Modeling and Optimizing of Integrated Multi-Modal Energy Systems for Municipal Energy Utilities

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Abstract

The development of energy-related business models is a challenging task since various factors like the business portfolio, technological progress, actor base, regulatory framework, and the market environment might influence the results of an assessment. Given the complexity at the municipal level, energy system interdependencies between different alternatives need to be considered to systematically develop sustainable future systems. In this doctoral thesis, decisive energy system characteristics are subsumed with the term integrated multi-modal energy system. One possibility to support decision makers is to apply system optimization models. Adequate models show a coherent design which is able to theoretically abstract elaborated energy system characteristics. Due to the increasing decentralization of energy systems, it is especially necessary to find business models that provide an opportunity for different market actors, such as municipal utilities and residential prosumers. As shown in this doctoral thesis, existing optimization models, however, ignore the roles different actors play and the resulting impact they have.

To address this research issue, this doctoral thesis presents an integrated techno-economic optimization framework called IRPopt (Integrated Resource Planning and Optimization). A proven graph-based energy system approach allows the accurate modeling of deployment systems by considering different energy carriers and technical processes. In addition, a graph-based commercial association approach enables the integration of actor-oriented coordination. This is achieved by the explicit modeling of municipal market actors on one layer and technology processes on another layer as well as resource flow interrelations and commercial agreements mechanism among and between the different layers. Using the optimization framework, various integrated optimization problems are solvable on the basis of a generic objective function.

For demonstration purposes, this doctoral thesis assesses the business models demand response and community storage at differing system conditions and from different actor perspectives such as municipal utility and household prosumer. The optimization results of the business model demand response show a small economic potential in terms of the combined revenues of both parties. The assumption is based

on variable tariffs. Besides, the shiftable load and the shift horizon are aligned with the practical feasibility. According to the optimization results of the community storage, a profitable business model is understood only if both parties optimally utilize the storage. This is even reduced by the simultaneous operation of different flexibility options. The applied examples demonstrate the modeling capabilities of the developed optimization framework. Further, the dispatch results show the usefulness of the described optimization approach.

Finally, this doctoral thesis presents a conceptual techno-socio-economic model vision. The coupling of system optimization with an actor simulation allows a combined analysis of sociological and technological dynamics in terms of business model assessment. In this context, empirically grounded agent-based modeling turned out to be one of the most promising approaches as it allows for considering various influences on the adoption on a micro-level.

Zusammenfassung

Innovative Geschäftsmodelle im kommunalen Umfeld müssen einer Vielzahl von Einflussfaktoren gewachsen sein, um eine nachhaltige Lösung für das Energiesystem darzustellen. Eine mögliche Bewertung wird unter anderem durch das bestehende Geschäftsportfolio, den technologischen Fortschritt, die beteiligten Akteure, dem regulatorischen Rahmen und dem vorliegenden Marktumfeld beeinflusst. Aufgrund dieser Komplexität sowie der damit aufkommenden Wechselwirkungen von Alternativen kommt der umfassenden Entwicklung von Geschäftsmodellen eine gewichtige Bedeutung zu. Entscheidende Systemeigenschaften im kommunalen Umfeld werden in dieser Arbeit mit dem Begriff integrierte multimodale Energiesysteme zusammengefasst. Eine Möglichkeit zur Unterstützung von Entscheidungsträgern stellen computergestützte Optimierungsmodelle dar. In diesem Zusammenhang weisen adäquate Modelle ein kohärentes Konzept auf, welches die theoretische Abbildung der entscheidenden Systemeigenschaften erlaubt. Die Zunahme dezentraler Einspeise- und Eigenversorgungssysteme steigert diese Notwendigkeit sogar, da Flexibilitäts- und Koordinationsaufwand der Geschäftsmodelle ansteigen. Die Veränderungen erfordern die Entwicklung von Geschäftsmodellen, die Vorteile für diverse partizipierende Akteure entlang der Wertschöpfung eröffnen. Existierende Optimierungsmodelle vernachlässigen jedoch die unterschiedlichen Rollen sowie den daraus resultierenden Einfluss, die den einzelnen Akteuren zukommen.

Diese Arbeit knüpft an diese Erkenntnis an und präsentiert ein integriertes techno-ökonomisches Optimierungsmodell IRPopt (Integrierte Ressourcen Planung und Optimierung). Während ein bewährter graphenbasierter Ansatz die akkurate Abbildung des sektor- und technologieübergreifenden Energiesystems ermöglicht, erlaubt ein darauf aufbauender graphenbasierter Ansatz die explizite Integration des akteursbezogenen Zusammenspiels. Die konzeptionelle Umsetzung erfolgt durch die Modellierung von Marktakteuren auf einer und von Technologiekomponenten auf einer weiteren Modellebene. Die anschließenden Definitionen von Vertragsbeziehungen und Flussrichtungen bewerkstelligen die erforderliche Verknüpfung innerhalb und zwischen den Ebenen. Im Zusammenspiel mit der generischen Optimierungssystematik unterstützt das gemischt-ganzzahlige Optimierungsmodell IRPopt die flexible Modellierung und Bewertung von

Geschäftsmodellen unter Einbeziehung der Rahmenbedingungen des Marktes sowie der Freiheitsgrade der Akteure.

Zu Demonstrationszwecken untersucht diese Arbeit die Geschäftsmodelle Lastverschiebung und Quartierspeicher. Die modellbasierte Flexibilitätsbewertung erfolgt im Rahmen unterschiedlicher Szenarien aus Geschäftsfeld- und Haushaltskundensicht. Die Optimierungsergebnisse des Geschäftsmodells Lastverschiebung zeigen, dass im Falle von sehr dynamischen Tarifmodellen mit einem geringen ökonomischen Mehrwert zu rechnen ist, wenn beide Akteursgruppen profitieren möchten. Die Zeitdauer und die Intensität der Lastverschiebung orientieren sich jeweils an der praktischen Umsetzbarkeit durch die Haushalte. Im Geschäftsmodell Quartierspeicher ist ein ökonomischer Erfolg gemäß den Optimierungsergebnissen nur bei Berücksichtigung der geforderten rechtlichen Abgabenordnung sowie bei optimaler Speicherausnutzung durch beide Akteursgruppen möglich. Diesbezüglich wirkt sich auch die gleichzeitige Auswahlmöglichkeit unterschiedlicher Flexibilitätsoptionen negativ auf das Profitabilitätsergebnis aus. Die Anwendungsfälle demonstrieren vor allem die Modellierungsmöglichkeiten des vorgestellten Optimierungsmodells. Darüber hinaus unterstreichen die Ergebnisse auch den Nutzen des entwickelten Optimierungsansatzes.

Den Abschluss der Arbeit markiert eine konzeptionelle techno-sozio-ökonomische Modellvision. Eine Verknüpfung des Optimierungsmodells mit einer Akteurssimulation erlaubt die gemeinsame Berücksichtigung technologischer und soziologischer Dynamiken im Rahmen der Geschäftsmodellbewertung. Für die Umsetzung eignet sich die Modellierungstechnik der empirisch fundierten agentenorientierten Softwareentwicklung. Diese erlaubt die Verhaltensabbildung auf der Mikro-Ebene und die Interaktionsausführung auf der Makro-Ebene.

Publications

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Contents

Chapter 1

Introductory Remarks

"What is the most effective strategic direction for the energy provider of the future? [...] The answer depends on regulatory and market environments, technological capabilities, the size and nature of a utility's consumer base, its internal appetite for change and its current business portfolio." [1].

1.1 Problem statement

Energy systems in many countries face different challenges in coping with future requirements. Various trends precisely attribute municipalities with a decisive role in terms of a successful energy transition. First of all, the traditionally passive consumer demonstrates a growing awareness of sustainability issues and claims participation. From the societal perspective, municipal communities are ideally suited to come together and achieve common goals. While in 2016 there have been around 1024 energy cooperatives in Germany [2] and 2400 in Europe [3], the actual numbers are likely to be larger. Furthermore, the growing utilization of renewable-based energy generators and distributed co-generation systems require the reassessment of the existing infrastructure. By 2020, the German government targets to increase the share of renewables to 35 % [4] and by 2030, it is expected that this share globally reaches 20 % [5]. Since various systems are organized in a decentralized manner and the linkage between supply and demand are embedded locally, employing a different energy carrier infrastructure is an attractive way to improve sustainability. Finally, statutory regulations like energy efficiency measures directly affect municipal businesses. Planning and implementation lead to considerable regional economic effects [6].

The trends described lead to changes in the market environment and also in the industry structure. As a direct result, the conventional business of municipal energy utilities might get undermined [7]. Yet the encouragement of useful cooperation between different system representatives, reliable integration of decentralized technologies and associated system transformations in the regulatory sense represent an opportunity. Feasible and profitable business models are expected to constitute a key element for the successful energy turnaround [8]. Currently, energy system innovations related to decentralized on-site generation, storing and consumption as complementary solutions to the conventional grid consumption are of major interest for academia as well as practitioners despite the low-anticipated monetary potential [9].

Municipal energy utilities might play a decisive role regarding successful transition as they represent the linkage of supply and demand and as they are locally embedded with direct customer relations [10–13]. In the system context, their role could be seen in scaling up of emerging energy business models and services [10]. Despite significant efforts of utilities to define their future role, the main hindrances to innovation yet prevail: uncertainties in unpredictable policy frameworks, lacking profitability of projects, insufficient budgets for innovation investments, lack of reliability and the possibility of even mistakes, to name but a few [14]. In this context, decision makers need to assess under what conditions certain business models can become a sustainable part of the future municipal system and contribute to utilities strategy. While the development of a sustainable future strategy is important, the identification of such strategies is challenging for decision makers since both internal and external conditions need to be taken into consideration [1, 11, 15, 12]:

- First, utilities need to cope with the existing business portfolio and energy generation structures on the supply side. For a sustainable strategy it is beneficial to exploit resulting synergy effects but also to avoid resulting adverse effects. Thus, business model assessment should consider the technical system topography in place.

- Second, arising regulatory frameworks, market mechanisms and technological capabilities are decisive on municipal and national levels. In some countries, the energy policy landscape nowadays is changing continuously. Robust business models therefore require the consideration of uncertainties. The assessment of technological trends might help in preventing mistaken investments.

- Third, the nature and dynamics of the system actors need to be taken into account. Particularly, customer orientation is seen as a key lever for successful business model development. In this context, electricity of decentralized systems is currently to the largest extent only used by the system owner directly or fed into the public grid. To make better use of such systems, it is necessary to find business models that provide opportunities for different actors.

Given the complexity of energy systems at the municipal level, interdependencies and interactions between different alternatives need to be considered to design business models on a solid decision basis. Numerical energy models necessarily play a central role in this overall endeavor, if the interactions are too complex for intuitive analysis [16]. In this context, a variety of theoretical approaches have been developed to abstract the real-world characteristics, each with its own advantages and limitations. Mathematical optimization is widely considered as an effective methodology to generate insights that inform decision makers within the field of complex system modeling [17, 18]. Even though the methodology is able to generate economically optimal insights that inform energy and environmental policies regarding various public interest issues [19], the application of *Energy System Optimization Models (ESOMs)* to municipalities is limited [20]. Since assessment findings might be influenced by an entire range of system characteristics, rather holistic frameworks and profound models are needed to sufficiently map the system complexities at the municipal level [17]. Corresponding characteristics of municipal energy systems are subsumed in this doctoral thesis with the term *Integrated Multi-Modal Energy System (IMMES)*. Regarding this, an IMMES enables the integrated operational optimization of technical and environmental energy chain processes of multiple energy fuels, carriers and services in a multi-energy system network by simultaneous consideration and coordination of the social, economic and institutional network of relationships of market actors in a spatial context.

1.2 Research scope

In view of the problem statement, this research aims to provide decision makers of municipal energy utilities with a model-driven decision support system for business model assessment at differing system conditions of interest. The model environment (or model for short) intends to match highly stylized modeling for theory inquiries as well as highly specific modeling for practical application and is capable of incorporating the market environment, the supply system, and the market actors. For systematic processing, this doctoral thesis addresses the following *research objectives*:

- *System Requirements:* Identify requirements of business models in the context of public and private system policy analysis at the municipal level.
- *Modeling Approaches:* Review building blocks and research gaps of optimization models at the municipal level to guide the model development process.
- *Model Development:* Design and implement an actor-oriented optimization framework to evaluate business models at differing municipal system conditions.
- *Case Demonstration:* Demonstrate the capability of the optimization model to tackle business model issues by means of theoretical business cases.

From the *methodological perspective*, the first research objective is achieved using a literature analysis. The objective aims to identify opportunities and challenges to model business strategies at a real-world setting. Relevant literature covers system processes, market actors, strategic initiatives and regulatory stipulations. The second objective is elaborated by means of a model review. The aim is to provide an overview of the existing body of knowledge and to identify research gaps in order to systematically guide the model development process. Research papers concerned with the mathematical formulation of ESOMs are in focus. In this context, the first objective and the second objective demonstrate the research issue of this doctoral thesis. Subsequently, the third research objective is processed by a design study. The conceptual design and the mathematical formulation of the energy system optimization model need to ensure a high flexibility in terms of modeling and accuracy. The aim is to enhance proven modeling approaches by incorporating market actors and commercial relationships. To explore the challenges and opportunities of the developed and implemented optimization model, the fourth research objective is accomplished with the help of a model-based analysis. The aim is to demonstrate the capability of the model to assess business models at differing system conditions and actor perspectives.

Consequently, the *main contribution* of this doctoral thesis is the systematically designed and developed bottom-up ESOM *IRPopt (Integrated Resource Planning and Optimization)*. The model addresses a number of research issues that have been largely neglected in energy system optimization modeling so far. First, the incorporated proven energy system network approach allows the accurate modeling of different municipal systems by integrating various energy carriers and considering different process components for demand, collector, transmission, conversion, storage and import-export of energy. The user can freely assemble different system technologies with respect to a variety of energy sectors. Second, the designed optimization framework enables the involvement of an actor-oriented multi-level coordination approach with the help commercial association networks. This is achieved by explicit modeling of municipal market actors on one layer and technology processes on another layer as well as resource flow interrelations and service agreement mechanisms among and between the different layers. Third, the provided market principles are taken into account for the detailed assessment of business model innovations. On the one hand, the optimization model provides modeling blocks like load shifting, energy contracting, direct consumption, and direct energy marketing. On the other hand, theoretical concepts as capacity measurement bundling, virtual power plants, regulatory tariff options, and reserve market block bids are available. Fourth, the formulated generic objective function merges the technical and commercial aspects of the modeled system. The mathematical approach allows a multi-level optimization procedure from different actor perspectives. Thus, the ESOM IRPopt addresses existing theoretical and practical modeling issues as identified in this doctoral thesis. Besides, the preparation work synthesizes important system requirements and highlights potential areas for future scientific research. The model demonstration expands existing optimization studies and increases theoretical insights for practical implementation.

1.3 Research outline

This doctoral thesis comprises five research papers that are presented in the following chapters. Four out of five research papers have been submitted for publication in blind peer reviewed journals. All four publications have also been accepted. One out of five research papers has been published as a working paper. Besides, all of the research papers have been written with co-authors. The author of this doctoral thesis is always lead author of each research paper. An overview of the contribution of the individual authors is outlined in the Statement of Contribution. The first research paper “Energy System Optimization at the Municipal Level: An Analysis of Modeling Approaches and Challenges” has been co-authored with Thomas Bruckner [21]. It is published in the journal *Renewable Sustainable Energy Reviews* (chapter 2). The second research paper “Legal Framework of Decentralized Energy Business Models in Germany: Challenges and Opportunities for Municipal Utilities” has been co-authored with Simon Johanning, Stephan Seim, Kerstin Schuchardt, Jonas Krone, Rosa Haberland, and Thomas Bruckner [22]. It is published in the journal *Zeitschrift für Energiewirtschaft* (chapter 3). The third research paper “Provoking Residential Demand Response Through Variable Electricity Tariffs - A Model-Based Assessment for Municipal Energy Utilities" has been co-authored with Jonas Krone, Stefan Kühne, and Thomas Bruckner [23]. It is published in the journal *Technology and Economics of Smart Grids and Sustainable Energy* (chapter 4). The fourth research paper "Towards integrated multi-modal municipal energy systems: An actor-oriented optimization approach" has been co-authored with Balthasar Burgenmeister, Hendrik Kondziella, Stefan Kühne, David G. Reichelt, and Thomas Bruckner [24]. It is published in the journal *Applied Energy* (chapter 5). Finally, the fifth research paper "IRPsim: A techno-socio-economic energy system model vision for business strategy assessment at municipal level" has been co-authored with Simon Johanning, and Thomas Bruckner [25]. It is published in the publication series *Studies in Infrastructure and Resources Management* (chapter 6). In addition to that, further descriptions regarding the model design and the optimization approach of the developed ESOM IRPopt are outlined in the appendices (appendix A and appendix B). In the following, the research problems, the objectives, and the findings of the five research papers are briefly outlined.

1.3.1 Energy system optimization modeling

The first research paper [21] reviews energy system optimization models. Given the complexity at the municipal level, system interdependencies and interactions between different strategy alternatives need to be considered to systematically develop sustainable future systems. One possibility to support decision makers is to apply ESOMs [19]. Since assessment findings might be influenced by an entire range of factors, rather holistic frameworks and profound models are needed to sufficiently map the system complexities at the municipal level [17]. Adequate models show a coherent logical and physical design which is able to theoretically abstract the deployment environment. The development of such design approaches to describe characteristics of the real world might also lead to opaque models which are hard to capture for external modelers [26]. In this context, this research paper reviews selected ESOMs with a high level of modeling detail that can be applied to support the decision-making process at municipalities. *The main objective is to identify modeling approaches and future challenges relative to a municipal deployment environment for robust energy system model design.* The research paper addresses the first and second research objective of this doctoral thesis.

First, the focus of the review is specified. On the one hand, model-based system analysis is explained. Given the operation purpose and the complexity of the system characteristics, a variety of theoretical approaches have been developed to abstract the real world. To facilitate a detailed analysis of exogenous measures, the focus of this research paper lies on the detailed techno-economic representation of real systems. Since top-down models oftentimes lack of technical detail, they are not so well-suited for the purpose. In line with this, mathematical optimization is a widely considered underlying methodology to generate insights. On the other hand, necessary system characteristics at the municipal level are elaborated. This is done with the help of existing municipal system definitions. Decisive characteristics of the environment are summarized with the newly coined term IMMES. The working definition reads as follows: An IMMES enables the integrated operational optimization of technical and environmental energy chain processes of multiple energy fuels, carriers and services in a multi-energy system network by simultaneous consideration and coordination of the social, economic and institutional network of relationships of market actors in a spatial context. For a sufficient mapping of the system complexities, associated characteristics are to be theoretically abstracted.

Second, selected bottom-up ESOMs are presented and investigated. In this context, the models deeco (Dynamic Energy, Emission, and Cost Optimization), xeona (Extensible Entity-Oriented Optimization-Based Network-Mediated Analysis), DER-CAM (Distributed Energy Resources Customer Adoption Model), EnergyHub, urbs (Urban Research Toolbox: Energy Systems), KomMod (Kommunales Energiesystem-Modell (Urban Energy System Model)), MMESD (Multi-Modal On-Site Energy System Design), and RE^3ASON (Renewable Energies and Energy Efficiency Analysis System Optimization) have been reviewed in terms of the requirements of the system definition. Initially, an overview of the modeling strategy regarding the operation purpose, planning issue, mathematical approach and documentation process is presented. This is complemented with precise statements about the temporal, spatial and modeling resolution. Subsequently, existing fundamental design approaches of the ESOMs are demonstrated and compared. Even though existing ESOMs already cover the characteristics with some detail, none of the analyzed models includes all characteristics regarding a complex approach. At the same time the review shows that a few modeling approaches are quite prevalent. Future design of models can be directly based on these best practices.

Third, certain modeling issues are derived and initial solutions are provided. While different implementation approaches define an excellent foundation for further model development, according to this review future ESOMs need to address the following six research challenges: integrated view, business modeling, spatial planning, complexity level, temporal resolution and uncertainty analysis. Individual issues are in line with similar reviews. Prospect ESOMs need to systematically tackle the challenges on the basis of novel mathematical concepts and approaches. Based on the analysis of existing approaches, this research paper also outlines initial solution approaches. In this context, the further research papers of this doctoral thesis deal with certain modeling issues raised in this research paper. In particular the integrated view is addressed with an analysis of the legal and regulatory framework of decentralized business models as investigated in the second research paper [22] and a more complex modeling approach as formulated in the fourth research paper [24]. The basic idea of modeling market actors and commercial relationships is inspired by the descriptions of the authors of the ESOM xeona [27, 28]. A case study application of the actor-oriented approach is shown in the third [23] and also fourth research paper [24].

1.3.2 Business model analysis

The second research paper [22] investigates the legal and regulatory framework of the German energy landscape in order to judge legal conditions of the selected on-site electricity business models. Until now, generated electricity of decentralized systems is to the largest extent only used by the property owner directly or fed into the public grid. To make better use of the generated electricity, it is necessary to find business models that provide an opportunity for different market actors, such as municipal utility and residential prosumer. Due to the importance and low-anticipated monetary potential of such solutions, the legislator encourages their implementation by exemption of statutory fees, levies and taxes as well as by offering public remunerations, premiums and compensations in some cases. Capitalizing on these benefits, however, is only feasible under compliance with the legal requirements. In the light of the considerations above, this work states and analyzes the legal and regulatory framework of different business models as within the German energy landscape. *The main objective is to identify and quantify opportunities and challenges for the implementation of selected on-site business models for different market actors at the municipal level.* The research addresses the first research objective of this doctoral thesis.

First, decisive laws and regulations and the corresponding statutory costs and compensations of the German energy landscape are stated. In this context, relevant specifications for electricity price components of on-site business models can be found in various acts, ordinances and guidelines as the German Energy Industry Act (Energiewirtschaftsgesetz; EnWG), the Electricity Grid Charges Ordinance (Stromnetzentgeltverordnung; StromNEV), the Ordinance Regulating Concession Fees for Electricity and Gas (Konzessionsabgabenverordnung; KAV), the Ordinance on Agreements Concerning Interruptible Loads (Verordnung zu abschaltbaren Lasten; AbLaV), the Electricity Grid Access Ordinance (Stromnetzzugangsverordnung; StromNZV), the Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz; EEG), the Renewable Energy Ordinance (Erneuerbare-Energien-Verordnung; EEV), the Equalisation Scheme Ordinance (Ausgleichsmechnismusverordnung; AusglMechV), the Combined Heat and Power Act (Kraft-Wärme-Kopplungsgesetz; KWKG), the Electricity Tax Act (Stromsteuergesetz; StromStG), the Energy Tax Act (Energiesteuergesetz; EnergieStG), and the Energy Tax Ordinance (Stromsteuerverordnung; StromStV). Based thereupon, the major electricity price components and remuneration possibilities are described. Moreover, decisive roles in the energy sector are introduced, differentiating between legal entities and market actors. This is necessary since the exact legal interpretation depends on the structure of the network of relationships.

Second, legal characteristics as well as statutory requirements of the specified on-site business models are pointed out. Initially, the business model is briefly described. Subsequently, the legal characteristics are demonstrated, and the obligations in terms of the costs and compensations are determined. The primary concern is to elaborate design details for which fees, taxes and charges are avoidable and remunerations, premiums and compensations are obtainable. Since currently energy system innovations related to decentralized autarky solutions are of major interest, this research focuses on the assessment of potential business models of self-consumption, direct consumption, direct marketing, demand response, net metering and community energy storage systems. To ensure a comparison with the traditional business model, grid coverage serves as the reference scenario. The concept of self-consumption refers to direct usage of self-produced electricity by homeowners. From the utility's viewpoint, the decentralized energy systems could be sold or leased to respective prosumers within the usual market margins. To differentiate between self-consumption and circumstances where the personal identity regarding the plant operation is not satisfied, e.g. tenants living in a multi-family building, the business model of direct consumption is relevant. In this business model the utility could be system owner and operator leasing the roof from the building owner and selling the electricity directly to the individual tenants. In contrast to this, regional direct marketing refers to situations where electricity is sold to consumers by using the grid. The generation and consumption takes place at different locations and by different parties. The utility could take the role of the broker between the two parties, to ensure that all legal requirements are met. In the context of demand response prosumers are able to partially shift loads. An adequate tariff structure might help utilities to integrate renewables and to increase trading revenues. Finally, community energy storage systems on a community-scale represent physical storage facilities able to receive and release energy to maximize self-consumption for different participants. As an operator the utility is able to benefit by utilizing the storage by spot market trading and by offering balancing services. In comparison to that, net metering represents a virtual grid-related storage by utilizing a meter that is able to spin and record energy ow in both directions. Among others this technically simple solution allows utilities to oppose against the trend of private storage systems which might lead to certain demand uncertainties. Due to the expected strategic importance for the future energy system, photovoltaic-related models make up the core of the cases. The on-site business models analyzed can be mainly distinguished by three legal characteristics: (a) the relation between system operator and consumer, (b) the spatial context and (c) the utilization of the public grid, resulting in different legal obligations.

