". In: *Neue Energie für unser bewegtes Europa.* Ed. by U. Bachhiesl and H. Stiegler. URL: `https://www.tugraz.at/fileadmin/user_upload/Events/Eninnov2018/files/allg/EnInnov2018_Programm_180211.pdf` (cit. on p. 146).

IEA Coal Industry Advisory Board (2015). "The Impact of Global Coal Supply on Worldwide Electricity Prices" (cit. on p. 41).

IPCC, M. Allen, O.P. Dube, W. Solecki, F. Aragón–Durand, W. Cramer, S. Humphreys, M. Kainuma, J. Kala, N. Mahowald, Y. Mulugetta, R. Perez, M. Wairiu, and K. Zickfeld (2018). *Framing and Context* (cit. on p. 1).

JRC (2019). *Smart Metering deployment in the European Union — JRC Smart Electricity Systems and Interoperability.* URL: `https://ses.jrc.ec.europa.eu/smart-metering-deployment-european-union` (visited on 03/04/2019) (cit. on pp. 5, 109).

Kleboth, A. and I. Granzow (2016). *Interview on characteristic blocks for Linz/Austria with civil engineers by A. Fleischhacker* (cit. on p. 32).

Kotzur, Leander, Peter Markewitz, Martin Robinius, and Detlef Stolten (2017). "Kostenoptimale Versorgungssysteme für ein vollautarkes Einfamilienhaus". In: *Klimaziele 2050: Chance für einen Paradigmenwechsel.* Ed. by H. Auer, R. Haas, and A. Hiesl. URL: `eeg.tuwien.ac.at/iewt2017/` (cit. on pp. 145, 146).

Land Oberösterreich (1994). *Oö. Bauordnung 1994 - Oö. BauO 1994* (cit. on p. 43).

Lettner, Georg, Hans Auer, Andreas Fleischhacker, Daniel Schwabeneder, Bettina Dallinger, Fabian Moisl, Eduardo Roman, and Daniela Velte (2018). *D2.1 - Existing and Future PV Prosumer Concepts*. Technical Report. Vienna: PVP4Grid Project. URL: https://www.pvp4grid.eu (cit. on p. 108).

Linz AG (2016). *Kennzahlen 2016: Auf einen Blick*. URL: https://www.linzag.at/media/dokumente/infomaterial_2/linzag-kennzahlen.2016.pdf (cit. on p. 42).

Meir, Reshef, Jeffrey S. Rosenschein, and Enrico Malizia (2011). "Subsidies, Stability, and Restricted Cooperation in Coalitional Games". In: *IJCAI* (cit. on p. 90).

MINES ParisTech / Transvalor (2018). *Irradiation values from HelioClim-3 and meteorological data (MERRA-2 and GFS): Generated using Copernicus Atmosphere Monitoring Service Information 2016*. MINES ParisTech and Transvalor Dpt SoDa (cit. on pp. 24, 43, 93).

openmod. (2019). *openmod - Open Energy Modelling Initiative*. URL: http://openmod-initiative.org/ (visited on 01/25/2019) (cit. on p. 23).

Pause, Fabian and Maximilian Wimmer (2018). "The impact of the CE4AE-Package on legal and regulatory problems for aggregators, encountered in the BestRES project". URL: http://bestres.eu/wp-content/uploads/2018/09/BestRES_policy_recommendations_EU_level_SUER_Sep-2018.pdf (cit. on p. 3).

Rakos, B., P. Stumpf, and I. Nagy (2012). "Investigation of the effects of nonlinear model of super-capacitors in local DC microgrids supplied by renewables". In: *2012 15th International Power Electronics and Motion Control Conference (EPE/PEMC)*. 2012 15th International Power Electronics and Motion Control Conference (EPE/PEMC), DS3b.11–1–DS3b.11–8. DOI: 10.1109/EPEPEMC.2012.6397331 (cit. on p. 3).

Roberts, Mike B, Anna Bruce, and Iain MacGill (2015). "PV in Australian Apartment Buildings – Opportunities and Barriers". In: 2015 Asia-Pacific Solar Research Conference, p. 10 (cit. on p. 2).

Schuster, A., C. Leitinger, and G. Brauner (2010). "Begleitforschung der TU Wien in VLOTTE" (cit. on p. 43).

Schwabeneder, Daniel, Carlo Corinaldesi, Andreas Fleischhacker, Georg Lettner, and Simon De Clercq (2019). *Assessment of the Value of Aggregation.* BestRES D5.1, p. 46 (cit. on pp. 5, 19).