Third, the implications in terms of business model feasibility and profitability are assessed. The findings show various advantages for municipal utilities to engage with on-site business models even though the legal specifications are not always apparent. In contrast to other market actors, they are better suited to handle the legal burdens due to their experience and their administrative infrastructure. The profitability of on-site business is mainly influenced by the amount of grid charges, the electricity tax and the EEG levy due to the declining electricity generation costs [9]. Due to the statutory exemptions, self-consumption is currently an attractive solution even though this happens to the detriment of the conventional business of utilities. If the municipal utility does not engage in this business field, others might. A profitable implementation of direct consumption is also possible in collaboration with real estate companies. The situation is not as favorable as in self-consumption however, but legal amendments are on the way. Regional direct marketing finds much less appeal in the course of the legal amendments of the last years. Taking into account costs and compensations, this business model hardly seems successfully implementable for utilities. Similar considerations apply to community storage systems. Demand response seems to be an adequate business model for the integration of decentralized energy, especially for end consumers without direct system access. However, a precondition is the obligatory widespread introduction of smart meters. The not yet disseminated concept of net metering can be implemented in two ways. While the physical model is not permitted under the current legislation, the balancing model might lead to a profitable business model, given certain circumstances.

1.3.3 Model-based demand response assessment

The third research paper [23] initially demonstrates the capability of the developed optimization model to analyze business models at differing municipal system conditions. In this context, the research paper deploys a scenario-based analysis at the municipal scale to assess the present and future potential of residential demand response for municipal energy utilities with regard to economic benefits as well as energy autonomy. While the demand response potential of energy-intensive industries is already being exploited, the corresponding potential of household customers is still laying dormant [29]. Simultaneous, recent developments in the field of electricity metering offer the chance to exploit the residential demand response potential. Without any doubt, smart meters are essential to create the flexible consumer [30]. The fact that active demand response is ultimately mediated by contracts with consumers qualifies energy utilities, particularly, municipal energy utilities for the role of flexibility aggregator [31]. To quantify the potential, a model-based analysis based on the newly developed techno-economic ESOM IRPopt is applied. *The main objective of this research paper is to investigate the business potential and the implications for energy utilities in terms of demand response by offering variable electricity tariffs to residential customers.* Thus, the research findings addresses the fourth research objective of this doctoral thesis.

First, the research paper reviews existing literature to identify residential customer preferences to demand response on the basis of different electricity tariffs. In this research paper, demand response is defined as the changes in electricity consumption in response to changes in the price [32]. Thereby, only load shifting is adopted. On the one hand, it can be argued that energy utilities prefer highly dynamic tariffs [33], in order to minimize their price risks. On the other hand, the preferences of energy customers are more complex. The results of an acceptance study, performed by [34], show that customers prefer simple over complex variable electricity tariffs. Besides, automatic control of household appliances, leading to almost no perceived discomfort for customers, will make dynamic variable electricity tariffs more attractive to customers. Nonetheless, since demand response is associated with a level of discomfort, it is elaborated that a maximum of 40 % of residential load can be shifted for 4 h. A realistic average share of shiftable load has been identified with 20 % for 2 h.

Second, the impact of the implementation of demand response on the targets of the provider and the customer is shown in terms of differing electricity tariffs. The design of variable electricity tariffs is oriented to time-of-use and dynamic pricing. Doing this, a multi-level dispatch strategy to determine actor-related optimal results has been applied. Technology processes of operator and user sides are optimally controlled and scheduled with an economic objective under peak-shifting constraints. More details about the theoretical design and mathematical formulation of the optimization framework IRPopt is given in research paper four [24]. Besides, appendix A and appendix B present a comprehensive overview of the model design and the optimization approach. Additionally, the potential laying in residential demand response at community-scale has been analyzed by differentiating between three different types of energy utilities, which are characterized by distinct generation portfolios: low-priced orchestrator, green municipal utility, and conventional municipal utility [35]. The results show that even when residential customers who exclusively perform demand response with the help of electric household appliances are exposed to a very dynamic variable electricity tariff, they are financially worse off than in the reference case, in which they are facing a flat tariff. A small economic potential is only visible in terms of the combined results between the utility and the consumer. Naturally, the larger the share of total shiftable load and the longer the load shift horizon, the bigger the economic potential of variable electricity tariffs. Nevertheless, in order to achieve any gains in overall welfare, even in the scenarios with the four best performing tariffs, households need to reach a share of total shiftable load of at least 20 % and a load shift horizon of two hours. Furthermore, it can be observed that a change in the demand response parameters has only a minimal effect on the utility result.

Third, implications regarding demand response implementation at different energy system conditions with respect to utility and customer structure are derived. The results show that variable electricity tariffs have a small economic potential for communities. However, all variable tariffs applied in this analysis put customers in a worse financial position rather than the initial flat tariff scheme. The reason for this lies in the price risk that has to be taken on by the customers in variable pricing schemes as already stated by [33, 34]. Consequently, to make variable electricity tariffs competitive, utilities need to transfer a portion of the gains that they realize due to residential demand response to their customers. In this context, successful business models require the direct cooperation of different municipal energy market actors. Furthermore, taking the specific generation profiles of municipal energy utilities into account in the design of variable electricity tariffs helps to increase the energy autonomy of municipalities.

1.3.4 Actor-oriented multi-level optimization approach

The fourth research paper [24] constitutes a multi-level actor-oriented modeling framework to facilitate the flexible analysis from different market actor perspectives. Additionally, the model applicability is once again demonstrated by analyzing the flexibility potential of community energy storage systems. Market actors along the energy value chain might assess challenges and opportunities from different actor perspectives and various interest criteria since every single consumer and operator has a differing technology-mediated relationship [36]. Individual households, neighborhood communities, organizational units, and market institutions represent major system drivers [18] so that an integrated view of supply and demand side is necessary for optimal investigation of the interaction at the municipal level [37]. Usually, not one single actor contains all relevant components for distribution, conversion, and the storing of energy, but rather individual actors are spatially distributed over a municipal area and are equipped with respective components. Existing ESOMs ignore the roles different actors play in existing system architectures and the resulting impact they might have [38]. On the one hand, actors which can be prosumer groups, business units and public institutions need to be modeled separately and so do also the spatially distributed load, storage and generation systems. On the other hand, multi-party cooperation needs to be incorporated. Individual actors hold bilateral contracts with each other that handle the business transactions. Thus, a comprehensive coordination design needs to merge the technical and commercial aspects and facilitate the allocations when costs and benefits do not amount to the same actor [38]. *The main objective of this research paper is to develop and apply an actor-oriented multi-level optimization framework.* Thus, the research findings address the third research objective but also the fourth research objective of this doctoral thesis.

First, the design of an integrated model framework called IRPopt to evaluate business model strategies under differing municipal system conditions is outlined. The integrated multi-modal approach is built around a six-layer modeling framework comprising commercial actors, engineering components, components relations, system coordinations, market principles, and municipal context. Taking into account the required design principles of IMMES, the development of IRPopt has been mainly guided by the following modeling approaches: the graph theoretical concept of the deeco model [39] serves as foundation to interconnect processes. Furthermore, high resolution modeling in terms of the engineering processes is also inspired by deeco and DER-CAM [40]. A similar multi-carrier approach in terms of multi-vectors as initially presented by the EnergyHub framework [41] has been also adopted. Additionally, commercial association networks based on individual commerical actors as implemented by the xeona [27] have been taken into account. At the same time, to support decision makers regarding business model management, the energy system model allows a policy-oriented, technology-based and actor-related configuration of varying energy system conditions in general, and innovative business models in particular. This is achieved by explicit modeling of municipal market actors on one layer and state-of-the-art technology processes on another layer as well as resource flow interrelations and service agreement mechanisms among and between the different layers. The division of the technical and economic networks with respect to different layers allows a flexible mapping of the actual real-world conditions. This also delimits IRPopt from existing ESOMs and addresses one major modeling issue as outlined in the first research paper [21]. Moreover, relevant market principles are taken into account for the detailed assessment of business model innovations. On the one hand, the optimization model provides modeling blocks like load shifting, energy contracting, direct consumption, and direct energy marketing. On the other hand, theoretical concepts as capacity measurement bundling, virtual power plants, regulatory tariff options, and reserve market block bids are available.

Second, a multi-level actor-oriented optimization approach to facilitate analysis from different market actor perspectives is formulated. IRPopt represents a bottom-up techno-economic optimization model, implemented in GAMS/CPLEX, for solving mixed-integer problems (MIP). The mathematical objective function of IRPopt is based on the determination of the optimal dispatch of the designed energy process graph considering the actor-related coordination graphs. The major objective is to maximize revenues from different actor perspectives. In this context, the objective function exhibits a novel formal interface between the supply and demand side which merges the modeled technical and economical aspects. By default, IRPopt initially optimizes from an aggregated prosumer' perspective, determining the residual energy demand and excess energy supply with all processes the customers have regulative access to. Subsequently, the model optimizes all other energy and financial flows from the utilities' perspective. Such an idea of a multi-level entity-oriented optimization approach has already been initially outlined by [27]. In addition to the explanations of the research paper, further information about the model design is given in appendix A and a comprehensive overview of the optimization approach is given in appendix B of this doctoral thesis.

Third, the applicability of IRPopt is demonstrated by analyzing the flexibility potential of community energy storage systems at differing municipal system conditions. The community storage stores excess electricity generated by decentralized energy systems of individual prosumers in a central storage to bridge the temporal and quantitative gap of electricity supply and demand. Each participating household is located in spatial proximity to the community storage and connected via the public grid.

The storage is managed by an operator [42]. Revenue potential includes spot market arbitrage, savings from self-consumption and reserve market offerings. In this context, the introduced two-step actor-oriented approach has been applied. The optimization scenarios have been built upon the findings of the second research paper [22] and the third research paper [23]. In this context, the corresponding conference paper [43] gives some additional background information. The optimization results of the synthetic case studies provide insights in the profitability level, the service provision and the flexibility potential. While even under requested legal circumstances a community electricity storage is only partially profitable, the economic situation improves in terms of an optimal storage utilization. This, however, is reduced through competition effects in terms of an simultaneous application of further flexibility options as demand response or sector coupling. Considering the individual and combined dispatch results of the applied cases it has been shown that the flexibility potential but also the capacity utilization of a community electricity storage for the operator is dependent on the utilization by the prosumers as visible in terms of the arbitrages. The novel designed and implemented approach of multi-level actor-oriented optimization is able to show these relations.

1.3.5 Multi-model vision

The fifth research paper [25] presents the multi-model concept called *IRPsim (Integrated Resource Planning and Simulation)* including bounded and unbounded rationality modeling approaches. Even though business portfolio decisions might be already supported by an ESOM like IRPopt, models only considering rational choices of economical drivers seem to be insufficient. Structural decisions of different market actors are often related to bounded rationality and thus are not fully rational [44]. A combined analysis of sociological and technological dynamics might be necessary to evaluate new business models by providing insights into the interactions between the decision processes of market actors and the performance of the supply system [36]. *The main objective of this research paper is to describe a possible multi-model concept which considers various energy-economic system drivers as a whole.* Thus, the research paper wraps up demonstration cases of the fourth research objective but also constitutes the future work of this doctoral thesis.

First, the necessity of a more comprehensive energy system model is demonstrated. Based on a discussion regarding the limitations of the optimization framework IRPopt, a novel multi-model concept is proposed. While techno-economic modeling can capture technological interactions, it cannot endogenize the commercial processes that arise between multiple market participants [36]. In order to understand how investment decisions of individual market actors are conducted, the techno-economic model IRPopt needs to be extended by a socio-economic model [44]. In the research paper the socio-economic model is refereed to as *IRPact (Integrated Resource Planning and Interaction)*. The mutual dependencies of the coupled models result in an interactive and dynamic energy model application for business portfolio assessment. The unbounded technical infrastructure optimization and the bounded interacting actors simulation enable the determination of system impacts of socio-economic behavior patterns of market actors on the techno-economic business performance of the energy supply system. In contrast to other ESOMs, IRPopt represents an adequate starting point due to the novel actor-oriented multi-level framework.

Second, an overview of socio-economic modeling approaches is given. It is argued that empirically grounded agent-based modeling demonstrates one of the most promising approaches regarding the design and development of IRPact as it allows for considering various influences on the adoption process on a micro-level [45]. Since software agents are capable of autonomous actions regarding a certain environment in order to meet its design objectives [46], not only the heterogeneity of behavioral patterns, but also the communication and interaction structures of market participants can be considered [47]. Besides, empirically grounded agent-based models are foremost applied to reflect real market issues and to provide forecasts [45]. Additionally, a large share of available applied research already deals with environmental and energy-related innovations.

Third, a research roadmap is suggested. The system model vision IRPsim aims to provide managers with a multi-model decision support system for innovative business model assessments of differing system conditions of interest like business portfolio, legal framework as well as customer behavior and market environment. Since IRPopt is already in a mature state, the focus of the future work needs to be on designing and developing IRPact. Finally, IRPopt and IRPact need to be coupled in order to exchange and to consider the results of the other models.

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Chapter 2

Energy System Optimization Modeling

*Energy System Optimization at the Municipal Level: An Analysis of Modeling Approaches and Challenges**

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Energy System Optimization at the Municipal Level: An Analysis of Modeling Approaches and Challenges

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Abstract

The development of sustainable system strategies at the municipal level is a challenging task since various factors like the business portfolio, the technological progress, the actor base, the regulatory framework and the market status might influence the results of an assessment. Given the complexity, system interdependencies between different alternatives need to be considered. One possibility to support decision makers is to apply Energy System Optimization Models (ESOMs). This paper reviews selected ESOMs with a high level of modeling detail and thus with high spatial, temporal and contextual resolutions that can be applied to support the decision-making process at municipalities. The main objective is to identify modeling approaches and future challenges to design such systems using several modeling frameworks. First, necessary system elements and interrelations are elaborated based on existing municipal system descriptions. The requirements are included in the derived definition of Integrated Multi-Modal Energy System (IMMES). Second, selected ESOMs are analyzed in terms of the requirements of the system definition. In doing so, existing fundamental approaches are demonstrated. Third, challenges for new mathematical approaches are provided. This review shows that a few modeling approaches are quite prevalent. Future design of models can be directly based on these practices. Additionally, most of the reviewed ESOMs only fulfill certain requirements of IMMES with a more complex approach. Concluding, future ESOMs need to address six research challenges: integrated view, business modeling, spatial planning, complexity level, temporal resolution and uncertainty analysis.

Keywords: Energy system optimization models, Optimal structure and operation optimization, Theoretical approaches and frameworks, Robust modeling guidance

1. Introductory remarks

1.1. Problem statement

Various general trends attribute municipalities with a decisive role in terms of a successful energy transition. First, the traditionally passive consumer demonstrates a growing awareness of sustainability issues and claims participation. From the societal perspective, municipal communities are ideally suited to come together and achieve common goals. While in 2016 there have been around 1024 energy cooperatives in Germany [1] and 2400 in Europe [2], the actual numbers are likely to be larger. Furthermore, the growing utilization of renewable-based energy generators and of distributed co-generation systems require the reassessment of the existing infrastructure. By 2020, the German government targets to increase this share to 35 % [3] and by 2030, it is expected that the global share of renewables reaches 20 % [4]. Since various systems are organized in a decentralized manner and since the linkage between supply and demand are embedded locally, employing different energy carrier infrastructure is an attractive way to improve sustainability. Finally, statutory regulations like energy efficiency measures directly affect municipal businesses. Planning and implementation lead to considerable regional economic effects [5].

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Thus, finding novel future system solutions for sustainable municipalities is important. The identification of such strategies is challenging for the decision maker since a variety of factors that point to the trends need to be taken into consideration. This applies amongst other things for the current business portfolio, the technological progress, the actor base, the regulatory framework as well as the market status [6, 7].

Given the complexity of these environments, system interdependencies and interactions between different alternatives need to be considered to systematically develop strategies. One possibility to support decision makers is to apply energy system optimization models (ESOMs) [8]. Even though the methodology is widely recognized to generate economically optimal insights that inform energy and environmental policies regarding various public interest issues [9], the application of optimization-based models to municipalities is limited [10]. Since assessment findings might be influenced by an entire range of factors, rather holistic frameworks and profound models are needed to sufficiently map the system complexities at the municipal level [8]. In this context, adequate models show a coherent logical and physical design which is able to theoretically abstract the deployment environment. Logical design deals with the conceptual model, whereas physical design focuses on implementation approaches. Corresponding characteristics of the system environment are summarized in this research paper with the newly coined term Integrated Multi-Modal Energy System (IMMES).

At the same time, the development of complex internal approaches to describe some characteristic of the real-world might also lead to opaque models which are hard to capture for external modelers [11]. Over time, this has led to a crowded landscape of ESOMs that can overwhelm in terms of designing and implementing new and robust models. A discussion about chosen modeling approaches gives insights into proper modeling practices and future modeling challenges.

1.2. Research scope

This research paper is an effort to analyze and discuss logical and physical design practices with a focus on ESOMs. The main objective is to identify modeling approaches and future challenges relative to a municipal deployment environment for robust system model design. In this context, this research paper assesses the following research questions:

- Which requirements must be addressed for a holistic energy system analysis at the municipal level?
- Which fundamental modeling concepts and approaches assist in the development of optimization models that match the different system requirements?
- Which modeling challenges exist during the process of conceptualizing and designing optimization models?

1.3. Previous reviews

Different reviews have already examined individual aspects of this research objective. In this context, Koirala et al. [12] and Keirstadt et al. [10] present issues and trends of modeling at the municipal level. Huang et al. [13], as well as Mirakyan and De Guio [14], introduce and assess the respective methods and tools for energy planning. The same applies to the articles of Mendes et al. [15], Markovic et al. [16], Allegrini et al. [17] and Tozzi and Jo [18]. A review of 37 tools in collaboration with the tool developers have been conducted by Connolly et al. [19]. Key features of low-carbon society model approaches are outlined by Nakata et al. [20]. An overview of multi-energy systems at different scales is given by [21]. Hybrid renewable energy systems, including various optimization approaches, surveyed by Fathima and Palanisamy [22]. Different modeling techniques for demand forecasting are reviewed by Suganthi and Samuel [23]. The role of optimization techniques is also investigated by Bazmi and Zahedi [24].

DeCarolis et al. [11] highlight critical steps and formulate best practices for energy system optimization. Challenges and solutions for future system modeling are also provided by Bruckner et al. [25], Pfenninger et al. [26], and Keles et al. [8].

Building on the findings of previous reviews, this paper synthesizes characteristics of municipal systems definitions. This helps in fostering the scientific debate about the necessary requirements for energy system modeling at the municipal level. Additionally, this paper discusses selected models concerning their fundamental approaches and frameworks. In this context, the analysis is more detailed than in previous reviews. This provides modelers with guiding principles and assists in identifying further modeling challenges.

1.4. Research structure

The rest of this research paper is organized as follows: Section 2 introduces several types of decision support systems. Additionally, the system characteristics are elaborated to formulate model requirements in terms of IMMES. Section 3 describes the underlying methodology used in this review. On this basis, Section 4 presents and analyzes selected system optimization models and Section 5 analyzes the fundamental modeling approaches applied. Section 6 formulates existing challenges and proposes future research options. Section 7 conclusions are presented, and future research suggested.

2. System modeling

To implement a systematic review, relevant domains must be first conceptualized [27]. While Section 2.1 introduces to model-based system analysis, Section 2.2 describes the characteristics of municipal energy systems.

2.1. System optimization

To develop consistent strategies in complex environments, decision support systems like computer-aided energy system analysis are a consideration [28]. *System analysis* aims to examine the structural characteristics of a system under a variety of different assumptions [28]. The operation purpose determines the level of detail of the system context and the well-thought-out choice of the system boundaries, which also basically characterizes a *system* [29]. The terms system and model are closely associated with each other. A *model* is defined as a conceptual framework that describes a system. Thus, it is as a purpose-oriented, simplified representation of reality describe the dynamics and interactions [29].

Given the *operation purpose* and the complexity of the system characteristics, a variety of theoretical approaches have been developed to abstract the real-world, each with its own advantages and limitations. Previous reviews of authors like Connolly et al. [19] provide additional insights. Consequently, these models vary considerably, and it begs the question which models are most suited for specific issues. For developing a sustainable future strategy, relevant models need to master given entities and dynamics at the municipal level.

The purpose statement already makes assumptions for selecting the right model strategy, analytical approach, underlying methodology, mathematical approach and resolution coverage [30]. Due to the diversity of methodological approaches and hybrid forms, a classification can only be general and not exact [29]. In this context, the literature provides a whole host of classification schemes [29–33].

Depending on the operation purpose, system models can serve different *planning issues* like design determinations and operation scheduling [34]. While in the first case, the composition and dimensioning of the plant facilities for a particular area are specified, in the second case the operation mode of the plant facilities is predetermined for a predefined structure area.

Energy system models have a long tradition of consulting policy. To facilitate a detailed analysis of exogenous measures, the focus lies on the detailed techno-economic representation of the real system [29]. Since top-down models oftentimes suffer from the lack of technical detail and tend to underestimate the complexity of obstacles [28], they sometimes deliver rather generalized results and are not so well-suited for the purpose to comprehensively capture the system entities and dynamics. However, there are also disadvantages to bottom-up models as they do not consider macroeconomic effects [28]. Future, bottom-up models must be further detailed by integrating partial model elements of top-down models into their design.

The choice of a suitable *underlying methodology* frequently follows for an analytical approach. Commonly used methodologies are [30]: (a) econometric, (b) macroeconomic, (c) economic equilibrium, (d) optimization, (e) simulation, (f) spreadsheet, (g) backcasting and h. multi-criteria. Although, there are exceptions, the methodologies mentioned first (a-c) are usually applied to top-down models, the methodologies mentioned second (d-g) are generally applied to bottom-up models [28].

Mathematical optimization is widely considered as an effective methodology to generate insights that inform policy within the field of complex system modeling [26]. While in simulation model's decisions are made outside the computer after a spectrum of options has been considered by the modeler, in optimization models crucial design decisions are made inside the computer on the basis of descriptive analysis. By capturing all in built-rules, restrictions, and presumptions, optimization models can come up with a global optimum in certain programming classes [9]. This implies that modelers of optimization models need to go into a bit more detail with the current system issues than modelers of simulation models need to do. The optimization results also define an optimal benchmark for explicit planning compared to other methodologies, even though there is no need to implement the outcomes. The use of the methodology is also tempting for decision makers since it (a) represents a quantitative method that results in specific recommendations, (b) ensures economically optimal solutions under existing conditions, (c) enables to forecast optimal future systems by considering incorporated presumptions, (d) and avoids the inclusion of emotions and irrationality [9, 11]. For these reasons, energy system optimization models (ESOMs) make up the core of this review. This does not necessarily imply that simulation models do not make valuable contributions.

Optimization means selecting the optimal solution for given variables from a set of alternatives while meeting the given constraints [9]. In the case of mathematical optimization, the selection criteria are a suitable selected function, called the *objective function*. The set of alternatives can be a discrete or continuous, finite or infinite, one- or multidimensional set of choices, called *feasible region*.

At the level of concrete models, an additional distinction of ESOMs can be made regarding the mathematical class. Commonly applied techniques include linear programming (LP), mixed integer programming (MIP), dynamic programming (DP), and nonlinear programming (NLP) [30]. Since modeling complexity but also the computational effort increases LP and MIP models are the most widely used [29]. Since MIP is already not always solvable, this work neglects NLP.

Finally, *resolution coverage* deals with temporal (hourly) and spatial resolution (municipal). Furthermore, sectoral coverage (multi-energy sectors) and data requirements (quantitative, (dis)aggregated) are considered [30]. Taking the objective into account, this research paper concentrates on high-resolution modeling. This means that the models to be reviewed provide a high level of modeling detail to accurately abstract the real-world characteristics. Figure 1 illustrates the focus.

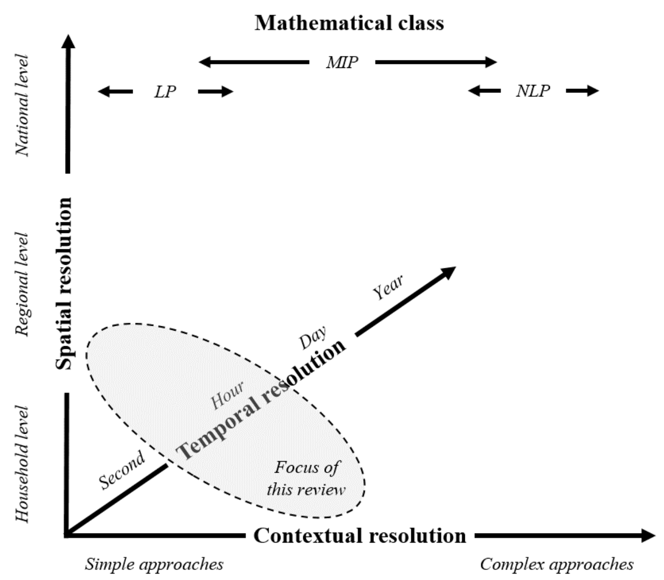

Figure 1: Focus area of relevant ESOMs for this review paper

2.2. System requirements

Even though ESOMs represent a simplified picture of the real system, they provide at best a good approximation [28]. Since characteristics for energy systems at the municipal level are denoted and delimited in different ways across the literature, this research paper aims to define the system boundaries and system contexts. The derived system requirements are applied by ESOMs for a necessary and comprehensive mapping of the system complexities. Considering this, a schematic municipal system structure has been sketched in Figure 2.

In general terms, Pfenninger et al. [26] define energy systems as "the process chain [...] from the extraction of primary energy to the use of final energy to supply services and goods." In line with this, an urban energy system model is seen as "a formal system that represents the combined processes of acquiring and using energy to satisfy the energy service demands of a given urban area." [10]. The objective is "to find environmentally friendly, institutionally sound, socially acceptable and cost-effective solutions of the best mix of energy supply and demand options for a defined area to support long-term regional sustainable development." [14].

According to Farzaneh et al. [35] an urban energy system can be described "as a system where, a locality strives toward establishing the delivery of energy service with maximum utility of its inhabitants, using an optimum combination of resources and technologies, subject to satisfying technical, institutional, environmental and economic constraints." While this later definition is, at first glance, not unlike the previous, Farzaneh et al. [35] explicitly stress the importance of the linkage between local government and municipal energy providers for the success of any city climate action plans. Additionally, the level of satisfaction of the directly affected end users is highlighted. Finally, different sectors are addressed in terms of the combination of resources and technologies.

The multi-faceted approach to energy supply is also denoted as hybrid energy hub [36] or as a multi-energy system [21]. "In particular, the analysis approach refers to explicitly expanding the system boundary beyond one specific sector of interest." [21]. The ideal interaction of electricity, heat, cooling, fuels, transport at

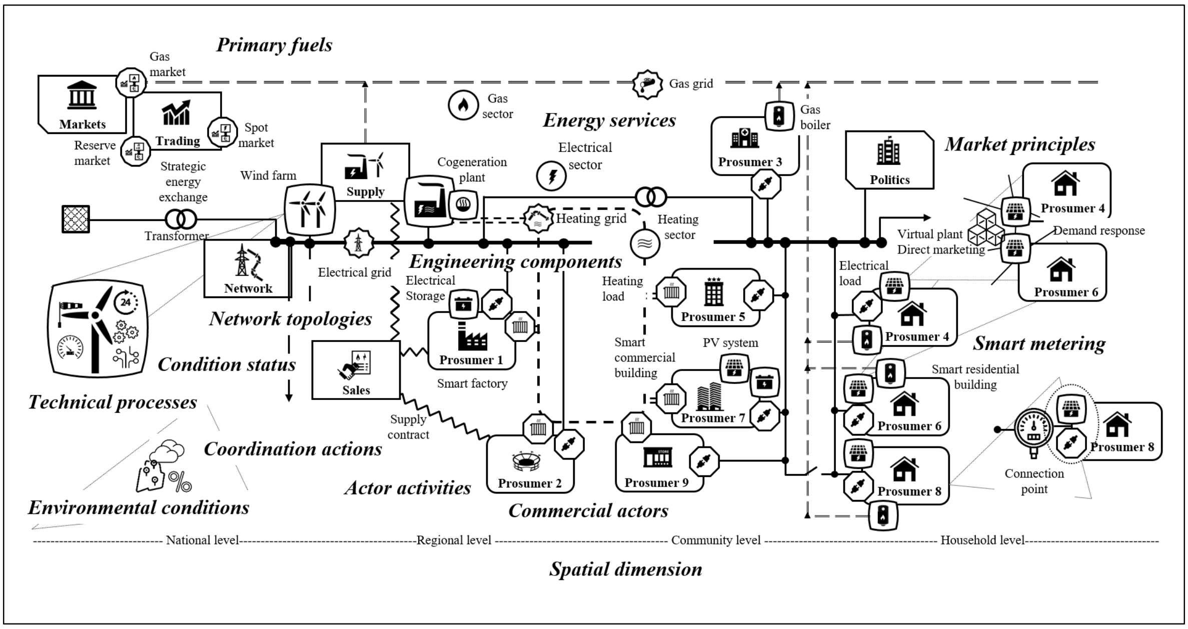

Figure 2: Illustrative schematic layout of municipal energy system entities and dynamics

various levels, for instance, within a district, city or region represents ”an important opportunity to increase technical, economic and environmental performance relative to ’classical’ energy systems whose sectors are treated ’separately’ or ’independently’.” [21].

The hub approach of Geidl [36] is an aggregation model that provides the basic features for multi-energy systems while including network constraints. According to Mancarella [21], four categories are decisive for describing such systems: the spatial, the multi-fuel, the multi-service, and the network perspective. More frequently, the integration of all energy carriers in an energy system is also designated by the term multi-modal energy management which also puts emphasis on the overall energy chain. Mauser [37] and Thiem et al. [38] state that multi-modal energy systems enable the integrated operational optimization of technical energy chain processes from the provision to the utilization of multiple energy sources, carriers and services in a multi-energy system.

A stronger focus on actor entities of the energy chain often seems to be more pronounced in definitions related to integrated systems, even though the term is also mentioned in various other contexts. According to Koirala et al. [12], integrated community energy systems are ”multi-source multi-product complex socio-technical systems consisting of different decision-making entities and technological artifacts governed by energy policy in a multi-level institutional space.” Moreover, physical interrelations of the technologies and the social relationships among participants of the municipal community represent a fundamental component [12]. This is also in line with Pfenninger et al. [26]. It is stated that a comprehensive energy system model requires technical, environmental and social elements, although most models generally focus on the first two. In this context, future urban systems must consider the various technology options and control strategies on both the supply and the demand side [35] and entail the following perspectives [12]: activities, scale, grid connection, initiatives, location, and topologies.

In summary, municipal energy systems are affected by spatial, cross-sectoral, technological, structural, social, economic, conceptual, environmental and institutional issues and interactions [12, 26]. Without focusing on a certain modeling domain, the system context is most appropriately described with the combined term *Integrated Multi-Modal Energy System (IMMES)*, which is comprised of the above definitions aligned to a municipal level. A working definition of this research paper reads as follows:

> An IMMES enables the integrated operational optimization of technical and environmental energy chain processes of multiple energy fuels, carriers and services in a multi-energy system network by simultaneous consideration and coordination of the social, economic and institutional network of relationships of market actors in a spatial context.

Based on the IMMES definition and the illustration in Figure 2, various system entities and system dynamics are in form of characteristics derivable. A brief description is given in Table 1. Even though such a categorization is only a conventional one, the elaborated characteristics represent requirements to comprehensively design municipal energy system models in this research paper.

Table 1: System characteristics of municipal energy systems

Term	**Description**
Spatial anchoring	Physical space of the municipality defining the system boundaries.
Network topology	Technical and commercial interconnection of system elements.
Commercial actor	Market participant from which distinct activities are derived.
Actor activity	Distinct services along the energy chain provided by social actors.
Coordination strategy	Decision rules for optimizing actor activities concerning their conditions.
Engineering component	Technical system components from which relevant processes are derived.
Energy service	Outbound energy portfolio that components can provide.
Primary fuel	Inbound energy portfolio that components can utilize.
Technical process	Functional characteristics of a specific component along the energy chain.
Operatinstatus	Service mode of a specific component along the energy chain.
Smart metering	Connection points required to measure bundled load capacities.
Market principle	Construct of regulatory and product requirements without market reference.
Environment issue	External setting which influences actor and component behavior.

3. Research methodology

A literature review demonstrates a solid foundation about an object of study and identifies crucial methodological insights as well as recommendations for further research [39]. While keeping in mind the research questions (section 1) and the research domains (section 2), this review follows a five step procedure in accordance with Vom Brocke et al. [40]: (1.) definition of the review scope, (2.) conceptualization of the topic and associated research domains, (3.) description of the search process, (4.) synthetization of the retrieved literature, (5.) presentation of findings and derivation of the research agenda.

The review scope can be described with the help of six characteristics each having a different number of categories [40]. The underlined categories in Table 2 summarize the corresponding selection.

Table 2: Scope of the review paper (based on [40])

Characteristics	**Categories**			
Focus	research outcomes	research methods	theories	practical applications
Goal	integration	criticism	identification of issues	
Perspective	neutral representation	espousal of position		
Coverage	exhaustive	selective	representative	central/ pivotal
Organization	historical	conceptual	methodological	
Audience	specialized scholars	general scholars	practitioners	general public

This research focuses on optimization-based decision support as well as municipal entities and dynamics modeling. The domain conceptualization is outlined in section 2 as requested by [27]. The main emphasis is put on critically analyzing existing modeling theories. Thereby, no specific perspective is taken. The literature search focused primarily on peer-reviewed journal articles in combination with dissertations. The review covers a selected sample of optimization models instead of explicitly considering the entire corpus of existing papers. The models have been identified during the conceptualization process. The decision criteria regarding the inclusion of a system model are in line with the research domains: First, only optimization models are in focus. Thus, individual well-known accounting models like *RETScreen* (alternative balance sheet screening) [41] as well as simulation models like *EnergyPlan* (analytical programming) [42, 43], *EnergyPlus* (convergence criterion) [44, 45], and *energyPRO* (individual dispatch priorities) [46] have been viewed but not considered. Second, the resolution of the optimization models needs to match the defined temporal, spatial and contextual focus. Concerning this matter, models like *HOMER* (very low complexity- specification of discrete capacities, heuristic scheduling) [47], *MARKAL/TIMES* (seasonal time slices, national level) [48, 49], *BALMOREL* ((inter)national level) [50, 51], *IKARUS* (national level, low temporal resolution) [52] and *TRNSYS* (NLP, building level) [53, 54], *EAM* (NLP) [55, 56] have not been considered further. Third, the selection is intended to give insights into a variety of modeling approaches covering various system characteristics. The selected models for this review are:

- *deeco - Dynamic Energy, Emission, and Cost Optimization model* [57–60],
- *xeona - Extensible Entity-Oriented Optimization-Based Network-Mediated Analysis model,* [61, 62]
- *DER-CAM- Distributed Energy Resources Customer Adoption Model* [63, 64],
- *EnergyHub Model* [36, 65–67],
- *urbs - Urban Research Toolbox: Energy Systems Model* [68, 69],
- *KomMod - Kommunales Energiesystem-Modell (Urban Energy System Model)* [34, 70, 71],
- *MMESD - Multi-Modal On-Site Energy System Design Model.* [38, 72, 73]
- *RE^3ASON - Renewable Energies and Energy Efficiency Analysis System Optimization* [74–76].

In this context, models related to the *technical superstructure* approach (*MMESD* builds upon this approach) [77, 78], as well as the model *REopt* (similar coverage as *DER-CAM*) [79, 80] and *MODEST* (similar coverage as *urbs*) [81] are also relevant but not discussed in detail.

The findings are conceptually organized: First, the models as a whole are presented. Second, using system characteristics, existing approaches are analyzed. Third, future avenues for research is stated. The audience for this review is primarily comprised of specialized scholars interested in designing and modeling of optimization systems.

4. Model review

This section provides an initial classification of selected ESOMs that are available for assessing an *IMMES*, each with a certain operational purpose.

A summary of general key modeling issues is outlined in Table 3 and 4.

Table 3: Comparison of the modeling strategy of *IMMES* related energy system optimization models

Model name	Operation purpose	Planning issues	Mathematical approach	Documentation process
deeco [57],[58],[59],[60]	High temporal and topological thermodynamic resolution modeling to identify integration deficits	Optimal operation optimization (operational plus investment mode by system evolution experimentation)	Quasi-dynamic recursive optimization scheme, LP for time-local prob., NLP for time-global prob. (C++,GAMS)	Open source code available (no longer active), modeling and application manuals
xeona [61],[62]	Multi-level entity orientation for low-stake commercial and domestic decision-making to mimic contract negotiations	Optimal operation optimization (operational plus investment mode by system evolution experimentation)	Dynamic recursive optimization scheme, LP or MIP (C++)	No source code repository identifiable1, scientific representations
DER-CAM [63],[64]	Design and operation decision of residential or commercial sites by taking into account multiple energy carrier microgrids	Optimal structure and operation optimization (two model versions: 1. investment and planning; 2. operations)	Dynamic (recursive) optimization scheme (version dependency), MIP (GAMS)	Source code on request, web service avail., modeling and application manuals, tutorial movies
EnergyHub [36],[65],[66],[67]	Multi-energy carrier management of non-hierarchical interconnected system components and networks	Optimal operation optimization (optimal optimization regarding hub coupling and hub layout is also possible)	Dynamic (recursive) optimization, NLP, in further work also LP or MIP (Matlab (Yalmip), GAMS)	Open source code available (no original code), various scientific representations
urbs [68],[69]	Multi-energy storage effects investigation on optimal planning decision by taking into account co-optimization	Simultaneous optimal structure and operation optimization	Dynamic optimization scheme, LP (Pyomo)	Open source cove available, modeling and application manuals, comprehensive example
KomMod [34],[70],[71]	Specific local circumstances integration for optimal energy system strategy determination at the municipal level	Simultaneous optimal structure and operation optimization	Dynamic optimization scheme, LP (AMPL)	No source code available, scientific representations
MMESD [72],[38]	Time dimensional decomposition strategy for multi-modal system design of a particular site on a superstructure approach	Sequential optimal structure and operation optimization, four layer approach	Periodic-dynamic optimization scheme (layer dependent), MIP (MATLAB)	No source code available, scientific representations
RE^{3}ASON [74],[75],[76],[8]	GIS based automated analysis of local buildings energy demand and local renewable energy potential	Optimal structure and operation optimization	Periodic-dynamic optimization scheme, MIP (GAMS), data retrieval (JAVA)	No source code available, scientific representations, video demonstration

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Table 4: Comparison of the modeling resolution of *IMMES* related energy system optimization models

Model name	Temporal resolution	Spatial resolution	Model resolution	Other specification
deeco **[57],[58],[59],[60]**	Representative year, 1h resolution, rolling horizon of a single time step, multi-year possibility	Graph-based network, multiple nodes represent processes (not necessarily spatial expansion)	Carriers w/o. (electr., fuel) and with (heat) technical properties, detailed processes, thermodynamic states	Outdoor and storage temperature integration (nonlinear properties), extensive process library
xeona **[61],[62]**	Representative year, 1h resolution, rolling horizon for multiple hours, multi-year possibility	Physical and actor related multi-graph based network (not necessarily spatial expansion)	Number of approaches of the previously described model *deeco*	Multi-participant commercial behavior modeling (counterpart of a centralized decision concept)
DER-CAM **[63],[64]**	Representative year, periodical perfect foresight, 84h or 36h time slices per month, up to five minutes resolution	Multi-node model network represents site's topology on the basis of distributed grid infrastructure	Carriers w/o. (heat, cold, fuel) and with (electr.) technical properties, simplified processes, power flow approach	Thermal-electric ratio, demand response approach, explicitly consideration of the transport sector
EnergyHub **[36],[65],[66],[67]**	Representative periods, single instant or multiple period optimization, 1h resolution	Interconnected hub network, hubs represent a certain spatial location (contain a set of processes)	Carriers w/o. (heat, cold, fuel) and with (electr.) technical properties, simple processes, const. efficiencies	Different power and pipeline network approaches, matrix-vector multiplication
urbs **[68],[69]**	Representative year, perfect foresight, year-round optimization, 1h resolution, multi-period assessment	Graph-based network, multiple nodes represent processes (not necessarily spatial expansion)	Carrier w/o technical properties (electr., heat, cold, fuel, water), simple processes, const. efficiencies	Reproducibility of case-study results, CO_2 forms an energy carrier, co-optimization approach
KomMod **[34],[70],[71]**	Representative year, perfect foresight, year-round opt., 15min/1h resolution, multi-period assessment	Spatial effect integration on the basis of four hierarchical levels: system, zone, sub-zone and building type	Carriers w/o. techn. properties (electr., heat, fuel), simple processes, const. efficiencies	Performance enhancement due to the applied spatial approach, mass flow measurement
MMESD **[72],[38],[73]**	Representative year, representative foresight (hourly, daily or periodically), layer dependent time resolution	Superstructure network, multiple nodes represent processes (not necessarily spatial expansion)	Carriers w/o. techn. properties (electr., heat, cold, fuel, drink. water), detailed processes, part-load efficiencies	Ambient condition integration, inlet air cooling approach, thermal energy at six different temperature levels
RE^{3}ASON **[74],[75],[76],[8]**	Representative periods, eight model years, seventy-two time slices (4 seasons, 2-day types, 9 time slices within each day)	Geographical renewable potential and flow capacities as data input, multiple nodes represent districts	Carriers w/o. techn. properties (electr., heat, fuel), simple processes, large scale processes not considered	Automated analysis of the system infrastructure by using open geodata and image recognition techniques

4.1. deeco

The ESOM *deeco* was developed by Thomas Bruckner in the late 90s at the University Würzburg [57] and later on at the Technical University Berlin [60]. *deeco* is defined as a decision support system for the planning and development of regional utility concepts given a predetermined, fluctuating energy demand [59, 60]. Through the optimal combination of conventional energy supply technologies and technologies employing regenerative energy sources possible savings of primary energy, emissions, and monetary costs might be quantified. Besides, upcoming correlational effects between supply opportunities, demand services and dynamics in terms storage solutions can be analyzed [59]. This goes in line with the statements of Mancarella [21] who describes *deeco* as “a tool for investment decisions to explore potential competition and synergies of different technologies to supply heat and electricity demand in a municipality while increasing energy efficiency and integrating renewable energy systems also taking into account energy taxes and various parameters.” Even though different energy sectors are included, the focus is on high temporal and topological resolution modeling of thermodynamic processes to capture fine-grain network effects [58]. A case study of a district in Würzburg is presented in [57] and a theoretical study with respect to various technologies in [60].

The deterministic bottom-up ESOM formulations take various flow attributes into account and consist of two major parts: a central kernel which contributes to the network structure, core algorithms, and certain housekeeping tasks like data input/output and a library of plant modules providing support for the various technologies and fuel types [60]. A given system can be modeled as a network of dynamic plants whose state may evolve [16]. Depending on average (hourly) time-variable energy demand input data, *deeco* determines optimized operation values of non-renewables, of emissions and of the costs, as well as the optimal shares of the considered energy supply technologies. LP is applied within a time-local quasi-dynamic recursive optimization scheme over a period of one representative year [60]. Nonlinear and time-dependent influences of intensive properties (such as outside and storage temperatures) on the efficiency of the different energy supply technologies are, however, also considered in terms of the time-global problem formulation [57]. This is also the reason that *deeco* constitutes an extreme type of rolling horizon. Only the current hourly time step is recursively optimized [57]. Thereby, time is represented discretely with an hourly default time discretization for one representative optimization year. The model is well suited to inter-seasonal studies of approximately two years [82].

The program is written using the object-oriented programming language C++. Thereby, data input, as well as output, are based on ASCII-data files [59]. The current version of the model at the University of Leipzig is implemented based on GAMS. The code is open source[1].

4.2. xeona

xeona was designed by Robbie Morrison in the early to mid-2000s. The project branched out from the *deeco* project [61, 62, 83]. *xeona* ”combines high-resolution modeling with multi-agent simulation” [61] and thus extends the pre-existing technology-centered *deeco* approach with “controllers, markets, actors, and proactive policy measures that exist in reality or are under consideration.” [62]. Thus, the deterministic bottom-up ESOM is particularly appropriate for liberalized energy system problems. It is described to be “suitable for questions involving public policy, private investment, or combinations thereof” [61] within “interconnected resource-transformative systems and industries, at an appropriate resolution, in terms of their public interest performance.” [61]. In this context, the ESOM can capture multi-participant domestic and commercial behavior rather than posit a single system actor who makes universally optimal choices centralized planner as most of the existing ESOMs do [61]. As stated by Morrison et al. [61], this entity approach is an extension of the entity-relations-attribute modeling. Thereby, the ESOM also takes individual public policy measures with respect to market concepts and environmental conditions into account.

Due to the scale-independent underlying numeric, *xeona* is ”suited to problems ranging in spatial scope from stand-alone facilities to a meta-national system” [61]. The core concept is based on two mathematical graphs. It entails the physical and instrumental resources network, also available in *deeco*, as well as the newly developed entity-based commercial associations network. The unit-commitment problem uses LP or

[1] https://github.com/robbiemorrison/deeco

MIP [62]. The physical resources (from physical constructs; examples include natural gas and precipitation) and instrumental resources (from institutional constructs; examples include carbon permits and funds) flow rates form the main variables [61].

Like *deeco*, the *xeona* software is implemented in the object-oriented programming language C++. In this context, a client-server model serves as the basic architecture. The ESOM uses a script-component architecture. For data input, XML data files are used. In addition, *xeona* uses open source software so “code and documentation can be potentially checked and run by citizens, NGOs, and business stakeholders” [61]. However, a source code repository has not been identified.

4.3. DER-CAM

DER-CAM represents an economic and environmental MIP that has been in development by Michael Stadler and the Microgrid Team at the Berkeley Lab since the early 2000s [18]. An update in March of 2016 also assisted in the ESOM utilization in microgrid modeling. In the initial versions, only residential modeling was possible [18]. It is an advanced, deterministic optimization tool for obtaining the best investment decisions regarding the design and the operation of residential or commercial sites by considering multiple energy carrier microgrids while co-optimizing multiple stacked value streams that include load shifting, peak shaving, power export agreements, or participation in ancillary service markets [63]. Relevant questions for the ESOM utilization according to [16] are: ”Which is the lowest-cost combination of distributed generation technologies that a specific customer can install?”, ”What is the appropriate level of installed capacity of these technologies that minimize costs?”, How should the installed capacity be operated so as to minimize the total customer energy bill?”. To answer these questions, *DER-CAM* is divided into two central versions.

Based on typical energy load curves, fuel prices, technology efficiencies and utility tariffs, the first version *Investment and Planning DER-CAM*, determines the best combination of building refurbishment measures on the one hand and distributed energy resources as decentralized technologies on the other hand [63]. The second version *Operations DER-CAM* optimizes the dispatch of the selected technologies with high temporal resolutions of up to five minutes (quarter-hourly, or hourly resolutions are also possible) [63]. Different strategic application examples are presented in [64]. The optimization tool has been initially implemented as MIP for one representative year. It is originally written in GAMS. While the *Investment and Planning DER-CAM* tool takes 36 hourly energy loads per month into account (one representative week, weekend, and peak day per month), the *Operations DER-CAM* takes 84 hourly loads (seven representative days of hourly energy loads per month to characterize a typical year).

The bottom-up ESOM is intended for utilities, research institutions, and industrial companies and has been largely applied to different problems with respective necessary enhancements. The more than 80 peer-reviewed publications are impressive evidence of the ESOM functionality [84]. An academic web-based version with limited features of *DER-CAM* is downloadable free of charge. A DER-CAM desktop interface allows the full use of the functionalities free of charge. However, only in certain collaboration cases, the full source code is exchanged for non-commercial.

4.4. EnergyHub

The modeling of an energy system using the *EnergyHub* concept was first reported at the Power Systems Laboratory of ETH Zurich in 2005 [85] while the concept itself was elaborated on by Martin Geidl [36, 65]. The underlying assumption of the project was to design and investigate a optimum system from scratch without considering the current power system structure. Afterward, the main findings of the fictitious system should be used to move from today’s structure toward the optimal future structure [36]. The energy hub is ”a unit that provides the basic features in- and output, conversion, and storage of different energy carriers.” [36]. Thus, the concept is “a multi-generation system in which production, transmission, storage and consumption of multi-energy carriers take place to meet different type of demands.” [67]. ”One of the main advantages [of the *EnergyHub* framework] is the efficient use of multi-generation (co, tri or polygeneration) systems in order to make optimal use of energy resources, increasing efficiency, and reduction in emissions and costs.” [67]. Furthermore, the concept provides advantages of generality, scalability, modularity and the combination of modeling techniques [66]. Mancarella describes the approach as “suitable for modeling of distributed [multi-energy systems] with the inclusion of network constraints and has proven itself to be flexible for manifold applications." [21].

A distinction between distributed multiple generation concepts like virtual power plants, microgrids, and *EnergyHub* approach is drawn in [86] and in [21]. While virtual power plants deal with the market integration of different distributed generation facilities, the *EnergyHub* approach can be utilized to mathematically formulate the individual distributed generation facilities. In a comparable way, the approach can also support microgrids. Thereby, energy hubs could be used for existing, multiple input sources or loads of the grid. In this context, the *EnergyHub* "concept mostly serves modeling, analysis, and planning purposes rather than matching the needs of the system operators for real-time operation." [66].

The core of the energy optimization problem is represented by a general multi-energy input and output conversion management in terms of a matrix-vector multiplication [36, 65]. Various variants and applications are based on the basic concept. In this context, the initial NLP [65] has been transferred into LP or MIP and expanded in terms of different publications [87–89]. A review article by Mohammadi et al. in 2017 lists 129 scientific papers using the *EnergyHub* concept [67] (it should be noted that the base case with a constant coupling matrix and a convex objective function also represented an LP problem from the beginning). Thus, the ESOM framework can be seen as one of the most common methods for optimal dispatching of multiple energy carriers in order to cover the demand of the end user. The major functionalities of the concept are inputs, conversion, storage as well as outputs. The main sectors are electricity, heat, and gas. Therefore, it is understandable that the main technology is represented by combined heat and power (CHP) processes [67]. . With respect to the spatial application, the approach can be used "to manage energy flows within a large building as well as systems ranging in size from neighborhood to national level." [17]. The ESOMs of the concept have used different approaches, different objective functions and constraints, and diverse tools including various high-level programming languages such as GAMS, Matlab, Fortran, Delphi, C++ [90]. Based on the described concept, an open source software[2] is provided by Bollinger and Dorer [91].