Scopus (2019). *Scopus - Document search.* Document search. URL: https://www.scopus.com/search/form.uri?display=basic (visited on 02/07/2019) (cit. on p. 11).

Statistics Austria (2018). *Motor vehicles: Vehicle stock in 2017.* URL: https://www.statistik.at/web_de/statistiken/energie_umwelt_innovation_mobilitaet/verkehr/strasse/kraftfahrzeuge_-_bestand/index.html (cit. on p. 43).

Team, QGIS Development (2018). *QGIS Geographic Information System. Open Source Geospatial Foundation Project.* URL: http://qgis.osgeo.org (visited on 11/30/2018) (cit. on p. 23).

Tesla (2017). *Powerwall.* URL: https://www.tesla.com/powerwall (visited on 10/06/2017) (cit. on p. 71).

UN (2016). *7. d Paris Agreement.* URL: https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&lang=_en&clang=_en (visited on 02/03/2019) (cit. on p. 1).

ZAMG (2012). *Meteorologische Messdaten der ZAMG.* ZAMG. URL: https://creativecommons.org/licenses/by/3.0/at/deed.de (cit. on pp. 24, 43, 93).

Zelger, T., J. Leibold, G. Lettner, A. Fleischhacker, V. Huemer-Kals, A. Kleboth, I. Granzow, Storch, A.Schieder, W., and N. Ibesich (2018). "SMART CITY - MIKROQUARTIERE Energie- und lebensqualitätsoptimierte Planung und Modernisierung von Smart City-Quartieren (Working Document): Endbericht" (cit. on pp. 31, 32, 43).

Appendices

A. Comparison of the three Energy Communities' Technical Parameters

Table 1.: Technical Parameters of Chapter 3-5

	Chapter 3	**Chapter 4**	**Chapter 5**
Paper	[1]	[2]	[3]
Perspective	Social planner	(1) Owner of DERs and ESSs and (2) consumers of electricity	(1) Prosumers of distributed DERs and ESSs and (2) owner of solar PV resources
Optimal investment decisions	Yes (DERs, grids and ESSs)	No	Yes (DERs and ESSs)
Optimal operational decisions	Yes	Yes	Yes
Period	Investment cycle of all assets, up to 40 years	One day	Investment cycle of assets, up to 20 years
Temporal resolution	1 hour	1 hour	15 minutes
Spatial aggregation	Large scale EC (city district)	Small scale EC (apartment house)	Small scale EC (apartment house)
Methods	Energy system optimization of a district; Pareto optimization;	Energy system optimization of an apartment house; Non-cooperative game theory (Stackelberg game); Consumer utility function	Energy system optimization of an apartment house; cooperative game theory (Shapley value, Coalitional Nash Bargaining)

Objective function	Costs and emissions	(1) Revenues of the owner and (2) consumers' utility function (composed of costs, emissions and share of local generation)	(1) Costs of the prosumers (2) Revenues of the owner
Technology portfolio	**DERs** (solar-photovoltaic, solar-thermal, solar-hybrid, electrolyzer, fuel cell, electric top-up coil, gas boiler, heat pump (liquid-water and air-water), Mikro CHP), **grids** (electricity, gas, and heat and) and **ESSs** (battery, thermal, and hydrogen)	**DERs** (solar-photovoltaic) **grids** (electricity) and **ESSs** (battery)	**DERs** (solar-photovoltaic, electric heater, heat pump air-water), **grids** (electricity, and heat) and **ESSs** (battery, thermal)
Consumer types	Residential and commercial consumers including electric vehicles	Residential consumers	Residential and commercial consumers
Sector couling	Electricity, heat, gas and mobility	Electricity and cooling	Electricity and heat

[1] (Fleischhacker et al., 2019b); [2] (Fleischhacker et al., 2018); [3] (Fleischhacker et al., 2019a)

B. Credit Author Statement

This thesis bases on three publications, Fleischhacker et al. (2019b), Fleischhacker et al. (2018) and Fleischhacker et al. (2019a). This section aims to give a statement about the roles of the authors. The authors responsible for the publications are, in alphabetical order, Audun Botterud (AB), Andreas Fleischhacker (AF), Carlo Corinaldesi (CC), Daniel Schwabeneder (DS), Georg Lettner (GL) and Hans Auer (HA).