4.5. urbs

urbs represents an ESOM for multi-commodity energy systems with a focus on optimal storage sizing and utilization. The main developer is Johannes Dorfner who designed and implemented the ESOM in the years between 2012-2015 at the Technical University Munich [68, 69]. It can be seen as a generalization of the preceding *URBS* model of Stephan Richter, which has been limited to single input and single output per conversion process [92]. The presented *deeco* model has been listed as one of the sources of inspiration.

The general objectives are described in terms of maintainability of the ESOM, the reproducibility of the results and the co-optimization between different ESOMs. A comprehensive model workflow description, the model code, the data analysis scripts as well as a real-world case study is downloadable free of charge[3] [69]. In addition, the ESOM has been applied for a case study in a small town called Haag in Bavaria in combination with a network-oriented model called *rivus*. In particular, "*urbs* helps to transform the results into the time domain and interpret them in multi-service perspective, taking local storage of different energy carriers into account."[68]. "It finds the minimum cost energy system to satisfy given demand time series for possibly multiple commodities." [69]. According to [68], the multi-energy ESOM is suitable for features as time, processes, storage, capacity expansion and unit commitment. A low suitability is attributed in terms of space and transmission.

Space and time are treated discretely in *urbs*. A graph-based network forms the basis of the ESOM. By default, the ESOM operates on hourly time steps. The coupling matrix of the *EnergyHub* approach serves as a basis for the model system enhancements in order to define multiple inputs and multiple outputs per process. In this context, emissions are remarkably considered as additional process outputs. The consumption and generation amount of the various processes is defined by a constant input and output ratio [68].

The bottom-up ESOM provides a perfect forecast. Thus, the data of the representative one year is optimized in terms of a fully dynamic optimization problem. LP is used for formulating the optimization

[2] https://github.com/hues-platform/ehub-modeling-tool
[3] https://urbs.readthedocs.io/

problem [68]. ”The model itself is quite small thanks to relying on the Pyomo package.” [69]. Besides, *urbs* provides diverse reporting and plotting functions.

4.6. KomMod

KomMod represents an optimization tool developed by Jan-Bleicke Eggers at the Fraunhofer ISE Germany and at the Technical University Berlin in the year 2016 [34]. ”It aims at integrating as many interdependencies as possible into one tool, calculation optimal solutions for a future municipal energy supply based on the specific local circumstances.” [34]. The software is designed to support decision-making of municipalities in terms of strategy development regarding ”Smart Energy Cities” [70]. A comprehensive example study of the city of Frankfurt am Main with several techno-economic strategy recommendations is shown in [34, 71]. A further analysis of the city quarter of Freiburg-Haslach is presented in [34]. In both studies, a comprehensive sensitivity analysis regarding temporal and spatial resolutions have been applied.

In contrast to other ESOMs, *KomMod* is equipped with a spatial hierarchical level structure in order to divide the investigation area into four levels: system, zone, subzone and building type. This approach allows the integration of spatial effects into the ESOM whilst at the same time enabling an acceptable calculation performance for the optimization of the system. Thus, it constitutes an ideal balance between the representation accuracy and mathematical complexity [34]. This might not be given in terms of a structuring with the powerful graph-based network approach of *deeco* or *urbs* [34].

The deterministic bottom-up ESOM is formulated as LP and exhibits a simultaneous optimization of the structure and the operation with perfect foresight. Thereby, one representative year is dynamically optimized in terms of hourly time steps (up to 15 min are possible). The implementation was accomplished on the basis of the language AMPL [34].

4.7. MMESD

MMESD is has been developed by Sebastian Thiem at the Technical University Munich financed by the Siemens AG [38, 72]. The ESOM builds upon the superstructure approach which has also been implemented by [78]. The aim of the ESOM is to “develop an energy system design method, which is capable of minimizing total expenditures encountered for the energy supply system at a particular site by selecting the best energy technologies, sizing their capacity and choosing their best operating strategy.” [38]. Thereby, a detailed analysis and planning is required to achieve a cost-optimal but also a reliable solution. It incorporates the demand of electricity, heat (4 different temperature levels), cold (2 different temperature levels) and even potable water and is mostly suited for newly constructed (Greenfield project) or expanded (Brownfield project) sites as large building complexes, such as airports or university campuses [38, 72]. In terms of the detailed component modeling, the research considers the various state of the art technologies with a certain focus on modeling part-load efficiencies, turbine inlet air cooling and ice-storage desalination [72]. Furthermore, short- and long-term storages are available in the superstructure [72].

The outcome of the energy system design method is a preliminary design of the energy system which needs to be post-processed and examined for its feasibility. The algorithm consists of four sequential layers and the optimization problems are formulated in the form of different MIP problems for a representative year. As stated by the authors [38] the major aim is to propose ”a novel strategy for decomposing the ESD problem in its time dimension.” Thereby, the different optimization problems increase the level of detail for the considered periods or days of the year with respect to the various layers. On the one hand, this allows an efficient solution to the system. On the other hand, the solution is only a near-optimal solution to the overall problem. Sensitivities are necessary to investigate the robustness of the solution [72]. The mathematical framework has been implemented in MATLAB including a graphical user interface.

4.8. RE^3ASON

Even though, the common graph-based network approach allows the modeling of different municipal energy systems, they are not highly transferable to other areas. This seems to be a substantial weakness of many energy-system models and the main motivation behind the development of the RE^3ASON model at the Karlsruher Institute for Technology (KIT) [74]. The ESOM itself was developed by Kai Mainzer in the team of Russel McKenna.

Data collection for an explicit city or district is very time-consuming, and in many cases, limited by privacy protection issues. The *RE³ASON* model almost exclusively includes publicly available data from Open Street Map and Bing maps, augmented by location-specific data from the user [8]. The add-on represents an automated approach for the geographically anchored estimation of demand structures, rooftop PV potential as well as wind or biomass potential estimation [76]. In this context, the amount of available land, which is essential for some technologies such as PV modules, is given explicitly to the ESOM and its use is therefore restricted by land use constraints [75].

RE³ASON represents a deterministic bottom-up ESOM. "The standard objective function embodies the minimization of total discounted system costs, but it is also possible to minimize the (discounted) CO_2-emissions, as well as the net energy imports from outside of the region." The application of the ESOM supports a multi-year energy system optimization (e.g. from 2015 to 2030), whereby usually every 5th year is modeled explicitly and divided into 72-time slices (4 seasons, 2-day types, and 9-time slices within each day). The results are available for expansion planning and dispatch optimization. The mathematical formulation of the dynamic optimization problem is based on MIP. The model allows the interconnection of different districts in form of a graph. Thereby, underlying electricity and heating network topology is not modeled. Furthermore, large scale processes of power plants are not considered [74]. While the optimization problem is implemented with GAMS, the data retrieval is implemented with the high-level language JAVA [74]. The software capabilities are summarized in a video demonstration[4].

5. Characteristics review

Bearing in mind the elaborated *IMMES* characteristics as outlined in Table 1 and the features of the presented ESOMs, this research aims to identify fundamental modeling approaches and challenges to guide the future quantitative model development process.

A comparative synthesis of relevant system characteristics and of existing modeling approaches is outlined in Table 5. Even though the assessment is based on the presented and analyzed approaches, it is noted that the subjectivity of perception cannot be excluded.

5.1. Spatial anchoring and network topology

From the system perspective, inbound energy utilization is entering the system and outbound energy provision is exiting of the system. [37]. Along with this, multiply interconnected energy chains including *engineering components* as well as alternating *primary fuels* and *energy services* comprise the *network topology* [93]. Since the network topology is dependent on the *spatial anchoring*, a modular configuration is desirable. This is also important to manage structural changes and technological adoption [12].

From a spatial perspective, existing models for different inquiries are intended for various levels of aggregation. While inter alia, the model *DER-CAM* is most suitable for applications for a small- or household-scale [63] but has also been applied at the municipal level. In contrast, the *EnergyHub* concept and *deeco* have only been applied to a city- or district-scale [58, 60, 94]. As outlined in [67], *EnergyHub* has been, among others, used for the planning of an energy supply system for a village in Switzerland [95]. Furthermore, the *EnergyHub* concept has been used for providing different hub structures [89]. An alternative model called *EnergyPlan* also often addresses questions on a city-scale [96, 97].

To model different municipal layouts, the reviewed models show different approaches. Among others, *deeco*, *xeona*, *DER-CAM*, and *urbs* apply a similar directed graph theory approach to interconnect system processes [57, 64, 68]. Such a network of nodes and edges has also been suggested as a foundation in regard to a universal scheme for modeling ESOMs [93]. This modular approach allows to model different conditions at various levels by linking engineering processes through directed edges. In this context, the directed graph of multiple nodes demonstrate an arrangement from the technical but not necessarily spatial point of view.

[4] https://www.youtube.com/watch?v=TrSTwH1Rpjs&feature=youtu.be

Table 5: Comparison of reviewed *IMMES* optimization frameworks and models (● = incorporated/complex, ○ = nonexistent/simplified)

	Spatial anchorings	Network topologies	Commerical actors	Actor activities	Coordination strategy	Engineering components	Energy services	Primary fuels	Technical processes	Operation states	Smart meterings	Market principles	Environment issues
deeco	◑	●	◔	○	◔	●	◕	◑	◕	○	◔	◔	◔
xeona	◑	●	●	◑	◑	●	◑	◑	◑	◑	◔	◔	◔
DER-CAM	●	●	◑	◔	◔	◕	◕	◑	◕	◑	◑	◑	◔
EnergyHub	◑	●	◑	◔	◔	●	◕	◑	◑	◑	◑	◑	◔
urbs	◑	●	◔	○	◔	◕	◑	◑	◔	○	◑	◔	◔
KomMod	◕	◕	◑	◔	◑	◕	◑	◑	◑	○	○	◔	◑
MMESD	◑	◕	◔	○	◔	◕	◕	◑	◕	◑	◔	◔	◔
RE³ASON	●	◕	◔	○	◔	◑	◑	◑	◔	○	○	◔	◑

This idea is illustrated in Figure 3. In this context, the user is able to set up a decentralized municipal energy supply system with without dimensional boundaries by coupling the necessary processes. This municipal energy system is embedded into a broader energy system, mimicking a national energy reservoir which further supplies the municipal energy system with energy carriers [57]. *MMESD* uses a super-structure approach based on graph theory for design optimization [38]. The framework has been also used by [78]. A superstructure-free design approach has been presented by [98].

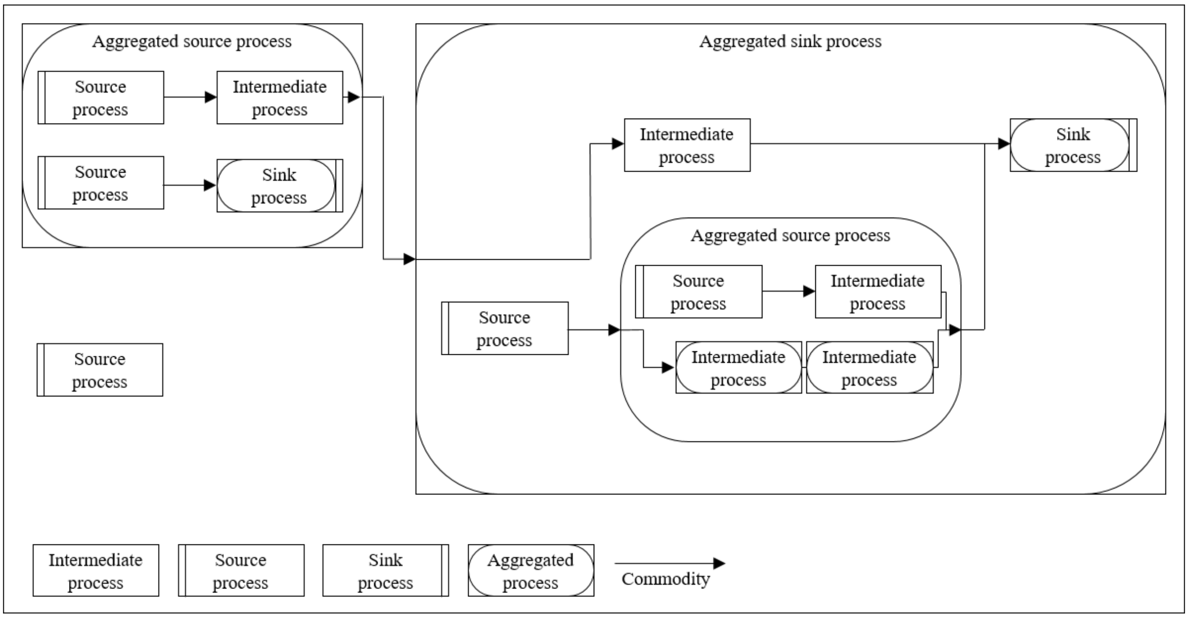

Figure 3: Energy system network based on graph theory (based on [93])

While the stated ESOMs only focus on a user-designed physical stock and flow resource network between engineering components [82], *xeona* adds a bilateral contract network between commercial actors [61].

A quite similar flexible approach is presented by Liu and Mancarella [99] on the basis of multi-vector interactions across networks. Three topological incidence matrices allow the consideration of the inter-network locations of the different conversion components. The relevant coupled electrical, heat and gas equations are solved simultaneously.

A hierarchical scheme based on four levels (system, zone, sub-zone and building type) is used in *KomMod* [34]. This approach allows the integration of spatial effects into the ESOM whilst at the same time enabling a satisfactory calculation performance for the optimization of the system. Especially in models with high time- and spatial-resolutions an optimization of the structure is a performance requiring. According to Eggers [34], it constitutes an ideal balance between the representation accuracy and mathematical complexity and thus is an advantage compared to graph networks.

An explicit spatial anchoring is considered within *RE*^{3}*ASON*. Based on Open Street Map and Bing maps, location-specificity planning is possible [8]. This automated approach allows a geographically anchored estimation of demand structures, rooftop PV potential as well as wind or biomass potential estimation with the help of public data [76]. This also allows the inclusion of the limited availability of private and public space as required by Koirala et al. [12].

5.2. Primary fuels and energy services

The application of multi- or poly-generation, not only requires an integrated view of transmission and distribution, but also the inclusion of different input and output energy sectors. Specific examples are listed by Mancarella [21].

The *multi-service perspective*, whereby sectors such as electricity, heat, cooling, chemicals and transport interact at their best results in the identification of the most efficient utilization of existing infrastructure. This demonstrates system benefits like reliability and flexibility synergy effects and optimization potential [36]. This integration of multiple sectors within ESOMs is also seen by Keirstead et al. [10] as a reasonable strategy.

In this sense, ESOMs must build on multiple energy vectors for the provision of integrated services. The deployment of a *multi-fuel perspective* and thus the integration of fossil fuels, but also renewable systems can be seen as an inevitable result thereof. Only by considering the input-output equivalent, an effective technical, economic and environmental assessment is possible [21]. This can also be summarized with the help of the four perspectives by Mancarella [21] in Figure 4.

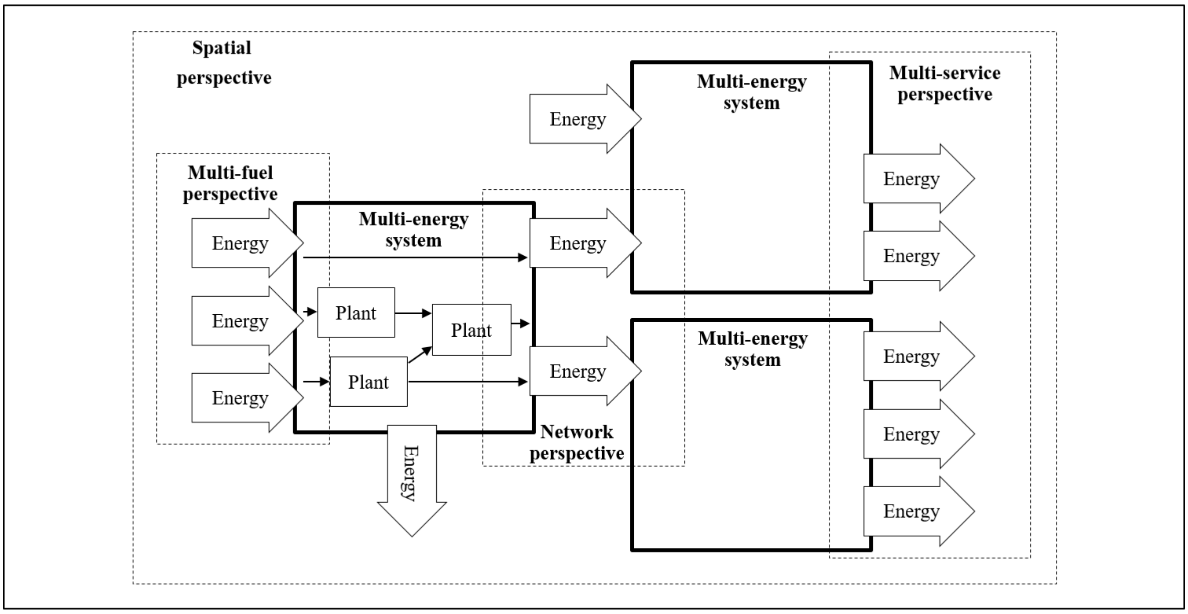

Figure 4: Four perspectives on multi-energy systems (based on [21])

All selected ESOMs include inputs of various fuels like natural gas, biomass, renewables, electricity, coal and support services like electricity and heat. The model *MMESD* also differentiates between air, saltwater, water (specifically hot and cold). In all cases, the input is always modeled without any technical properties. Emissions in the form of greenhouse gases might be incorporated as a commodity as well [68]. Mohammadi et al. [67] show that most of the publications related to *EnergyHub* only focus on the primary fuels like electricity, natural gas, and energy services as, for instance, electricity and heat. For successful strategies, attention must be paid to include a greater variety of options. Additionally, the transport sector is neglected in most of the models except of DER-CAM. The options have been summarized in a visionary, conceptual model [67].

While different output services are to the greatest possible extent represented by their power or energy content in the presented ESOMs [34, 68, 72], *EnergyHub* and *DER-CAM* model technical properties in terms of electricity with the help of power flow models. Additionally, *deeco* supports dependent intensities in terms of heat services. It treats, among others, "heat" as a differentiated commodity [57]. This means that the influence of store flows and store intensities are considered which might affect the input-output relationship. For example, the return temperature in a recirculating-media condensing boiler space-heating system can affect boiler conversion efficiency to the point where this influence warrants inclusion [82]. The effect on heat pumps is even more pronounced. *MMESD* uses a simplified method that considers e.g. heat and cold at different temperature levels [38]. This goes in line with the statements of Allegrini et al. [17]: there is an increasing need for accurate modeling of both thermal and pressure losses. The implementation of temperature differentiation is also mentioned as one outlook for the further development of the model *KomMod* [34]. Even though *urbs* allows the change of units, the ESOM does not support unit conversion, and so, all parameters must be scaled in regard to those units [69].

5.3. Engineering components and technical processes

The realization of the technical network requires the implementation of *engineering components* as energy grids, energy markets, generation facilities, storage systems and load profiles. From a functional perspective, the components realize *techno-economic processes* and thus represent physical, real-world characteristics. While *EnergyHub* focuses on conversion, storage, and transmission processes [36], *deeco* additionally lists demand, collector and import-export processes [57, 59]. Similar accounts for *urbs* [68].

Within *deeco*, around 40 pre-defined modules are described, distinguishable into demand processes (e.g. room temperature), transformation processes (e.g. co-generation unit), networking or import-export processes (e.g. district heating), storage (e.g. hot water tank) and collector processes (e.g. solar collectors). All the processes are defined by its thermodynamic limits, and consider incoming energy- or mass-streams, conversion or storage efficiencies as well as surrounding conditions like temperature or solar radiation as described in Bruckner [59].

Even though the other ESOMs show a wide range of technologies, such a high-resolution modeling in terms of component constraints is only partially available. *DER-CAM* includes linear current squared for loss calculations as well as linear voltage constraints in terms of the power flow model. Furthermore, the demand side is modeled in high resolution. According to a review by Mendes et al., start-up or other ramping constraints have not been considered [15]. The model *MMESD* [72] incorporates various part-load efficiencies based on equations by Yokoyama et al. [100] and also applies a detailed approach of turbine inlet air cooling. *KomMod* attaches importance to ramp rates. Eggers [34] concludes that future research of *KomMod* must be based on MIP in order to incorporate partial load behavior. A point of criticism in terms of the *EnergyHub* is the fact that generation technologies are only partially modeled based on constant efficiencies without considering the internal structure [67].

Furthermore, the NLP of *EnergyHub* raises doubts concerning its mathematical tractability [21]. Almassalkhi and Hiskens [88] treat this issue by linearizing the model via the introduction of dispatch factors and a binary expansion of the storage charge and discharge flows along with assuming constant conversion and storage efficiencies. This allows for a vast efficiency increases in the process of solving complex multi energy system problems, but the LP of the physical behavior of networks might also lead to considerable errors [21]. However, this problem is not unique to *EnergyHub* but applies to all ESOMs. Future extensions of the initial *EnergyHub* concept propose more accurate mathematical formulations including various process constraints [89, 101]. Nonetheless, Mohammadi et al. [67] criticize that e.g. CHP processes are frequently modeled as constant efficiencies without considering the internal structures. This falls in line with the statements of Thiem et al. [38]. *urbs* only shows quite simplified constraints for the different processes. However, it is applied in connection with a model called *rivus*, which includes quite sophisticated grid constraints [68].

Bruckner et al. [25] state that the resolution of modeling influences the complexity as well as the representation. Pfenninger et al. [26] even go a step further: due to simplification, stylized models might deliver the wrong conclusion. However, it seems to be obvious that ESOMs, focusing on operation optimization might incorporate more detailed constraints according to the *deeco* modeling framework. The challenges of high computational costs can be readily reduced by applying a dynamic optimization scheme based on a rolling horizon. In this context, a comprehensive *modeling approach* for wind turbines as well as photovoltaic (PV) plants is outlined in [59]. A CHP plant based on exergy and energy balances including a few typical plant characteristics for different operating conditions is outlined in [102]. Additional constraints for ramping limits and minimum up and down times are modeled in [103]. An advanced representation of demand response process constraints is outlined in [104].

5.4. Operating status and smart metering

The *operating status* represents a service mode and individual processes. This kind of physical property is closely linked with the process flow. In this sense, e.g. the dynamics of start-up modeling as well as of types of wear modeling of different processes might be integrated. *MMESD* provides binary variables for the online and offline behavior of individual engineering components. On the one hand, this allows for minimal working conditions to be considered. On the other hand, at every start-up or shut-down of a power plant, the variable can also be used for the calculation of additional labor costs.

Additionally, Silbernagl et al. [105] present a mathematical framework for integrating the temperature of thermal units and thus the off-time dependent start-up costs [105]. This formulation allows for the inclusion or reheating process costs of an engineering component, where the ramp-up depends on the off-time before a start-up.

Innovative future businesses might also place greater weight on a capacity charge instead of an energy rate. While today only commercial or industrial clients constitute smart metered consumers, it is expected that, in the future, residential clients might also be involved in smart meter technologies. Thus, the application of *smart metering* is important for strategic assessment. While different ESOMs, such as *deeco*, provide the possibility to measure the maximum power consumption of individual technologies, the review has not shown any literature which encompasses an innovative concept including different power connection points at a specific site or household.

5.5. Commercial actors and actor activities

At the same time, existing relationships between provision and utilization of energy services are necessary for the representation of actor-related social and economic activities along the energy chain. The creation of energy policy over a certain municipal area is a complicated exercise involving several private, system issues and interests [12]. *Commercial actors* along the energy value chain might assess challenges and opportunities from different perspectives and various interest criteria since every single consumer and operator has a differing technology component, process-mediated relationship [25]. Common actors are households or communities, energy producers, energy suppliers, service providers, aggregators, balance responsible parties, distribution system operator as well as government, policy-makers and regulators [12]. These actors are inter-dependent in the realization of their goals [12]. Existing ESOMs ignore the roles different actors play in an existing system architecture and the resulting impact they might have [12]. This lack of decision makers' heterogeneity is also seen as a major omission by DeCarolis et al. [11]. Individual actors who can be consumer groups, prosumer groups, business units and public institutions must be modeled separately, just as the spatially distributed load, storage, and generation systems. As a result of unbundling, the business units of an energy utility should also be individually modeled as sketched in Figure 5 to cover the different goals.

The focus on *actor activities* also allows the inclusion of varying degrees of adoption behavior within the community. In this context, technical behavior no longer requires to be in the presence of one internal decision maker as existent in most of the presented models. User acceptance of renewable systems is quite heterogeneous and has to be considered [8]. Additionally, in a free market, multi-party cooperation is present. Actors hold bilateral contracts between each other that handle business transactions. An integrated view requires the inclusion of individual actor decision-making as well as commercial association networks. This idea of a multi-level entity-oriented optimization approach has already been presented by the authors of the *xeona* model [61, 62]. The model concept is illustrated in Figure 6.

xeona includes approaches to represent price formations and commercial relationships, both based on agent entities of appropriate sophistication. Applied research with similar purposes including multi-node optimization without aggregation by incorporating various buildings of a site as presented in [78, 106, 107] is based on *EnergyHub*. Nazar and Haghifam [87] use a model for optimal electric distribution system expansion planning, differentiating between utility- and customer-owned hubs. In this context, the *EnergyHub* is equipped with an initial entity-oriented approach. Orehounig et al. [89] further developed the *EnergyHub* model to evaluate the integration of distributed energy systems amongst various consumers and producers at a neighborhood-scale. Doing this, various variable loads, systems, and energy sources of multiple buildings

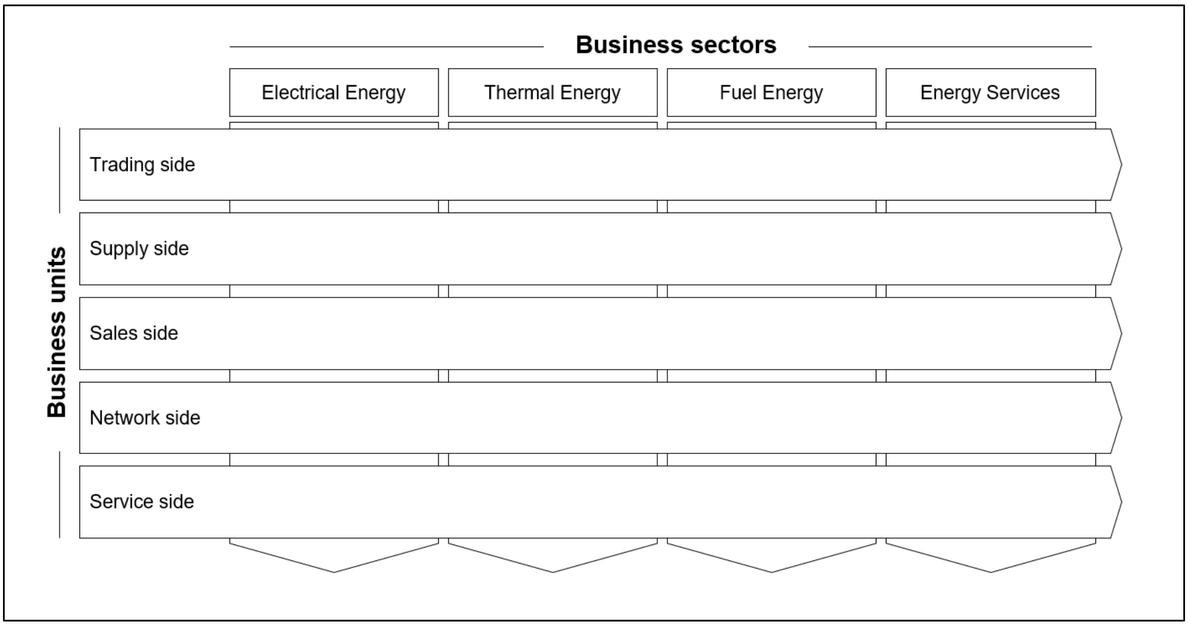

Figure 5: Business view of energy utilities

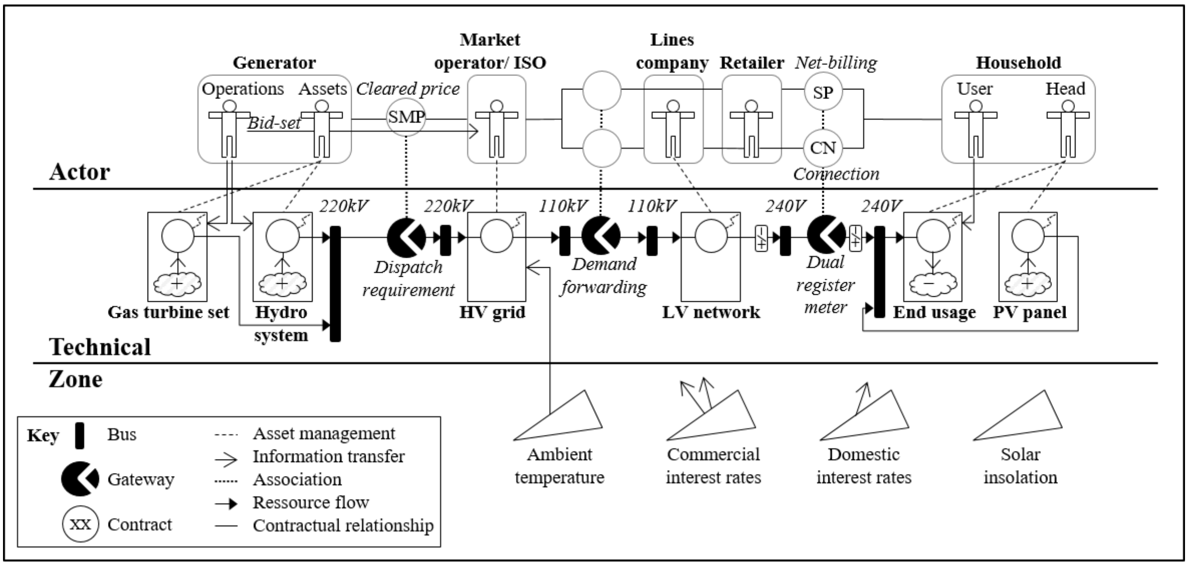

Figure 6: Multi-level entity modeling approach (based on [62])

are considered. The initial potential for a structural division regarding actors might also be seen in the hierarchical approach of *KomMod* [34].

5.6. Coordination actions and optimization issues

For successful performance of ESOMs, there is a need for a management framework that can manage the various components of the system optimally [67]. The issues of coordination and split-incentives especially arise if costs and benefits cannot be assigned to the same commercial actor [12]. Thus, the entity-oriented approach enables not only the inclusion of heterogeneous mindsets but might also result in a different cost-optimal allocation. In this context, Figure 7 suggests a broad structural concept to support the inclusion of commercial actors. In contrast to Figure 6, a coordination layer is added. This coordination layer serves as a management framework to *coordinate actions* and contains operational coordination mechanisms [25].

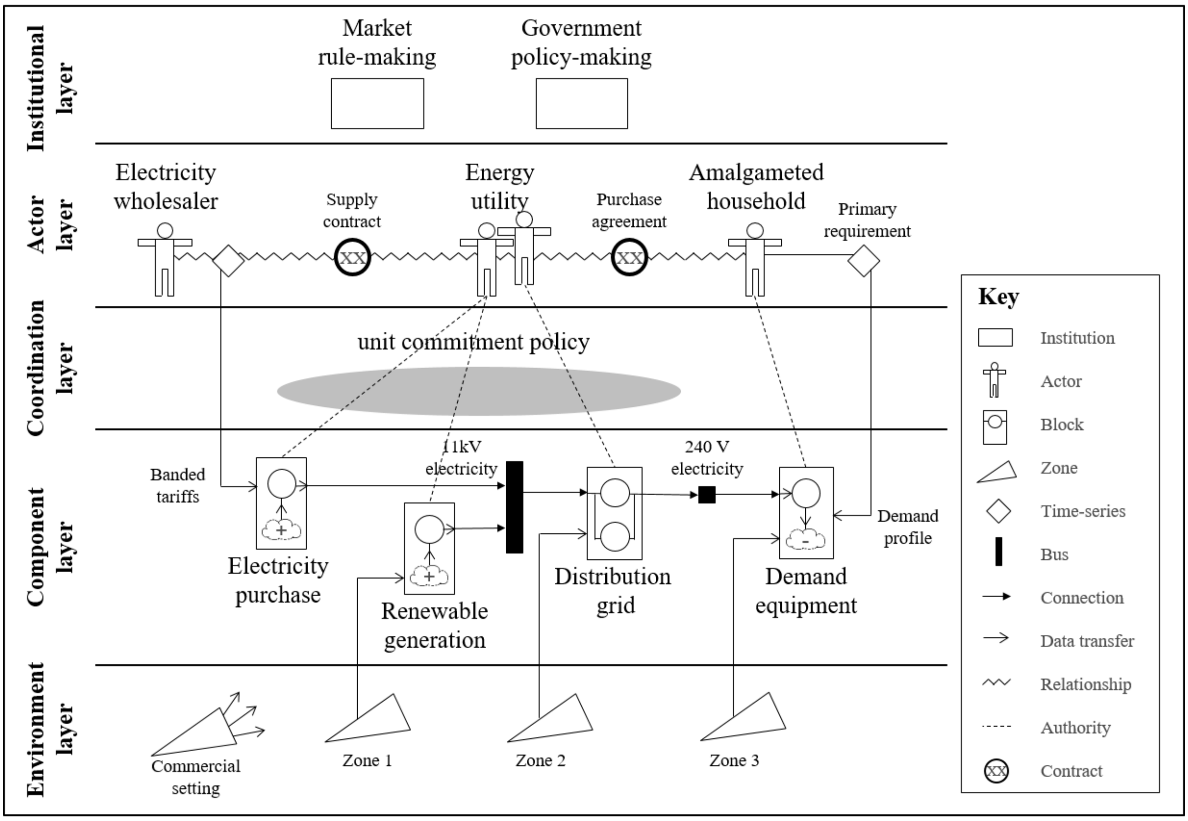

Figure 7: Five-layer entity-oriented model concept (based on [25])

An innovative framework design allows for the merger of technical and commercial aspects as called for by [21] and facilitates allocations when costs and benefits do not boil down to the same actor as posed by [12]. First, new coordination frameworks should be modular in order to account for the different goals of commercial actors. Moreover, based on contractual relationships multi-participant domestic and commercial behavior should be incorporated. As illustrated in Figure 8, the system owner, system operator and end-consumer are central to decentralized PV projects, as their interrelation determines the legal framework to apply. They are surrounded by other entities that complement the internal project structure.

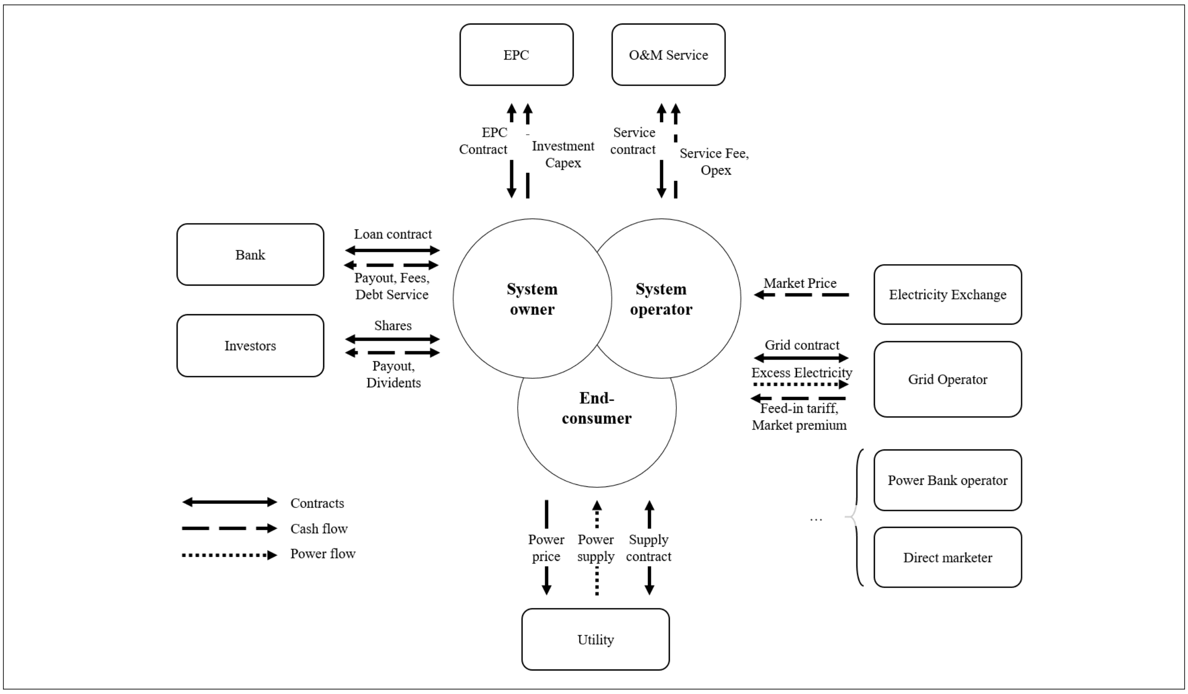

Figure 8: Structure of decentralized technology project (based on [108])

5.7. Market principles and environment conditions

The development and assessment of IMMES also require the integration of advanced *market principles*. Only by using comprehensive modeling of the complexity of the system interactions and by capturing the main aspects of the market perspective, relevant synergies and the challenges can be determined [21]. Noticeable concepts are according to Mancarella [21] and Koirala et al. [12] are multi-energy conversion, aggregation and system service modeling, community microgrids control as well as virtual power plant coordination and balancing service provision. In this research, major concepts might be classified as *decentralization*, *flexibilization*, and *virtualization*. Different associated constructs of ESOMs are summarized in Figure 9 [109–111].

Even though all presented ESOMs are able to map constructs like power-to-heat or power-to-gas due to the multi-conversion approach, according to Mohammadi et al. [67] potential is squandered. An analysis of publications related to *EnergyHub* shows that ESOMs mostly focus on standardized input, such as electricity and natural gas ,along with applications, like CHP, and on heating and electricity loads. To find sustainable strategies, attention needs to be paid to the variety of options also summarized in a vision statement [67].

Investigations into policy measures, or business cases, by taking reserve market offerings and corresponding reserve pooling into account are hardly to be found in the literature. At the same time, Koirala et al. [12] state that the design of prices for services based on markets such as energy markets, capacity markets and balancing markets are crucial for a sustainable evaluation of IMMES, especially because of the competition between centralized and decentralized resources. Gamarra and Guerrero [112] likewise insist that ancillary services like voltage support, peak load reduction, and spinning reserve provision need to be included. Additionally, according to Keles et al. [8] the availability of flexibility on the consumption side is often neglected as well as the inflexibility on the production side. The load shift potential has only been considered in a simplified way by electricity focused ESOMs [8]. Further multi-sectoral implementation requires additional temporally coupled variables and a high temporal resolution. The ESOM *DER-CAM* offers different load management

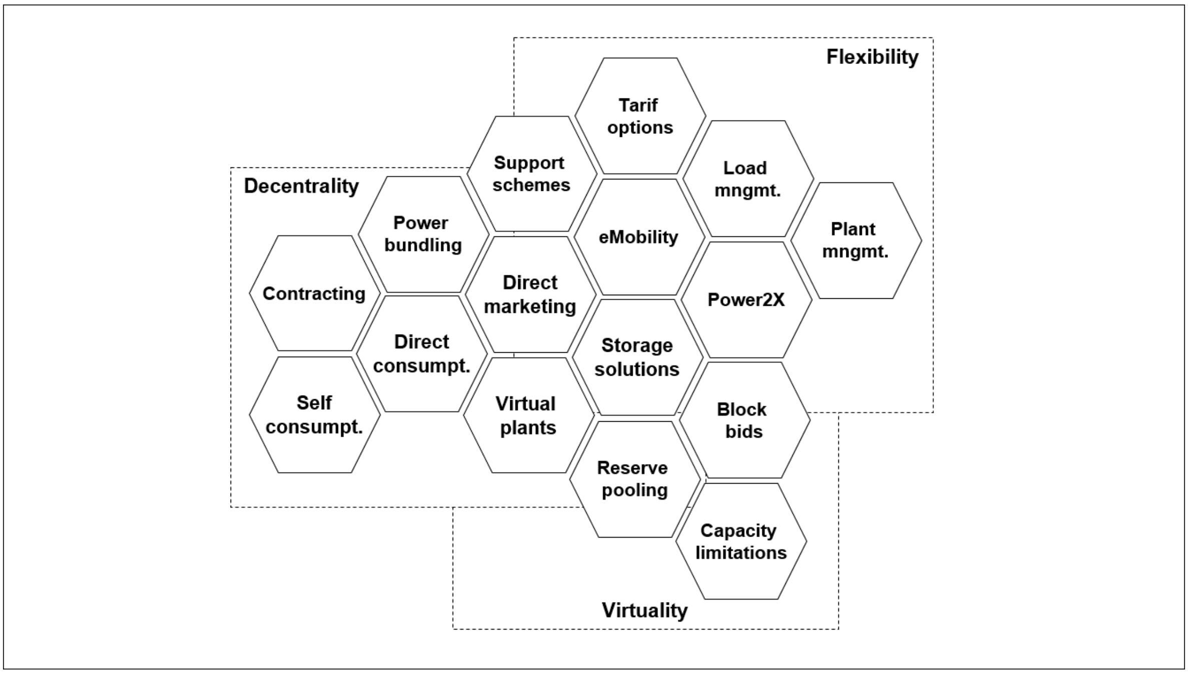

Figure 9: Overview of important market concepts and model constructs

strategies for demand response, load shifting and load shedding. This is supported by a tariff database. Passive technologies are provided as well. The latter also applies for *deeco*.

Even though e.g. *urbs* [69] focuses on the integration of storage units, innovative constructs like community energy storage system as optimized by [89] hardly play any role. Further ESOMs need to pay more attention to the development of storage systems [67]. The same applies to other important business constructs at the municipal level: electric mobility, direct consumption, direct marketing and contracting models. For a future strategy, modeling and assessment of these constructs need to be standardized.

There is also a trend towards broader spectrum tools that attempt to optimize many aspects of the municipal system at once [17]. According to Koirala et al. [12], a bottom-up solution, which can capture both the benefits of renewable energy systems and the public welfare, is still missing. Most of the existing ESOMs target individual technology issues related to implementation, but often lack a comprehensive and integrated approach for municipal energy systems. Specifically, *environmental conditions* are assessed only conditionally. Thus, one challenge of IMMES is to design ESOMs that capture some of the linkages between energy systems and aspects of municipal policy [10].

The predecessor model of *urbs* included three simulation models for predicting municipal development, energy demand and environmental effects [68]. Even though a simplified consideration is possible, presented ESOMs do not account for feedbacks between the macro-economy and energy systems as stated in [11]. From the perspective of the coordination scheme and the local policy, this might also be important when determining the best system structure and operation.

Additionally, the integration of renewable processes requires weather-driven or micro-climate model approaches [8] as initially shown in *KomMod* [34]. Looking on the consumption side, load profiles are also heavily dependent on regional patterns and the competition for the use of zones, areas, and land [8]. The necessity of detailed land-use planning at the municipal level is also identified by Huang et al. [13]. In this context, a further evolution and integration of automatic and spatial approaches as shown in RE^3ASON is important. Thereby, one possible option could be to raster digital elevation models in which every cell has an elevation value [17]. This allows analysis to be performed on spatiality data. For example, some models use elevation data to calculate the wind conditions for potential new wind turbines. A geographical information system (GIS) integration is also seen as one key modeling aspect by different researchers [17, 112]. Thereby, *DER-CAM* provides an interactive interface with GIS front-end. A rather simple constraint approach of competition for land has been incorporated by *KomMod* [34].

6. Research prospect

Selected ESOMs already cover a wide range of required system characteristics. Different implementation approaches define an excellent foundation for further model development. At the same time, none of the assessed models address all the requirements as summarized in Table 5. In view of the results of the analysis conducted in this research, the following key issues need to be considered for an advanced mapping of an IMMES: *integrated view*, *business modeling*, *spatial planning*, *complexity level*, *temporal resolution* and *uncertainty analysis*. Individual issues are in line with similar reviews [8, 12, 25, 26]. Prospect ESOMs need to systematically tackle the challenges on the basis of novel mathematical concepts and approaches frameworks. Based on the analysis of existing approaches, this research paper also derives initial solutions.

6.1. Integrated view

The analyzed ESOMs scarcely support integrated optimization options as shown by a comparative synthesis of relevant system characteristics. Specifically, the model analysis is lacking regarding the role different market actors play in existing system architecture and the resulting impact they might have [12]. *Commercial actors* along the energy value chain might assess challenges and opportunities from different actor perspectives and various interest criteria since every single consumer and operator has a differing technology-mediated relationship [25]. Thus, individual households, neighborhood communities, organizational units and market institutions represent major system drivers [26], so that an integrated view of supply and demand side is necessary for optimal investigation of the interaction at the municipal level [113]. The coordination design should merge the technical and commercial aspects as called for by [21] and facilitates the allocations when costs and benefits do not boil down to the same actor as posed by [12].

One approach to solving this problem and to allow an actor-oriented optimization can be seen in terms of a multi-graph implementation. In this context, the market actors are modeled on one layer and the engineering components on another layer. While the conjunction of the components results in a resource flow network, the conjunction of the actors demonstrates the contractual relationships. The connections between actors and components demonstrate the sovereignty and combines the networks. The sketched multi-graph approach expands the proven network approach as outlined in [93].

6.2. Business modeling

The presented *market principles* pertain to decentralization, flexibilization, and virtualization are hardly incorporated or applied in different ESOMs. However, they are important in fully assessing decentralized business model synergy and competition effects at the municipal level, especially in comparison with centralized business models [12]. In this sense, at least constructs for ancillary services like voltage support, peak load reduction, and spinning reserve provision need to be included in addition to spot market trading [112].

A multi-stage approach might enable the integration of a more realistic reserve market assessment. While in the first optimization stage the load-frequency reserve is determined, in the second stage the balancing energy is retrieved by taking into account the results of the first stage. Additionally, new modeling constraints regarding reserve pooling, block bids as well as minimum and maximum restrictions for biding are required in terms of a holistic market framework. In this context, the market components need to be modeled as high-resolution processes just like technology processes.

6.3. Spatial planning

To represent specific patterns of an IMMES, *spatial anchoring* is gaining significance. In this context, a further evolution and integration of the automatic and spatial approach based on GIS are useful [8, 34]. On this basis, higher coverage of *environmental conditions* as detailed land-use planning is valuable [13]. Moreover, at the municipal level, schemes of energy from waste and biomass should be identified [12].

A future approach could be seen in multi-node systems from a technical but also spatial point of view. In this context, a GIS based automated data input approach as applied by [76] could support the spatial arrangement.

6.4. Complexity level

The consideration of various levels of complexity can lead to dramatic changes in optimization results since emergent effects are driven by the interaction between their constituent parts [26]. Since ESOMs related to representing an IMMES are aimed at helping to understand a real-world system, high-resolution process modeling is recommended as outlined in [25]. In this context, MIP might be useful for mathematical formulation of detailed *technical processes* including *operational states*. ESOMs should include, for example efficiency, capacity, and cost/impact creation. Performance dependence can derive from external conditions, process attributes set by neighboring plants and internal state information to account for inventory and operational history. Higher topological resolution refers to network detail but allows the use of component aggregation where appropriate. At the same time, thermodynamic processes, including electro-technical principles are necessary [17, 25]. Additionally, for successful identification of synergies, more attention needs to be paid to a greater variety of sectors [67].

6.5. Temporal resolution

This along with a larger temporal disaggregation is required to retain important temporal cross-correlations within time-series datasets [25]. Real-time series are necessary since models which do not consider the full variability of fluctuations that might overestimate the degree of demand load coverage by highly variable renewable energy systems [26]. For instance, Pfenninger et al. [26] imply that recent research shows that intuitive effects such as the financial attractiveness of rooftop PV due to its smoothing of afternoon demand peaks are not as simple as they seem and should be investigated using high-resolution models.

In cases that *high-resolution coverage modeling* reaches its boundaries of being solved in a reasonable time [26], more-scale models as shown by Thiem et al. [38] might be applied. The planning and operational step are divided in regard to different time scales with different levels of detail as suggested by Pfenninger et al. [26].

6.6. Uncertainty analysis

The consideration of additional technical infrastructure and economic framework conditions not only requires new methods, but also reliable data-sets. Thus, data uncertainty and data collection as posed by Keirstead et al. [10] must be addressed since data quality is important [8].

System users should be to perform a sensitivity-based ”what-if” analysis with assistance provided by an energy system visualization tool, a sensitivity management tool, and a schematic representation of the comparison of results. Automated analysis of the municipal system data by using open geodata and image recognition techniques allow a good starting point for the analysis [76]. Besides, a *master data management* including a time series analysis to support the scenario generation is useful in providing relevant data in order to make data collection, organization and sharing easier as suggested by [10].

7. Concluding remarks

Municipal energy system analysis is of growing interest. In recent years there has been a deluge of models with various operational purposes and mathematical constructs. At the same time, there are only partial reviews that help to compare different concepts and approaches to apply them as a fundamental basis for the model design. Moreover, necessary requirements for municipal system analysis are hardly ever used to guide the development.