In accordance with Casrai (2019), this work uses Contributor Roles Taxonomy (CRediT) to give information about the authors' contributions, especially of this thesis' author. CRediT includes 14 roles and describe each contributor's specific contribution to the scholarly output:

Conceptualization: Ideas; formulation or evolution of overarching research goals and aims

Methodology: Development or design of methodology; creation of models

Software: Programming, software development; designing computer programs; implementation of the computer code and supporting algorithms; testing of existing code components

Validation: Verification, whether as a part of the activity or separate, of the overall replication/ reproducibility of results/experiments and other research outputs

Formal Analysis: Application of statistical, mathematical, computational, or other formal techniques to analyze or synthesize study data

Investigation: Conducting a research and investigation process, specifically performing the experiments, or data/evidence collection

Resources: Provision of study materials, reagents, materials, patients, laboratory samples, animals, instrumentation, computing resources, or other analysis tools

Data Curation: Management activities to annotate (produce metadata), scrub data and maintain research data (including software code, where it is necessary for interpreting the data itself) for initial use and later reuse

Writing – Original Draft: Preparation, creation and/or presentation of the published work, specifically writing the initial draft (including substantive translation)

Writing – Review and Editing: Preparation, creation and/or presentation of the published work by those from the original research group, specifically critical review, commentary or revision – including pre-or post-publication stages

Visualization: Preparation, creation and/or presentation of the published work, specifically visualization/ data presentation

Supervision: Oversight and leadership responsibility for the research activity planning and execution, including mentorship external to the core team

Project Administration: Management and coordination responsibility for the research activity planning and execution

Funding Acquisition: Acquisition of the financial support for the project leading to this publication

The following Table 2 gives information about the publications leading to this thesis.

Table 2.: Credit Author Statement of the publications this thesis bases on.

	[1]	[2]	[3]
Conceptualization	AF and GL	AB and AF	AB and AF
Methodology	AF	AF	AF and CC
Software	AF	AF	AF
Validation	AF, GL and DS	AB and AF	AF, AB and CC
Formal Analysis	AF	AF	AF and CC
Investigation	AF and GL	AF	AF and CC
Resources	GL	AB and GL	GL
Data Curation	AF	AF	AF
Writing – Original Draft	AF	AB and AF	AF
Writing – Review and Editing	AF and DS	AB and AF	AB and AF
Visualization	AF	AF	AF
Supervision	GL and HA	AB and HA	AF and AB
Project Administration	GL and HA	GL	GL
Funding Acquisition	GL	AB and GL	GL

[1] (Fleischhacker et al., 2019b)
[2] (Fleischhacker et al., 2018)
[3] (Fleischhacker et al., 2019a)

C. Data for the Energy Community analyzed in Chapter 3

Table 3.: Technical and economic parameters of processes

Process	inv-cost in EUR/building	inv-cost-p in EUR/kW	fix-cost in % of inv	wacc in %	area-per-cap in m^2/kW	depreciation in a	Source
Photovoltaics	3,494	1,038	1	2	6.5789	25	Loschan, 2017
Solarthermal	4,000	2,461	1	2	1.25	25	Loschan, 2017
Hybrid collector	6,000	3,000	1	2	6.5789	25	Adam et al., 2014
Electrolyser	5,235	4,278	1	2	-	20	Kotzur et al., 2017
Fuel cell	4,635	3,753	1	2	-	20	Kotzur et al., 2017
Electric top-up coil	100	60	2	2	-	25	Lindberg et al., 2016
Gas boiler	1,200	600	1	2	-	20	Loschan, 2017 and Lindberg et al., 2016
Heat pump (liq-water)	17,000	770	2	2	-	20	Lindberg et al., 2016
Heat pump (air-water)	3,000	1,150	2	2	-	18	Lindberg et al., 2016
Mikro CHP	1,200	3,400	3	2	-	20	Lindberg et al., 2016

Table 4.: Technical and economic parameters of grids

Grid	inv-cost in EUR/m	inv-cost-p in EUR/kW	fix-cost in % of inv	wacc in %	depreciation in a	Source
Elec. grid	400	390	1	2	40	Mühlecker, 2016
Heat grid	500	742	1	2	40	Mühlecker, 2016
Gas grid	400	594	1	2	40	Mühlecker, 2016

Table 5.: Technical and economic parameters of storages

Storage	eta in %	inv-cost in EUR/builing	inv-cost-p in EUR/kW	inv-cost-c in EUR/kWh	depre-ciation in a	wacc in %	Source
Battery	96	1000	10	1200	15	2	Hiesl, 2018
Hot Water Storage	90	0	1	90	15	2	Lindberg et al., 2016
H2 Storage	98	0	0.1	25	25	2	Kotzur et al., 2017