First, the term IMMES has been defined. For a sufficient mapping of the system complexities, associated characteristics are to be fulfilled. Subsequently, several bottom-up ESOMs have been presented and investigated. Even though existing ESOMs already cover the characteristics with some detail, none of the analyzed models includes all characteristics regarding a complex approach. Future ESOMs must cover several issues raised, like: integrated view, business modeling, coordination effects, spatial planning, co-modal optimization, complexity level, temporal resolution and uncertainty analysis.

Future investigations into ways that improve the robust modeling of ESOMS will include the analysis of further concepts and approaches, and more detailed theoretical overviews of modeling fundamentals. Besides, in order to complement this review about decision support systems at the municipal level, a similar analyzes of simulation models need to be conducted.

Declarations of interest

There are no competing interests.

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Chapter 3

Business Model Analysis

*Legal Framework of Decentralized Energy Business Models in Germany: Challenges and Opportunities for Municipal Utilities**

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Legal Framework of Decentralized Energy Business Models in Germany: Challenges and Opportunities for Municipal Utilities

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Abstract

Feasible and profitable business models to better integrate and harness decentrally generated renewable energy are expected to constitute a key element for the energy transition in Germany. Until now, generated electricity of decentralized systems is to the largest extent only used by the property owner directly or fed into the public grid. To make better use of the generated electricity, it is necessary to find business models that provide an opportunity for different market actors, such as municipal utilities and residential prosumers. Due to the importance, yet low-anticipated monetary potential of such solutions, the legislator encourages their implementation by exemption of statutory fees, levies and taxes as well as by offering public remunerations, premiums and compensations in some cases. Capitalizing on these benefits, however, is only feasible under compliance with the legal requirements. In the light of the considerations above, this work states and analyzes the legal and regulatory framework of different business models within the German energy landscape. The major aim is to identify opportunities and challenges for the implementation of the business models *self-consumption*, *direct consumption*, *direct marketing*, *demand response*, *community electricity storage* and *net metering* at the municipal level. The findings show that the profitability of various decentralized on-site business models depends primarily on the current statutory cost exemptions and compensations. At the same time, the regulation is characterized by unsystematic specific exemptions which leads to uncertainty regarding long-term planning. Additionally, although not directly privileged by the existing legal framework, municipal utilities are better suited to handle the legal burdens due to their experience and their administrative infrastructure.

Keywords: On-site business models, Decentralized energy systems, German energy law, Statutory electricity cost components, Strategic opportunities and challenges for regional development, Profitability and feasibility of business models

1. Introductory Remarks

In the course of the energy transition, the German energy policy landscape is in constant flux. Particularly, the expansion of electricity generation through decentralized renewable systems is accompanied by increasingly complex and constantly changing legal frameworks. Related laws, regulations and ordinances are not infrequently redesigned within a few years or even months. At the same time, feasible and profitable business models for a better integration and harnessing of decentrally generated electricity are expected to constitute a key element for the energy turnaround in Germany [1]. Until now, generated electricity of decentralized systems is to the largest extent only used by the property owner directly or fed into the public grid. To make

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better use of on-site electricity and to harness local potential, it is necessary to find business models that provide an opportunity for different market actors such as municipal utilities and residential prosumers [2].

Currently, energy system innovations related to decentralized on-site generation, storing and consumption as complementary solutions to the conventional grid consumption (GC) are of major interest for academia as well as practitioners [2]. Consequently, this research focuses on the assessment of the much discussed business models of self-consumption (SC), direct consumption (DC), regional direct marketing (DM), demand response (DR), net metering (NM) and community electricity storage (CS). Due to the expected strategic importance for the future energy system as well as the increasing dominance of the technology, photovoltaic (PV)-related models make up the core of the cases.

Due to the systemic relevance of such solutions, and in spite of their still limited monetary potential, the legislator encourages their implementation by exemption of statutory fees, levies and taxes as well as by offering public remunerations, premiums and compensations. An exploitation is, however, only feasible under compliance with the legal requirements. In light of the above considerations, this work analyzes the legal and regulatory framework of the German energy landscape in order to judge legal conditions of the selected business models. The aim of this paper is to identify opportunities and challenges for business model implementation at the municipal level. For a systematic approach, the following research questions are used as a guideline:

- What laws and regulations shape the German energy legal landscape and what statutory electricity costs and compensations are relevant?
- What legal characteristics as well as statutory requirements specify on-site business models within the German energy law?
- What implications can be derived in the course of a feasibility and profitability assessment of the selected business models?

To answer the research questions raised, this work is divided into five sections. Following the motivation presented in section 1, section 2 lays out the legal foundations of the German energy landscape. Special attention is given to the components of the electricity price and remuneration possibilities. Additionally, fundamental roles in terms of legal entities and market actors are introduced. The main body in section 3 analyzes the mentioned business models in the context of the energy-related legislation of Germany. In this context, the business models are sketched with respect to design, structure and actors. This forms the basis for the subsequent legal analysis regarding characteristics, obligations and specifics. In section 4, the elaborated legal conditions are discussed with a particular focus on feasibility and profitability aspects in order to state current and future opportunities as well as challenges. Finally, section 5 concludes with a recapitulation of the main findings, followed by a presentation of limitations and recommendations for further research.

2. Legal Foundation

The German energy policy landscape is in constant flux. At the same time, the legal and regulatory frame is increasingly important for the feasibility and profitability of various business models in the energy sector. This is particularly true for on-site electricity models. According to [2] on-site electricity (Vor-Ort Strom) comprises the generation, storing and consumption of renewable electricity with and without usage of the public grid at distribution level. Decisive characteristics are the spatial context and the subsidiary arrangement. Relevant specifications can be found in various acts, ordinances and guidelines. For this reason, this section will give an overview of current German energy laws relevant for electricity price components, which the analysis of the business models will be based upon. Following the outline of these relevant price components (i.e. fees, levies and taxes), remunerations, premiums and revenues will be sketched. Finally, decisive roles in the energy sector are introduced, differentiating between legal entities and market actors.

2.1. German Energy Law

The *German Energy Industry Act (Energiewirtschaftsgesetz; EnWG)* contains fundamental regulations about the rights and duties of energy utility companies. The last amendment was ratified in December 2016. The main goals of the EnWG are to ensure a reliable, cost-effective, consumer-friendly and environmentally-friendly supply of power and gas (§ 1 (1) EnWG) as well as a fair and unrestricted competition between the energy utility companies (§ 1 (2) EnWG). Furthermore, the European community law needs to be realized and carried out (§ 1 (3) EnWG). Beyond that, the EnWG states that the distribution of electricity requires a notification of the regulatory authority by the operator prior to the start of operations according to § 5 EnWG but does not require a permit as necessary by the operation of a power grid as stated in § 4 EnWG.

The EnWG serves as a basis for numerous legal ordinances. Of particular relevance for this paper are the *Electricity Grid Charges Ordinance (Stromnetzentgeltverordnung; StromNEV)* from December 2016 and the *Ordinance Regulating Concession Fees for Electricity and Gas (Konzessionsabgabenverordnung; KAV)* from November 2016. The StromNEV regulates how the electricity grid charges for accessing the transmission and distribution grids are determined, including the fees for decentral feed-in (§ 1 StromNEV), while the KAV comprises regulations for the admissibility and determination of concession fees from the energy utility companies to municipalities and districts (§ 1 KAV). Further relevant ordinances are the *Ordinance on Agreements Concerning Interruptible Loads (Verordnung zu abschaltbaren Lasten; AbLaV)* and the *Electricity Grid Access Ordinance (Stromnetzzugangsverordnung; StromNZV)*.

The goal of the *Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz; EEG)* is to further develop and extend regenerative energies, in order to spare fossil resources and to promote renewable development in Germany (§ 1 (1) EEG). The last amendment is from January 2017. Central elements of the EEG are the remuneration and market integration of EEG electrical energy (hydropower, wind power, solar power, geothermal power, energy from biomass), as well as cost redistribution utilizing the EEG levy. More detailed regulation of this mechanism can be found in the *Renewable Energy Ordinance (Erneuerbare-Energien-Verordnung; EEV)*, or the *Equalisation Scheme Ordinance (Ausgleichsmechnismusverordnung; AusglMechV)*.

Similar to the EEG is the *Combined Heat and Power Act (Kraft-Wärme-Kopplungs-gesetz; KWKG)*. Operators of combined heat and power plants can be supported through a feed-in tariff. The KWKG further regulates surcharges for the promotion of heating and cooling networks and storage systems. The latest amendments were made in December 2016.

The taxation of electrical energy in Germany is regulated by the *Electricity Tax Act (Stromsteuergesetz; StromStG)* and the *Energy Tax Act (Energiesteuergesetz; EnergieStG)* as well as the corresponding *Energy Tax Ordinance (Stromsteuerverordnung; StromStV)*. The latest rework was done in December 2016. Within these, the regulations regarding tax exemptions and reductions are regulated.

2.2. Fees, Levies and Taxes

The electricity price comprises three major components. First, the cost for procurement and sales as well as the sales-related utility margin regarding the final consumer, which represent the competitive part of the electricity price. Second, the federally ordered components of the electricity price, and finally the cost for the utilization of the electricity grids. The average total costs of grid electricity as of February 2017 amounts to 29.16 ct/kWh for a residential household with a yearly energy consumption of 3500 kWh as outlined in Table 1 [3]. The trend shows the development of the last two years [3, 4]. In this context, legally prescribed components currently account for around 55 % of the electricity price. A skillful exploitation of statutory exemption of these components might affect the profitability of various on-site business models.

The *grid-usage fees (Netznutzungentgelte)* are paid to the grid operators. Their amount may vary depending on the used grid voltage level as well as special regional characteristics. However, they are regulated through an authorization procedure by the Federal Network Agency (Bundesnetzagentur) according to § 23a EnWG.

Under certain circumstances, electricity intense enterprises can apply for relief in the form of an individual grid-usage fee, according to § 19 (2) of the StromNEV levy. The losses resulting from these reduced fees have to be refunded to the distribution system operators downstream by the Transmission System Operators

Table 1: Price components and average values of residential electricity rates of 2017 [3]

Price component	Value [ct/kWh]	Proportion [%]	Trend [↑ | ↓]
Energy generation	5.63	19.30	↓
Grid fees	7.48	25.65	↑
Concession fees	1.66	5.69	→
EEG levy	6.88	23.59	↑
Cogeneration levy	0.438	1.50	↑
§ 19StromNEV levy	0.388	1.33	↑
Offshore liability levy	-0.028	-0.10	↑
Deferrable loads levy	0.006	0.02	→
Electricity tax	2.05	7.03	→
Value added tax	4.66	15.99	→
	29.164	100	↑

(TSOs). These costs are distributed proportionally to the end users in the form of a *§ 19 StromNEV levy (§ 19 StromNEV-Umlage)* on the network charge.

The *concession fees (Konzessionsabgaben)* are paid by the utility companies to the municipality for using municipal paths. This fee is regulated by § 48 EnWG, in conjunction with the KAV. The extent of the fee is limited by § 2 KAV, and varies locally between 1.32 and 2.39 ct/kWh [3].

The *EEG levy (EEG Umlage)* is used to finance the cost incurred by the four TSOs by accepting and reimbursing the electric energy generated from renewable sources, through redistributing the difference cost to the non-privileged end users. Thus, this levy is the financial basis for the promotion of renewable energies, but also constitutes the highest levy of the electricity price.

Under certain circumstances, the operators of heat-and-power co-generation facilities are entitled to a statutory promotion for their feed-in energy. Through the *co-generation levy (KWK Umlage)*, as regulated in the KWKG, the cost caused by this are, in analogy to the EEG levy, transferred to the end user.

The *offshore liability levy (Offshore-Haftungsumlage)* according to § 17f EnWG serves to finance liability cases for potential delays and disruptions in grid connection of offshore wind plants. Thus, the affected network operators can assert the cost incurred by compensation payments in the form of a premium on the network charges towards the end users. The levy is limited to 0.25 ct/kWh (§ 17 f (5) EnWG).

The *levy of deferrable loads (Umlage für abschaltbare Lasten)* according to § 18 AbLaV serves to cover the cost of disengageable loads. In exchange for reducing their electricity demand or disengaging from the grid on instruction for securing grid stability, operators can receive a remuneration by the TSOs. These expenses are passed on to the end users via this levy.

The *electricity tax (Stromsteuer)* is raised for the usage of electric energy. It arises with the extraction of electrical energy from the grid as well as with self-consumption of electricity according to § 5 (1) StromStG. The major contribution of the electricity tax is used to subsidize the German pension fund [5].

The *value added tax (Umsatzsteuer)* for electricity amounts to 19 % and is raised on all price components.

2.3. Remunerations, Premiums and Compensations

There are also different remunerations, premiums and compensations for plant operators in order to get reimbursed for self generated electricity. According to § 19 EEG, two statutory support opportunities are provided: The *feed-in remuneration* (§ 21 EEG) and the *market premium* (§ 20 EEG). Additionally, operators can obtain further *compensations by balancing market participation* under certain conditions. Thus, an optimal exploitation of the following described components might affect the profitability of different business models.

The guaranteed *feed-in remuneration (Einspeisevergütung)* according to § 21 EEG offers a constant market premium for the commissioning year as well as the following 20 calendar years (§ 25 EEG), depending on the time of installation, the type and composition of the generation plant and the installed power, and thus offers a large degree of security for planning and investment. According to § 21 (1) No. 1 EEG, this is only granted up to an installed power of 100 kW. Independent of size however, all facilities can be granted a reduced feed-in tariff (Ausfallvergütung) of 20 % in exceptional cases, for at most three consecutive months and at most six month within a calendar year (§ 21 (1) No. 2 EEG). With regards to the type of plant, § 48 EEG primarily differentiates between solar plants installed on buildings and free standing ones, and requires zoning regulations for utilization of the remuneration. Current remuneration rates as of July 2017 for buildings in accordance with § 48 (2) EEG are 12.21 ct/kWh for PV-installations up to 10 kWp, 11.87 ct/kWh for PV-installations up to 40 kWp and 10.60 ct/kWh for PV-installations up to 100 kWp [6]. If the construction of the new PV-installations takes place within a fixed corridor according to § 49 (1) EEG, a basic digression of 0.5 % per month comes into effect, which only influences the amount of fixed EEG remuneration at the time of installation. If however this construction corridor is undershot or exceeded, the digression will be raised or reduced accordingly. The fixed feed-in remuneration for PV-installations is removed when an installed total power of 52 GW in Germany is reached (§ 49 (5) EEG 2017). However, the law requires that the government submits a proposal for a new form of implementation before reaching this goal (§ 49 (6) EEG).

The EEG levy is used to cover all cost incurring in the framework of the EEG remuneration, following a five-step redistribution mechanism [7]. In the first step, the distribution network operator (Verteilnetzbetreiber; DNO) receives generated electricity by the PV-system operator, and remunerates according to the EEG feed-in tariff. In the second step, the DNO passes on the electricity to the control area operator responsible (Regelzonenverantwortlicher) transmission grid operator for financial compensation. The third step consists of an adjustment of energy amounts and remuneration payments among the four TSOs (horizontaler Belastungsausgleich). All TSOs are obliged to sell the EEG-electricity in the electricity exchange. Since the revenues generated at the electricity exchange do not cover the whole costs for remuneration, to cover revenue shortfalls the respective TSO charges utilities for the differential amount with the EEG-levy for every kWh delivered to customers. The utilities, in turn, are entitled to pass this EEG-levy on to the end-customers. Since the revenues generated by the sale at the electricity exchange do not cover the costs for the remuneration and marketing of the EEG electricity, the expected differential amount in the form of the EEG apportionment will be allocated pro rata to the total German EEG electricity consumption.

The *market premium (Marktprämie)* according to § 20 EEG is another support mechanism of the EEG. Like the guaranteed feed-in tariff, the market premium is paid by the responsible grid operator. The market premium is intended for plant operators who are not eligible for feed-in remuneration, but instead make use of direct marketing within the frame of the EEG. This premium represents the difference between the fixed feed-in tariff and the monthly market value of the sold electricity. Thus, the amount of the market premium is calculated monthly on the basis of § 23a EEG and Annex 1 EEG. Furthermore, it contains a priced-in management premium, set to 0.4 ct/kWh for solar plants (§ 53 No. 2 EEG). It serves as a compensation for additional overhead caused by direct marketing (feed-in forecasts, direct marketing commissioning and balancing group management).

Due to their system responsibility, the TSOs are obliged to guarantee the security of their electricity supply grids at all times according to § 13 EnWG. Imbalances cause a deviation from the nominal value of the grid (50 ± 0,05 Hz) [7]. When this occurs, the TSOs are obliged to eliminate these disturbances with appropriate measures (§ 13 (1) EnWG). A market directed measure is the use of balancing electricity (§ 13 (1) No. 2 EnWG), which is remunerated with a load-frequency control price (Leistungspreis), and in the case of a power request the additional payment of a balancing energy price (Arbeitspreis) [8]. The acquisition of this positive and negative balancing power takes place via a non-discriminatory and transparent tendering procedure (Ausschreibungsverfahren) of the TSOs according to § 22 (2) EnWG, in conjunction with § 6 StromNZV. Plant operators that make use of the guaranteed feed-in tariff are excluded from this tendering process (§ 21 (2) No. 2 EEG). Plant operators using direct marketing of the power however are permitted to it. In order to participate in the tendering process of the TSOs for the *balancing power compensation (Regelleistungsvergütung)*, suppliers have to conform to certain pre-qualification criteria, according to annex D of the Transmission Code 2007, and prove that they dispose of the demanded availability, responsibility and controllability capability. At present, mostly conventional power plants and biomass provide balancing electricity. However, large or pooled storage systems are seen as promising alternatives of provision of balancing electricity [9]. Additionally, PV systems are considered as options for negative control energy which is requested in those case where there is a surplus of energy deed-in compared to energy demand.

2.4. Roles, Entities and Actors

The legal analysis also requires the definition of the involved *functional roles* in terms of the selected business models. These roles are classified in legal entities and market actors. This is necessary since the exact legal interpretation depends on the structure of the network of relationships. Fundamental *legal entities* in decentralized energy systems are the system owner, the system operator and the end-consumer as well as authorities of the energy system. Matching *market actors* in course of this work are the municipal utility, the house owner, the house resident as well as the technology supplier and optionally, the partner network.

3. Legal Analysis

Based on the legal foundations laid out in the previous section, this section aims to identify and describe the legal framework of the selected business models within the energy-related legislation in Germany. Therefore, the analysis of each of the on-site electricity business models is done in a similar fashion. First, the model is briefly described. Second, the legal characteristics are demonstrated. Third, the obligations in terms of the costs and compensations are determined. Fourth, legal specifics are presented. The primary concern is to elaborate design details for which fees, taxes and charges are avoidable and remunerations, premiums and compensations are obtainable. The order of the presentation and analysis follows the illustration of business models in Figure1. Due to the expected strategic importance for the future energy system as well as the increasing dominance of the technology, PV-related models make up the core of the cases.

The on-site business models are compared against the conventional business model *grid consumption (Netzbezug; GC)*. In this business model the end-consumer consumes electricity from the public grid, distributed by the municipal utility, and pays the associated rate as outlined in Table 1 including all the introduced cost components. According to [10], grid electricity prices are expected to remain high in the future due to increasing statutor components.

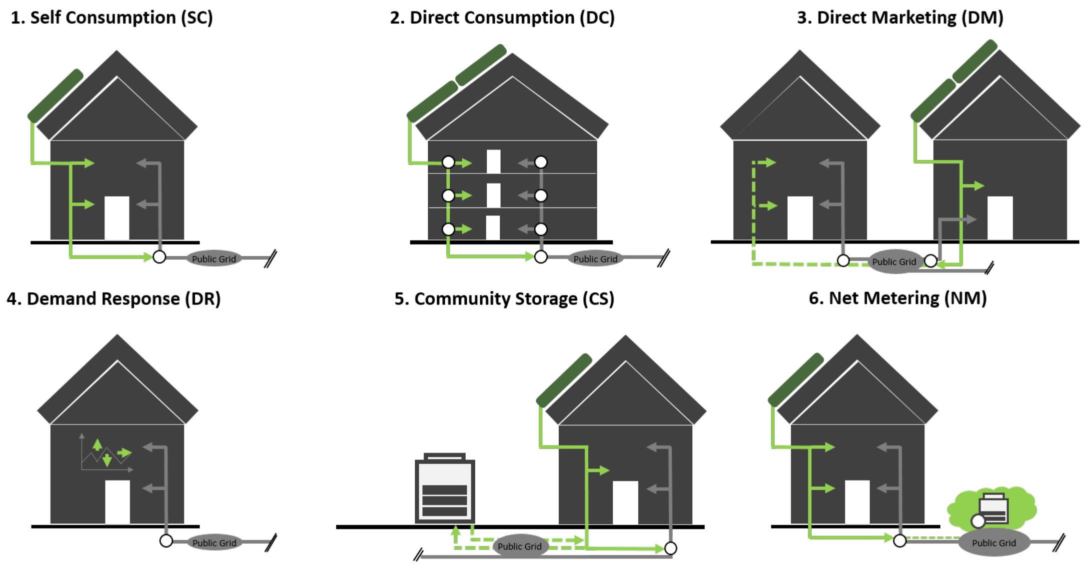

Figure 1: Illustrative presentation of on-site electricity business models

3.1. Self-consumption

Model Descriptions

The construct of *self-consumption (Eigenverbrauch, Selbstverbrauch; SC)* describes probably the most known business model. It refers to a setting of a residential single-family household in possession of a decentralized source of electricity generation such as PV. The electricity generated on-site allows, at least to some extent, for the satisfaction of energy needs of the respective house owner without utilizing the public grid. The key driver is cost-saving by consuming self generated electricity instead of grid electricity since grid parity has already been reached in 2012 in terms of PV [11]. Excess electrical energy is fed into the grid. The self-consumption rate is generally between 20-40 % without a storage system [12]. The residual demand can be satisfied by grid electricity, for which the energy rate of GC incurs.

From the utility viewpoint, different business cases are possible. The decentralized energy systems could either be sold or leased to the prospective house owner as end-consumer, but also operated by the utility. Alternatively, the municipal utility can rent roof areas, bear the investment, operate the system and sell the generated electricity to the house owners. Further business models sketched are based on this model.

Legal Characteristics

The model SC is defined as the direct usage of self produced electricity while simultaneously fulfilling the following legal criteria according to § 3 No. 19 EEG 2017: (1) sameness of system operator and electricity consumer, (2) immediate spatial proximity between generation and consumption, and (3) no usage of the public grid. The operator of the installation is the entity who bears the economic risk of the plant. This includes the available power of the installed system and the actual responsibility to bear the costs for maintenance and operation of the installed system [6, 13]. Thus, SC is also feasible if the operator and consumer is not the proprietor as is the case in contracting models [14].

The immediate spatial context is not defined in more detail. However, [6] states that this is given if the equipment and appliances of the self consumer are located in the same building, land or premises. Attention should be paid that interrupting elements such as public roads, buildings or even natural obstacles between the place of production and the place of consumption can already lead to the loss of the spatial connection [6].

The obligation to tender for all systems with an installed capacity of more than 750 kW results in a limit of the self supply for PV systems. In accordance with § 27a EEG 2017, the self usage of the generated electricity is forbidden for the facilities participating in the tender. Exceptions are listed in § 27a No. 1-5 EEG 2017.

Legal Obligations

The utilization of the public grid forms the basis for the payment of the grid-usage fees, but also for the grid-related charges such as co-generation levy, offshore liability levy, deferrable loads levy and StromNEV levy. Since this is not necessary within the scope of self supply, the associated legal obligations are not relevant. The same applies to concession fees as long as no power lines are used on public and private roads. The EEG levy, however, is also required for self-consumption, as long as no special legal definitions (Sondertatbestände) are applicable (§ 61 EEG 2017). In contrast to conventional power plants, only a reduced EEG levy of 40 % applies to consumed electricity consumed from renewable energy plants according to § 61b (1) No. 1 EEG 2017 (for 2017 this corresponds to 2,752 ct/kWh). Under certain conditions the EEG levy can even drop to 0 % (§ 61a-f EEG 2017), namely grandfathering, power plant internal consumption, stand-alone plants, self consumers who cover themselves completely with electricity from renewable energies and do not make use of remuneration according to part 3 of the EEG 2017 and installations with an installed capacity below 10 kW for a maximum of 10 MWh per year.

The electricity tax is generally mandatory for electricity consumption. Nonetheless, the StromStG provides two exemptions, which are also of relevance for SC. No electricity tax is required if electricity from renewable energy sources is extracted from a grid or a power line fed exclusively with electricity from renewable energy sources (§ 9 (1) No. 1 StromStG). The tax does also not apply if electricity is extracted by an operator for private use in a spatial context which is generated by plants with an electrical rated output of up to 2 MW (§ 9 (1) No. 3a StromStG). If the feed-in remuneration is taken into account for excess energy according to § 21 EEG, an exemption from electricity tax due to § 53c EEG 2017 reduces the costs to be applied and thus reduces the payment claim by the amount of the tax exemption granted. An exemption of the self consumed electricity from value-added-taxes is possible if the system operator uses small business regulation (Kleinunternehmerregelung) according to the § 19 (1) UStG or if the investment is attributed to a non-entrepreneurial activity [15]. However, the allocation as non-entrepreneurial activity also eliminates the possibility of claiming a deduction from the acquisition or production costs of the PV system.

Legal Specifics

The system operator needs to comply with the notification requirements (§ 71, § 74a EEG 2017). Failure to do so might lead to the loss of reduction or exemption of the EEG levy (§ 61k EEG 2017). In addition, PV systems need to meet the technical specifications according to § 9 EEG 2017. This includes the possibility of remote-controlled reduction of the feed-in power in the event of a grid overload (§ 9 (1-2) EEG 2017). For installations with a capacity greater than 100 kWp, grid operators need to be able to recall the actual feed-in at any time (§ 9 (1) No. 2 EEG 2017).

The expansion of the described system by an electrical storage leads to the same statutory cost components even though the legal situation of storage systems is only of temporary nature [14, 16, 17]. In this regard, home storage systems can be seen as part of SC according to § 3 No. 19 EEG 2017, if the operator of the systems and the consumer are the same person and if the public grid is not used. Thus, there is no obligation for the payment of the grid-usage fees, nor the grid-related charges. Concession-fees do not apply either. Regarding the duty of payment of the EEG-levy, § 61k (1) EEG 2017 prevents that there is a double burden. In this context, the EEG-levy does not apply to the feed of the storage systems but only the extraction (§ 61b (1) No1 EEG 2017). Storage device losses are exempted from the EEG-levy (§ 61k (1) EEG 2017). For storage systems in accordance with § 61a No. 4 EEG 2017 (installed capacity lower than 10 kW, maximum of 10 MWh per year, limited to 20 years) there is even a release of the EEG-levy for feeding and extraction [6]. In addition, the exemption from the electricity tax can be also applied for temporally stored electricity even though the StromStG is not equipped with a separate arrangement for electrical storage systems [18]. The requirement for this is the SC in an immediate spatial context and an installed capacity below 2 MW (§ 9 (1) No. 3a StromStG).

3.2. Direct Consumption

Model Descriptions

The construct of *direct consumption (Direktverbrauch, Mieterstrom; DC)* represents a case quite similar to SC. The relevance of the business model arises from apartment buildings with several tenants. The end-consumer is equal to the tenant and differs from the house owner who wants to supply electricity from his roof PV-system to these tenants without using the public grid.

In this business model, the system operator is able to generate revenue by selling the generated electricity for a competitive price to contracted tenants. Additionally, excess electricity can be fed into the grid. Both streams allow the system operator to cover expenses regarding the PV system.

The residual energy demand of tenants is satisfied by electricity from the grid for which conventional electricity costs incur. It is noteworthy that the tenants can freely choose whether they want to enter into the electricity supply contract. In this business model, the utility likely represents the system owner and the system operator, leasing the roof from the building owner and selling electricity to the tenants. Reason for this is that in the first case, building owners are not confronted with any investment costs. Furthermore, due to the complex regulatory requirements regarding the energy supply [19], building owners usually cooperate with utilities or energy service providers [20]. Thus, from the utility perspective there are two kinds of legal relationships. First, with the building owner who profits from a leasing fee for the roof area and image improvements. Second, with the tenants who can profit from inexpensive electricity generated in spatial proximity.

Legal Characteristics

The model DC is defined as the usage of PV electricity, which is generated on or in a residential building, if the electricity is being consumed within this building by end-consumers living in this building (§ 21b EEG 2017). A residential building is defined by § 3 No. 50 EEG, whereby a minimum of 40 % of its area must be used as living area (§ 21 EEG 2017).

In July 2017, a new law for the promotion of DC (Mieterstromgesetz) came into force [21]. The law, however, must still be approved by the European Commission (§ 100 EEG 2017). The former option to issue a statutory ordinance regarding DC (§ 95 No. 2 EEG 2017) has therefore been bypassed [22]. In order to qualify for the tenant electricity premium, the system operator needs to notify the Federal Network Agency (§ 18, No. 6 Marktstammdatenregisterverordnung).

Legal Obligations

As stated above, in the construct of DC the electricity needs to be used within the same building without using the public grid (§ 21b EEG 2017). Thus, similar to SC, there is an exempt of the grid-usage fees, the grid-related charges as well as the concession fees. In contrast to SC, the full EEG-levy is compulsory according to § 60 EEG 2017, since the equality between the operator and the consumer is not fulfilled.

According to the framework of the passed law, however, directly consumed electricity will be remunerated with a tenant electricity premium (Mieterstromzuschlag) which will be paid on top of the revenue generated (§ 21 EEG 2017). The premium is 8.5 ct/kWh lower than the above mentioned guaranteed feed-in tariff (§ 23b,c EEG 2017). In practice, the premium is presently between 2.2 ct/kWh and 3.8 ct/kWh. The exact level, however, depends on the PV system size and the current PV expansion. The maximum allowed system size is 100 kW, and remunerated projects will be limited to an annual installed capacity of 500 MW (§ 23b EEG 2017).

Legal Specifics

A central element of this business model are the contractual arrangements between the system operator and the tenants as end-consumers. The electricity supply contracts in the framework of DC must not be combined with tenancy agreements (§ 42a EEG 2017). Furthermore, DC electricity contracts can only be fixed for a maximum of one year and – complying with the liberalized market – each tenant is free to decide whether they want to enter into the contract.

Consequently, the metering concept needs to enable tenants' individual choice of an electricity supply contract. The electricity must be accounted for and the metering concept must be in compliance with the law (§ 21 No. 3 EEG 2017). To avoid additional billing costs for tenants entering into the DC contracts, the residual energy demand must be supplied by the same electricity supplier (§ 42a No 2 EnWG). According to the law, the total tenants' costs for DC and grid electricity within the business model of DC must not exceed 90 % of the general tariff of that particular network area (§ 42a EnWG).

In the framework of DC, the plant operator will take on the role of an electricity supplier in accordance to § 5 No. 13 EEG (2014) and § 3 No. 18 EnWG (2015), with resulting guidelines and obligations. However, the tenants can also form a civil law partnership (German: GbR) and operate the decentralized system jointly, supposedly complying with the requirements for power self supply. Nevertheless, there are legal uncertainties in the definition of power self supply of a civil law partnership solution as well as high contractual and administrative barriers [13].

3.3. Direct Marketing

Model Descriptions

The construct of *direct marketing (Direktvermarktung; DM)* refers to a situation whereby operators of PV-systems do not directly feed-in their generated electricity, but sell it completely or partially to third parties using the public grid. The most common is the delivery of the electricity to a direct marketing company (DMC), which is charged with selling it on the power exchange. Another option is the direct sale to end-consumers (e.g. end-consumers in spatial proximity) by means of a power supply agreement without the interim switching of a DMC. In this case, the plant operator himself might act as a direct marketer and electricity supplier and supplies the self generated electricity directly via the public grid. Direct marketing, however, is accompanied by a number of duties and increased effort.

To ensure that all legal requirements are met in a regional direct marketing case, a municipal utility would be a predestined entity for the marketer. As such, excess energy of a self consumer can cover the load of a neighboring end-consumer via the public grid. Conventional GC is used for both end-consumers to cover residual demand.

Legal Characteristics

DM is defined as the electricity sale (1) from renewable energy sources to third parties (2) whilst using the public grid, (3) unless the electricity is being consumed in a spatial context of the system (§ 3 No. 16 EEG 2017). The main differences to direct power consumption (§ 21b (4) Nr. 2 EEG 2017) lie in the grid usage and spatial context. For all PV-systems put into operation after January 1, 2016, the direct marketing of electricity is obligatory for all systems larger than 100 kWp (§ 21 EEG 2017). Existing installations approved before the commencement of EEG 2014 are eligible to choose to switch to direct marketing.

Legal Obligations

In general, plant operators must fulfill the following prerequisites and obligations in order to have a right to remuneration of the market premium according to § 19 and § 20 of the EEG 2017:

- Sales volume: a market premium is only paid for electricity actually fed into the grid and purchased by a third party (§ 20 (1) No. 1 EEG 2017);
- Technical configuration: energy systems need to be capable to reduce the power at any time remotely and to measure the amount of electricity supplied by each system in real time (§ 20 (1-4),§ 9 (1-2) EEG 2017);
- Accounting system: direct marketed electricity needs to be separately accounted in a (sub)balancing group. If the electricity in the balancing group does not meet these requirements, this must not be the responsibility of the system operator or DMC (§ 20 (1) No. 4 EEG 2017);
- Labeling possibility: marketed electricity can be labeled as electricity from renewable energies financed from the EEG levy (§ 20 (1) No. 2 EEG 2017);
- Double funding ban: avoided network charges can not be claimed according to § 18 (1) StromNEV (§ 19 (2) EEG 2017).

If these criteria are not met, other DM mechanisms according to § 21a EEG 2017 are applied. This serves as a catch-all element for the marketing of electricity without premium. In contrast to the use of the feed-in remuneration (§ 21 (2) No. 2 EEG 2017), the usage of the compensation through the market premium does not prohibit the participation in the balancing market.

In summary, DM might be promoted on the basis of market premiums, but due to the apparent disparity between the system operator and the end consumer as well as the utilization of the public grid all described fees and levies apply. An electricity tax exemption is, however, possible for installations up to 2 MW if the energy is delivered in a spatial context (§ 9 (1) No. 3b EEG). This led to the business model of regional direct marketing in the context of the EEG 2014. The saving is relativized in EEG 2017 (§ 53c EEG 2017). Although the tax exemption status (Steuerbefreiungstatbestand) remains unaffected by the amendment, the value to be applied - and thus the amount of the market premium - is reduced by the amount of tax exemption granted per kWh (§ 53c EEG 2017). Through this double funding is prevented. Thereby, waiving of the electricity tax exemption is not possible [23].

Legal Specifics

In particular, direct electricity supply in terms of direct marketing to third parties without a DMC requires legal specifics. The plant operator becomes an energy utility according to § 3 No. 18 EnWG and § 3 No. 20 EEG 2017 with respective obligations. These include the balance sheet management, the invoicing and the fulfillment of the notification obligations against the network operator. The sale of excess capacities and the purchase of shortfall capacities are also part of the responsibilities [24]. Additionally, electricity labelling with respect to regional evidence (Regionalnachweisen) is only possible with EEG 2017 (§ 79a EEG 2017). This can only be used with DM and the tags are issued by the Ministry of Environment. The region includes all postal code areas that are located wholly or partly within a radius of 50 kilometers around the postal code area in which the final consumer consumes the electricity [25]. However, in order to prevent excessive funding, the market premium is reduced by 0.1 ct/kWh (§ 53b EEG 2017) with the use of the label.

3.4. Demand Response

Model Descriptions

Demand Response (Lastverschiebung; DR) describes the adaptation of electricity consumption patterns by end consumers as a reaction to an incentive of a flexibility aggregator. It is assumed that the incentive to perform DR is provided in the form of price signals transmitted to the customers via variable electricity tariffs. To provoke residential DR through variable electricity tariffs, households need to be equipped with smart meter technology and electric appliances that can be monitored and controlled automatically to limit the discomfort connected to DR for the inhabitants [26].

Due to the close relationship between municipal energy utilities and their customers, they are well suited to take on the role of the flexibility aggregator. To make use of the load flexibility of residential customers, energy utilities need to aggregate the load flexibilities from a large number of households. Energy utilities can benefit from residential DR by adjusting the loads of residential customers to the power generation of their own generation plants and by taking available DR resources into account in their trading activity.

Legal Characteristics

According to § 40 EnWG, energy utilities are required to offer electricity tariffs to end-use customers that give them an incentive for energy savings, in particular load-variable or time-variable tariffs, if this is technically feasible and economically acceptable. However, the general obligation for energy utilities to charge customers according to the standard load profile impedes the wide-scale introduction of variable electricity tariffs so far [27].

To promote the dissemination of smart meters in German households, § 29 of the law for the digitalization of the energy transition (Gesetz zur Digitalisierung der Energiewende; GDEW) regulates the installation process of smart meters. According to the GDEW, metering firms are required to install smart meters, if technical feasible and economically acceptable (§ 29 (1)):

- at homes of end-use customers with a yearly electricity consumption of 6,000 to 10,000 kWh within 8 years starting from 2020,
- at homes of end-use customers, who agree to the control of controllable electric appliances resulting in benefits to the grid according to § § 14a EnWG within 8 years starting from 2017.
- at homes of end-use customers owning a distributed system (e.g. PV) with a capacity larger than 7 kW within 8 years starting from 2017.

In other cases, the installation of smart meters is declared as optional.

Legal Obligations

Since the end-consumers in the course of DR cover the load by grid-consumption, the same price components as in GC are prescribed. For DR no exemptions are possible.

Legal Specifics

To guarantee the safety of data recorded, processed and transmitted by smart meters, the smart meter gateway is required to fulfill a technical protection standard, the so-called protection profile, defined by the Federal Office for Information Security (Bundesamt für Sicherheit in der Informationstechnik; BSI) [28].

With respect to residential DR, the importance of customer data protection has to be underlined firmly. Since the involved flexibility aggregator needs to gather information about how customers adapt their energy consumption as a reaction to price signals, the success of residential DR might well depend on how much trust customers put in the aggregator's ability to protect their data.

3.5. Community Storage

Model Descriptions

A *community storage* system (Quartierspeicher; CS) represents a business model for large-scale battery systems with multi-use function. According to the scientific community, CS-systems are defined as "facilities which are able to receive energy and then release it again [...] in the form of electricity [...] at a later time. Additionally, community electricity storage systems provide services based on balancing strategies for an association of prosumers, renewable energy producers and loads that are connected to the same distribution grid. At least one of the following operation strategies has to be implemented: maximizing self-consumption for all participants, increasing shareholder's profits in electricity markets, or optimizing community welfare. Optionally the operation strategy should be grid supportive and increase the grid's hosting capacity for decentral renewable generation." [29]. In this context, studies indicate that operating battery storage systems for multiple uses promises to be both more profitable and environmentally reasonable than individual storage solutions [30].

The business model envisioned here has a municipal utility as owner and operator of the battery storage device, and prosumers as participants, which have access to the storage device capacity. Similar to electrical storage systems on the individual household level, the CS stores excess energy generated by decentralized energy systems of individual prosumers to bridge the time gap of renewable supply and demand. However, in contrast to individual solutions, every participant is connected to the CS via the public grid in spatial proximity. Prosumers can increase their account by charging and decrease their account by consuming electricity, thereby maximizing their individual self-consumption. Additionally, the CS operator can utilize the disposable positive or negative capacities of the storage system in terms of spot market trading and by offering balancing services in the reserve market. This corresponds to a secondary and tertiary operation strategy, resulting in a multi-use function of the CS.

Legal Characteristics

The current regulatory framework for CS is fragmented and rather inconsistent. To begin with, the legal definition of electrical storage systems in general is deficient [31]. In contrast to gas storage systems, electrical storage systems are legally treated both as final consumers (§ 5 No. 33 EEG 2017) and as generation units (§ 5 No. 1 EEG 2017) and are subject to the associated fees and levies. The consequences for CS business models are especially severe as the operation comprises two steps: the intermediate storage device of electrical energy and the feed-in of stored electrical energy. In contrast to the household storage case, both steps involve the public grid and thus might be associated with full grid fees and levies, possibly resulting in a double burden. While the German regulatory framework for the storage of energy provides some exemptions from fees, their applicability remains partly vague.

Legal Obligations

While the CS participants seek to optimize their self-consumption of PV electricity, their use of the storage device fails to meet the legal criteria for self-consumption (sameness of operator and consumer, no usage of the public grid). Hence, fees and levies generally incur.

Article § 61k EEG 2017 terminates the double burden of the EEG levy, which originally incurred both when the battery is charged and discharged. According to [18], this also holds true for mixed use storage systems, i.e. where the stored electricity is partly transferred to the grid and partly self consumed by producers. Still, the EEG surcharge has to be paid for all electricity that is taken out of the storage device, with no exemption or reduction for self-consumption.

The EnWG includes the regulations concerning the grid fees and further fees, namely the offshore liability levy, the concession fee, the cogeneration levy, the § 19 StromNEV levy and the levy for deferrable loads. § 118 EnWG exempts newly installed electrical storage systems from the grid fees for 20 years. With respect to the other fees, different perspectives exist. According to the Bundesnetzagentur, an exemption from the grid fees through § 118 EnWG does not include the exemption from other fees, which incur regardless [32]. The Bundesverband Energiespeicher (BVES) on the other hand refers to § 9 (7) KWKG to argue that the cogeneration levy is considered an annex to the grid fee and can thus only incur when grid fees incur. The remaining fees should be treated accordingly [18].

The electricity tax applies every time electricity is consumed. Pumped-storage power plants are explicitly exempted from this, batteries or other types of energy storage systems however are not mentioned. Furthermore, § 9 StromStG provides an exemption for the case of spatial proximity between the generation and the storage of electricity. However, as there is no clear definition of spatial proximity, its applicability for a given CS-system remains uncertain [29].

The BVES argues that self-consumption of CS stored PV electricity should be exempted from both EEG surcharge and electricity tax, in order not to put the community solution worse off than the private solution, i.e. the household storage device. Modern measuring technology allows to determine in which cases self-consumption occurs. Furthermore, the exemption from the electricity tax should be possible even when the prosumer and the CS operator are not the same person. Additionally, the BVES claims CS are eligible for reduced grid fees when they are operated in a way that relieves the distribution net in question. Indeed, § 19 Abs. 2 S. 1 StromNEV regulates grid fee reductions for a so-called atypical consumer, allowing a maximum reduction of 80 % [18].

Legal Specifics

According to § 22 EnWG, access to the balancing power market is supposed to be transparent, open to all suitable technologies and non-discriminatory. After proving that they meet the criteria and completing the pre-qualification process in accordance with annex D of the Transmission Code 2007, batteries can participate in the tendering process of the TSO. The participation of battery technologies is explicitly desired and consequently fostered by the recent shortening of the tendering periods for the secondary and tertiary balancing power [33]. Furthermore, batteries which do not meet the minimum capacity of the tender can be virtually pooled without suffering any disadvantage or change of regulation. Pooling is however only possible within the same control area.

3.6. Net Metering

Model Descriptions

In the case of net metering (Netzspeicher; NM) the grid is used as a kind of storage device for the PV-equipped end-consumer and represents a business model quite popular in the USA [34]. In general, NM "works by utilizing a meter that is able to spin and record energy flow in both directions. The meter spins forward when a customer is drawing power from the utility grid (i.e., using more energy than they are producing) and spins backward when energy is being sent back to the grid (i.e., using less energy than they are producing)." [35]. An implementation is possible by installing a bi-directional meter.

Households feed excess PV electricity into the grid, where it is virtually stored for them. In other words, the utility takes over this electricity for its own use and, at the end of a billing period, if the amount of PV generation is larger than that of electricity consumption, the household is paid for the net amount by the utility. Otherwise, the household must pay the net amount of electricity consumed at standard electricity rates.

Legal Characteristics

While NM is widely used abroad, the legal situation in Germany is not clear. There are no specific regulations which are aimed at the model of NM. However, the reference quantities from the grid must be assigned to a balancing group at the extraction point [6]. Unassigned extractions are not permitted. In particular, the reference quantities must not be netted with their own generated quantities. Reverse-rotating meters which measure the electricity extractions to the self consumer only in terms of the balancing of grid supply minus its grid feed-in and thus display too low current amounts for both directions would necessarily distort the assignment and invoicing.

4. Business Implications

While on-site electricity nowadays plays only a marginal role in the overall energy market since it only accounts for a share of around 1 % percent, its future potential is expected to be around 30 % [2]. This, however, depends essentially on the regulatory design due to the fundamental importance of incentives. In this context, the on-site business models analyzed can be mainly distinguished by three legal characteristics as outlined in Table 2: (1) the relation between system operator and consumer, (2) the spatial context and (3) the utilization of the public grid, resulting in different legal obligations as visualized in Figure 2. Taking into account the statutory provisions and possible promotions, the profitability of the single business models selected is discussed in the following. Additionally, challenges and opportunities for municipal utilities are stated.

Table 2: Distinguishing legal characteristics of analyzed business models

Business Model	(1) Legal Entities	(2) Spatial Context	(3) Grid Utilization
SC	same entities	within building	usage prohibition
DC	disparate entities	within building	usage prohibition
DM	disparate entities	regional proximity	usage obligation
CS	without specification	immediate proximity	usage necessary
DR	not relevant	regional proximity	usage necessary
NM	same entities	within building	usage benefits

Even though SC is not remunerated as it was between 2009 and 2012, this construct can still be seen as privileged [36]. For installations up to 10 kWp no statutory cost components are raised at all. In cases of installations with a capacity greater than 10 kWp, only the EEG levy at a fixed level of 40 % is statutory. Taking into account the average residential GC rate as well as the average PV generation cost of 7-10 ct/kWh [37], there is a margin potential of around 19-22 ct/kWh for a capacity up to 10 kWp (15-18 ct/kWh for a capacity greater than 10 kWp), depending on the system type and the local conditions. This shows that self-consumption maximization under the current conditions is much more attractive than feed-in of the self generated current for a feed-in tariff of 12.30 ct/kWh or less. A high self-consumption rate can thus be viewed positively from the perspective of the operator. However, an extension on the basis of household storage systems becomes more relevant in the future due to the high investment costs. Currently, SC electricity costs for a PV generation system combined with a storage device amount to around 30 ct/kWh [37]. It is worth mentioning that SC is less profitable for commercial consumers, since their rate of GC is considerably lower. Altogether, the overall profitability determines the profit margin a utility can apply, ensuring its own revenue and savings for the households [13]. The expected rise of residential electricity rates as well as the falling technology costs increase the attractiveness for model provider. Additionally, the desire of households to be independent of companies can be viewed as a driver [38]. At the same time, the legal uncertainties are an obstacle to the development of this model. Increasing burdens, e.g. in terms of EEG levies, can significantly reduce the profitability of the model [39]. Last but not least, transaction costs are not reflected yet. Due to the small project volume, the SC model faces considerable transaction costs making process standardization an important success factor.

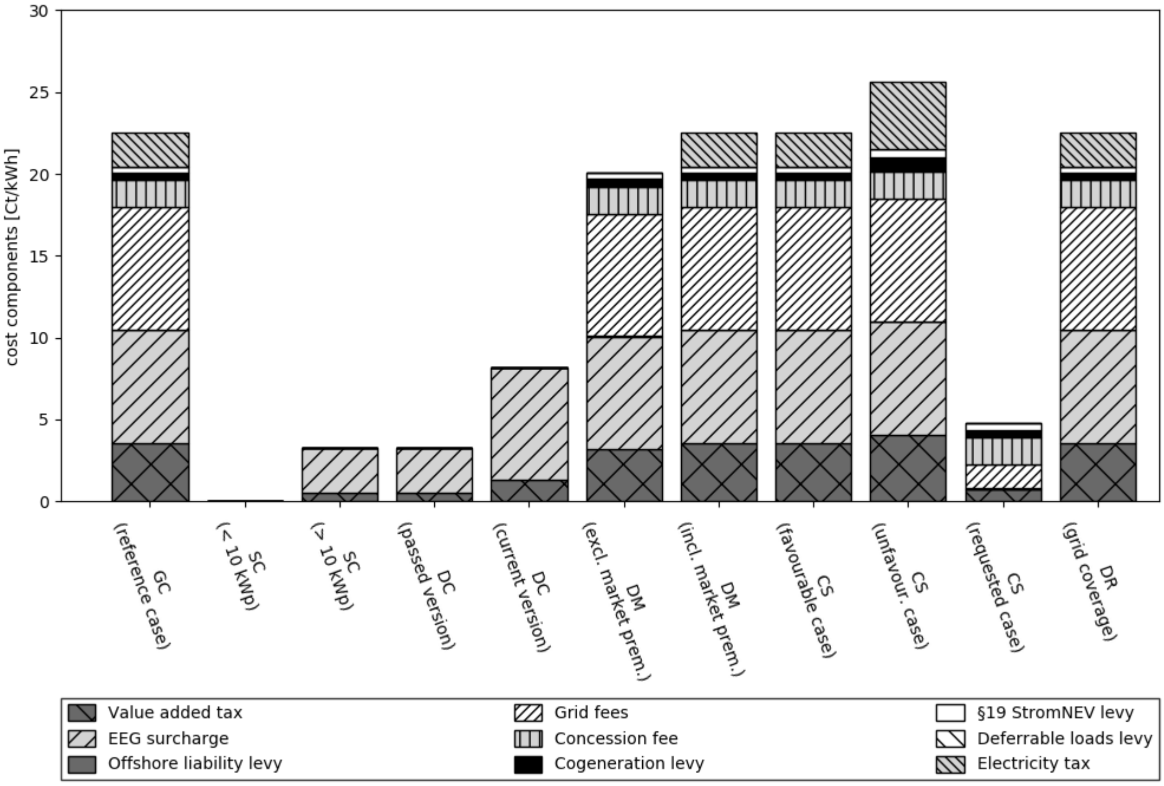

Figure 2: Overview of statutory cost components of business models selected

The construct of DC exhibits revenue potential from the premium and from the electricity sold to tenants. The tenants' costs of the overall electricity supply (DC and residual demand) has to stay below 90 % of the general tariff of that particular network area. Taking into account the GC rate as well as the PV costs, this business model exhibits a profit margin of around 15-18 ct/kWh if the tenant electricity premium is applicable. Otherwise only a margin of around 10-13 ct/kWh is possible. In addition to its profit potential, a major argument for utilities to engage in this business model is customer retention [40]. In comparison to SC, an advantage can be seen in the scaling potential: Systems of greater capacity can be installed and operated for more end-consumers simultaneously. Thereby, the project volume is closely linked with the number of rental units in terms of potential end consumers. However, tenants' free choice of electricity suppliers can be seen as a major obstacle. Additionally, parts of the outlined profit margin need to be shared with the property owner. An implementation of the business model solely by the real estate company is unlikely due to the high legal burden associated with the role of electricity producers and providers [20].

Energy utilities can benefit from residential DR by adjusting the loads of residential customers to the power generation of their own generation plants and by taking available DR resources into account in their trading activity. Energy utilities with a high share of electricity production from renewables, whose production is difficult to predict, can especially benefit from DR. Reasons are that an additional profit can be generated since any additional electricity is sold to their customers instead of via the spot market. By this, DR supports the integration of fluctuating electricity generation without investing in decentralized generation systems. The only condition for its applicability is the comprehensive implementation of smart meters. However, the regulation for the implementation of smart meters does not foster a fast and wide-scale roll-out of intelligent meter systems in residential homes with an electricity consumption of less than 6,000 kWh/year. Since the end-consumers for DR models cover the load by grid-consumption, the same statutory price components as in GC are prescribed. Savings can be achieved in terms of behavioral changes or, more realistically, by automated control of household appliances, resulting in a lower energy consumption in times of low electricity prices. However, even the best case estimations of the savings potential of residential DR are low, showing absolute savings per household of 35 /year [41]. Further, the reserve markets could become future marketplaces for demand flexibility, provided that existing rules are adapted in order to allow DR resources to enter the markets. Proposals for an adaptation of the mentioned rules suggest daily tender periods and shorter product lengths [42]. A disadvantage from the perspective of the provider can be seen in the required technical specifications for data protection.

The legal framework for CS is complex and there exists a number of uncertainties. For the case that the current legislation is interpreted unfavorably, CS is clearly not competitive against GC since the statutory cost components of 22,95 ct/kWh are already higher than those for GC. The favorable CS case requires a more differentiated look. While the same levies, fees and taxes occur as for GC, which would leave a margin in the amount of the electricity generation cost, the feed-in remuneration for renewable energy needs to be taken into account as well. For PV systems below 10 kWp it currently amounts to 12,30 ct/kWh. Consequently, the prosumer would be better off feeding the excess electricity into the grid for the remuneration. The adjustments requested by the BVES are currently not applicable but demonstrate how the economic performance of CS could change in case the legal framework is altered in the future. While CS-systems are clearly disadvantaged compared to household storage systems regarding the statutory costs, they provide significant advantages in view of the technology costs due to scale effects. This holds true for the battery itself, but also for the control systems required for the participation in the balancing power market. If the CS is scaled large enough - approximately 18 times that of residential storage system sizes -, half the price per kWh can be assumed [43]. Furthermore, additional revenue streams can increase the profitability of CS. The stored energy and free capacity can be used for trading on the spot market or to offer system services depending on the state of charge [30]. In this context, surveys show that a majority of households has no desire to actively control the marketing of their excess electricity, but rather wants the operator to achieve moderate profits for them [44]. In summary, CS displays some economic and environmental potential, but the current regulatory framework inhibits successful business models. It is thus considered the most crucial influencing factor for the future development of profitable CS solutions [45].

While NM is applied in Italy, Australia and the USA, the physical model is not permitted in Germany at the present time. In this model the feed-in is indirectly remunerated with a tariff equal to the electricity price of the household [46]. Rising electricity prices will therefore further increase the benefits of these business models. In most cases, such a high remuneration will significantly exceed the value of PV electricity [47]. Since the grid is used as a storage system in this business model, investment costs can be saved. However, a financially net metering model seems to be possible. This construct works on the basis of valuation of the estimated energy feed-in as offered with the product sonnenBatterie by the sonnen GmbH and not on the basis of a real bidirectional physical meter.

All in all, the analysis shows various advantages for municipal utilities to engage with on-site business models even though the legal specifications are not always apparent. The profitability of on-site business is mainly influenced by the amount of grid charges, the electricity tax and the EEG levy due to the declining electricity generation costs [2]. In this context, possible reform proposals of statutory price components as discussed in [48] need to receive particular attention. Additionally, municipal utilities seem to be perfect operators of local and regional markets due to the linkage of supply and demand and the local anchoring with direct customer relations [49, 50]. The existing legal burden for electricity producers and providers impedes the market entry for other actors. This gives opportunities for experiences which help to cope successfully with less tightly regulated and higher evolved decentralized markets in the future as claimed in [2].

5. Concluding Remarks

This work conceptually characterizes and legally analyzes decentralized on-site electricity business models and assessed them from a municipal utility perspective. It has been shown that the feasibility and profitability of various on-site business models depends primarily on the associated legal framework and the corresponding statutory costs and compensations. Simultaneously, the regulation is characterized by unsystematic specific exemptions which leads to uncertainty regarding long-term planning. An opportunity for a general improvement can be seen in the Clean Energy Package of the European Commission which promotes renewable self consumers but also renewable energy communities [2].

Due to the statutory exemptions, SC is currently an attractive solution even though this happens to the detriment of the conventional business of utilities. If the municipal utility does not engage in this business field, others might. A profitable implementation of DC is also possible in collaboration with real estate companies. The situation is not as favorable as in SC however, but legal amendments are on the way. Regional DM finds much less appeal in the course of the legal amendments of the last years. Taking into account costs and compensations, this business model hardly seems successfully implementable for utilities. Since sustainable integration of distributed electricity generation also requires electricity consumers at municipal level, DM seems to be a perfect integration model. In this regard, it is barely understandable why this model exhibits such little political support. Similar considerations apply to CS. With the right implementation this business model can help to reduce the environmental impact, while at the same time stabilizing the distribution grid. Thus, a harmonization of the current legislation with gas or pump storage systems seems appropriate. DR seems to be an adequate business model for the integration of decentralized energy, especially for end consumers without direct system access. However, a precondition is the obligatory widespread introduction of smart meters. The not yet disseminated concept of NM can be implemented in two ways. While the physical model is not permitted under the current legislation, the balancing model might lead to a profitable business model, given certain circumstances.

Future work needs to address uncertainties of the energy legislation but also to assess the economic potential of business models. The focus needs to stay on the successful integration and sustainable development of decentralized systems at municipal level on the basis of the current situation. Thereby, an application of techno-economic optimization models on the basis of various scenarios at differing municipal conditions might help to derive robust predictions of the business model potential in general, but also adequate policy action to enable the implementation in particular. The gained insights can on the one hand support decision makers regarding sustainable business model implementations, and on the other hand serve as a basis to adjust the legal framework of the presented energy-related laws.

Laws

AbLaV: Verordnung zu abschaltbaren Lasten vom 16. August 2016 (BGBl. I S.1984)
GDEW: Gesetz zur Digitalisierung der Energiewende vom 29. August 2016 (BGBl. I S.2034)
EEG 2017: Erneuerbare-Energien-Gesetz vom 21. Juli 2014 (BGBl. I S. 1066)
EEV: Erneuerbare-Energien-Verordnung vom 17. Februar 2015 (BGBl. I S.146)
EnWG: Energiewirtschaftsgesetz vom 7. Juli 2005 (BGBl. I S.1970, S.3621)
KAV: Konzessionsabgabenverordnung vom 9. Januar 1992 (BGBl. I S.12, S.407)
KWKG: Kraft-Wärme-Kopplungsgesetz vom 21. Dezember 2015 (BGBl. I S.2498)
StromNEV: Stromnetzentgeltverordnung vom 25. Juli 2005 (BGBl. I S.2225)
StromNZV: Stromnetzzugangsverordnung vom 25. Juli 2005 (BGBl. I S.2243)
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StromStV: Stromsteuer-Durchführungsverordnung vom 31. Mai 2000 (BGBl. I S.794)
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Chapter 4

Model-Based Demand Response Assessment

Provoking Residential Demand Response Through Variable Electricity Tariffs: A Model-Based Assessment for Municipal Energy Utilities[*] [**]

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[**]Further explanations about the model design are outlined in Appendix A. Besides, a comprehensive overview of the optimization approach is given in Appendix B.

Provoking Residential Demand Response Through Variable Electricity Tariffs: A Model-Based Assessment for Municipal Energy Utilities

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Abstract

With the suitable infrastructure of information and communication technologies in place, customers are able to perform demand response (DR), meaning that they can decrease or increase their electricity consumption in response to changes in their electricity tariff. In this research, different variable electricity tariffs are designed taking both customer and utility preferences into account. Subsequently, a model-based analysis on the basis of optimization model IRPopt (Integrated Resource Planning and Optimization) is carried out. Electricity customers are exposed to the designed tariffs in order to find out whether variable electricity tariffs are a suitable instrument for municipal energy utilities to exploit the potential lying in residential DR. Loads considered for DR in this work are those of selected electric household appliances and the loads of electric heat pumps. One major contribution of this work is that the assessment differentiates between different types of energy utilities, whose specific generation profiles are taken into account in the design of the variable tariffs. The results show that variable electricity tariffs have a small economic potential. However, customers only benefit if the design of the business model includes a proper compensation mechanism. In this context, successful business models require the direct cooperation of different municipal energy market actors. Furthermore, taking the specific generation profiles of municipal energy utilities into account in the design of variable electricity tariffs helps to increase the energy autonomy of municipalities.

Keywords: Demand response, Variable tariffs, On-site business models, Decentralized energy systems, Energy system optimization

1. Introductory Remarks

The transformation of the German energy system must be seen in the context of the significant changes that have been taking place in the European electricity sector during the last two decades. Among these changes are the liberalization of electricity production, wholesale trade and distribution markets for end customers [1]. Additionally, the unbundling of the market segments of sales and distribution set new rules regarding price design and market access. The introduction of a feed-in tariff scheme for electricity produced by renewable energy sources enhanced the competitiveness of renewable energy sources [1].

While these changes have accompanied the much-noticed *Energiewende* (energy transition) in Germany, they are also putting immense pressure on energy utilities. The growing share of electricity production from renewable energy sources has led to a considerable decrease of electricity prices and consequently, to an erosion of energy utilities' revenues [2, 3]. So far, energy utilities have failed to find a suitable response to these developments in the form of innovative business models. However, municipal energy utilities are especially able to play an important role in the transition of the energy system due to their decentralized nature, their infrastructure, their close relationship with customers and their strong interconnections with the municipality [4].

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It will no longer be profitable for energy utilities to act according to the old paradigm *supply follows demand* in an energy system relying more and more on predominantly uncontrollable renewable energy sources [5]. The proposed alternative for the future – a supply and demand that complement one another – requires flexible consumers to adapt their demand by providing demand response (DR) [5], meaning that they decrease or increase their electricity demand according to the supply.

While the DR potential of energy-intensive industries is already being exploited, the DR potential of household customers is still laying dormant [5]. Simultaneous, recent developments in the field of electricity metering offer the chance to exploit the residential DR potential. Without any doubt, smart meters are essential to create the "flexible consumer" [6]. Additionally, in order to make any use of the residential DR potential, the load flexibilities of a large number of residential customers need to be aggregated. The fact that active DR is ultimately mediated by contracts with consumers qualifies energy utilities, particularly, municipal energy utilities for the role of flexibility aggregator [7]. One way energy utilities can give consumers the incentive for providing DR is via variable electricity tariffs.

In view of the key question "Are variable electricity tariffs a suitable instrument for municipal energy utilities to exploit the economic and environmental potential laying in residential DR?", the objective of this work is to analyze the business potential and the implications for energy utilities offering variable electricity tariffs to residential customers. In order to quantify the effects, a model-based analysis on the basis of the techno-economic optimization model IRPopt (Integrated Resource Planning and Optimization) [8–10] is carried out. For a systematic processing, the research intends to accomplish the following sub-questions:

- What residential customer preferences are present with respect to the DR implementation on the basis of different variable electricity tariffs?
- How does the implementation of DR impact the targets of the provider and customer and what effects are noticeable with respect to the variable tariffs?
- What implications can be derived with respect to DR implementation at different energy system conditions as utility and customer types?

The research paper is organized as follows: Section 2 gives an introduction to the fundamental theoretical concepts of DR in general and of residential DR in particular. Subsequently, Section 3 provides an overview of the state-of-the-art in the field of residential DR modeling. The developed design of the applied energy system model is outlined in Section 4, before Section 5 defines case studies and the input data. The following section 6 presents the optimization results of the model-based analysis. Section 7 draws business implications and states research limitations. Finally, Section 8 summarizes results and outlines future research.

2. Demand Response

2.1. Model definition

In this work, DR is defined "as the changes in electricity usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time" [11]. The changes in the price can be described in more detail with hourly or daily or seasonal variable tariffs. According to [12], *load curtailment* and *load shifting* are two strategies that customers can adopt to change their consumption behavior. In this sense, DR can be seen as similar opportunity as the battery energy storage for densely populated urban areas as discussed in [13].

Through load shifting, temporary load reductions are compensated for by load increases in other time periods, while load reductions are not balanced out in load curtailment. Naturally, both strategies of consumption change lead to some sort of constraint on customer comfort. The goal of this research is to minimize the comfort constraints for residential customers originating from DR as far as possible. Hence, in this work, it is assumed that residential DR is accomplished exclusively via load shifting, the strategy with the lower constraint on customer comfort.

2.2. Program classification

Following [11], programs with the goal to motivate end-use customers to provide DR can be classified into two main categories: price-based and incentive-based programs, the latter of which can further be subdivided into classical and market-based programs. This classification is illustrated in Fig. 1, along with examples for the different DR program types.

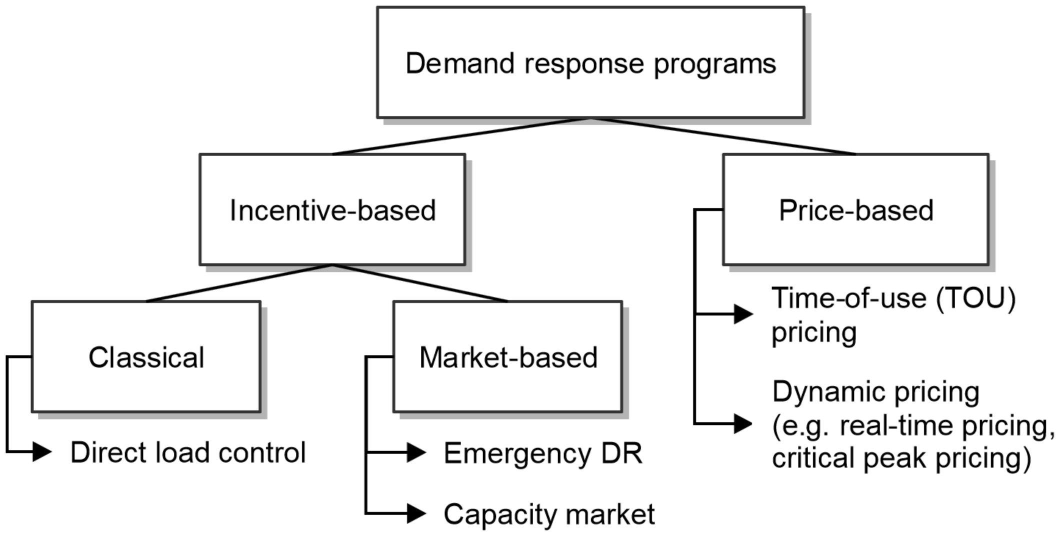

Figure 1: Demand response program classification, adapted from [11]

In direct load control programs, program participants grant the right to control their energy consumption to a *load scheduler* [5]. To establish the contract between the two parties, the extent to which the load scheduler is allowed to control the contracted loads needs to be determined [5]. This leads to a loss of autonomy for end-use customers due to the disclosure of personal information [7]. In the market-based emergency DR programs, participants are provided with incentive payments for load reductions during periods of reserve shortfalls [14]. In capacity market programs, customers commit to providing load reductions of a pre-specified amount to replace conventional generation [14].

The focus of this work lies on price-based DR programs in which changes in the electricity price over time are transmitted to residential customers via variable electricity tariffs that fluctuate following the real-time wholesale electricity price or rather the prevailing spot market prices [11] (at least to some extent). Price-based programs can be further subdivided into time-of-use (TOU) pricing and dynamic (dyn) pricing options, of which the latter represents the more flexible tariff design option.

In dynamic pricing contracts, the hourly electricity tariff is fixed at short notice and reflects the spot market prices [7]. One example for dynamic pricing is real-time pricing (RTP) for which price information is either provided one day ahead for the next 24 hours or, making RTP fully live up to its name, constantly on an hourly basis [15]. In contrast to RTP, in critical peak pricing schemes the price levels are known to the customers in advance. However, the information about when these price levels are effective is given to the customers at short notice [15]. This tariff option gives utilities the chance to raise a critical peak price, which is significantly higher than the average electricity price, in times of extreme stress on the network [15].

In TOU tariffs, the day is subdivided into different intervals with constant price levels [15]. Typically, the intervals are determined at the start of the contract. The price levels within these time periods are established on the basis of historical or forecasted electricity spot market prices. Naturally, TOU tariffs are

Table 1: Characterization of household appliance groups, adapted from [5]

Appliance group	**Examples**	**Control mode**	**Shifting distance**	**Discomfort**
User interaction	Dishwasher, washing machine, tumble dryer	Semi-automatic	Medium	Medium
Cooling	Refrigerator, freezer	Automatic	Low	Low
Heating & hot water provision	Electric heating system (with buffer storage)	Automatic	High	Low

characterized by higher electricity prices during periods of high demand and lower prices during periods with low demand [11]. Seasonal price fluctuations and inherent variations of prices between days – for example between weekdays, Saturdays and Sundays – can be accounted for in TOU tariffs.

2.3. Pricing preferences

In order to minimize their price risk, which originates from the volatility of electricity wholesale market prices, and to optimize their portfolio management (in case own generation facilities are operated), it can be argued that energy utilities prefer highly dynamic tariffs [16].

However, the preferences of energy customers are more complex. The results of an acceptance study, performed by [15], show that customers prefer simple over complex variable electricity tariffs, which are characterized by a rather low dynamic (for example fixed tariff zones (TZs) with fixed price levels instead of hourly fluctuating prices without predetermined price levels) and a low price spread between low and high price periods. However, [15] did not take for granted that household appliances perform DR automatically.

In this work, it is argued that automatic control of household appliances, leading to almost no perceived discomfort for customers, will make dynamic variable electricity tariffs more attractive to customers. It is necessary that energy utilities complement the introduction of more dynamic electricity tariffs with information on their advantages over the common flat tariff (FT) from an energy market and an individual perspective [15].

2.4. Shifting potential

Table 1 shows the characteristics of the three groups of household appliances with the ability to perform DR that are considered in this work.

In contrast to the group of base-load appliances, semi-automatically controlled appliances do not require constant, but only sporadic user interaction, for example a washing machine needs to be loaded by the customer, but can turn on whenever it is most suitable [5]. This makes this group of appliances usable for DR. Both shifting distance of loads and discomfort connected to load shifts from semi-automatically controlled appliances can be classified as medium. While washing machines and tumble dryers exhibit a load shift horizon of up to 4 hours, loads of dish-washers can be shifted over 12 hours [17]. However, there are some negative repercussions for the customers when using appliances of this kind for DR. For instance, in the case of a DR capable washing machine, customers do not exactly know the time at which the washing process is finished and after which they can take their clothes out for drying. Hence, it is debatable, to what extend the loads of such devices can be considered as shiftable. To account for the consumer discomforts connected with DR of semi-automatically controlled appliances, it is assumed that a maximum of 50 $*ofloadsfromthisappliancegroupcanbeshifted*.

All of the appliances of the other two groups can be controlled automatically. Consequently, load shifts by these appliances only lead to minor to no perceived discomfort of end-use customers. However, the shifting distance of cooling devices is limited by the length of their cooling cycle, a parameter that depends, in turn, on the quality of their insulation. Consequently, the length of load shifts of cooling devices is only 0.5 to 2.0 hours [18]. Compared to that, loads from electric heating systems, responsible for the provision of heat and hot water, can be shifted over much longer time periods, depending on the quality of insulation of the built-in thermal buffer storage. It should be noted that in this work, an electric heating system is defined as an electric heat pump system (hp) that is coupled with a thermal buffer storage providing heat and hot water to end-use customers.

In order to get an impression of the share of total load that can be shifted by household customers, the appliances of the three selected appliance groups need to be characterized in more detail. Of particular importance are their consumption share and their penetration level, which defines the percentage of households that are equipped with a certain appliance. An overview of this detailed characterization of household appliances is given in Table 2. Excluding electric heating, flexible household appliances are responsible for up to 38.5 % of the overall residential electricity consumption. However, as aforementioned, shifting loads of semi-automatically controlled appliances is associated with a considerable level of discomfort for the customers. Hence, it is safe to assume that loads from these appliances will not be shifted completely, even if households owning one or more of these appliances meet all the technical requirements necessary for performing DR.

Table 2: Specification of household appliances suitable for DR, adapted from [19]

Appliance	**Penetration level (%)**	**Consumption share[1] (%)**	**Control mode**
Refrigerator	100.0[a]	8.3[b]	Automatic
Freezer	50.3[a]	11.3[b]	Automatic
Dishwasher	69.8[a]	6.9[b]	Semi-automatic
Washing machine	96.2[a]	4.5[b]	Semi-automatic
Tumble dryer	41.1[a]	7.5[b]	Semi-automatic
Electric heating system	5.0	49.0	Automatic
Sources: [a][20], [b][21]			

It is assumed that a maximum of 50 % of loads from semi-automatically controlled appliances can be shifted. Taking this into account, the realistic maximum share of shiftable load in households without electric heating system can be estimated to be about 30 % of their total electricity consumption. Not surprisingly, households, whose heating is provided via electric heating systems with thermal buffer storage exhibit a much higher share of flexible electricity consumption.

3. Related Work

An overview of the presented literature on residential DR modeling is displayed in Table 3. The review shows that:

- flexible loads are in most cases optimized with regard to the electricity market, in fewer cases also with regard to the reserve market.
- appliances for electric heating and hot water supply are among the most promising devices for demand response, apart from electric vehicles, which are named as a favorable option for the future.

[1] The consumption share of the appliances is calculated with respect to a total electricity consumption of 3500kWh$_{el}$. Only the share of the electric heating system is determined with respect to a considerably higher overall electricity consumption of 6900kWh$_{el}$ (of which 3400kWh$_{el}$ of electricity is used for heating and hot water provision)

Table 3: State-of-the-art literature of residential DR modeling

Publication author	Optimization objective	Model core	Model formulation	DR program
[22]	Customer electricity cost reduction	Electricity market	Stochastic combinatorial optimization model	Real-time pricing
[23]	Customer electricity cost minimization	Electricity market	Mixed integer nonlinear optimization model	Time-of use pricing
[24]	Customer electricity cost minimization	Electricity market	Medium-grained stochastic hybrid model	Direct load control
[25]	Customer electricity cost minimization	Electricity market	Mixed integer nonlinear optimization model	Dynamic pricing
[19]	Aggregator's generation cost minimization	Electricity market	Mixed integer linear optimization model	Direct load control
[5]	Minimization of utilities' generation costs/ Customer electricity cost minimization	Electricity market	Mixed integer linear optimization model	Direct load control
[26]	Customer electricity cost minimization	Electricity market	Mixed integer linear optimization model	Real-time pricing
[27]	Customer electricity cost minimization	Electricity market/ Balancing market	Linear optimization model	Real-time pricing
[28]	Customer electricity cost minimization	Electricity market/ Balancing market	Linear optimization model	Real-time pricing
[29]	Customer electricity cost minimization	Electricity market/ Balancing market	Agent-based demand-side model/ Mixed integer linear stochastic supply-side optimization model	Real-time pricing
[30]	Operational cost minimization of district heating system	Electricity market	Mixed integer linear optimization model	Real-time pricing

This research deploys a scenario-based analysis at the municipal energy utility scale to assess the present and future potential of residential DR for municipal energy utilities with regard to economic benefits as well as energy autonomy. It aims to analyze the benefits of electricity market optimization to gain a profound insight into the overall potential of residential DR for customers and utilities. Shiftable loads included in the applied model are the electric loads of household cooling appliances and semi-automatically controlled devices representing commonplace household appliances with high penetration levels on the one hand and the loads of electric heat pumps in combination with a thermal storage system on the other. The main original contributions of this research with regard to the cited literature can be summarized as follows:

- application of multi-level dispatch strategy to determine actor-related optimal results. Technology processes of operator and of user sides are optimally controlled and scheduled with an economic objective under peak shifting constraints. Multiple actors along the energy value chain might assess challenges and opportunities from different perspectives and various interest criteria, since every single consumer and operator has a differing technology-mediated relationship. The multi-level dispatch strategy integrates the different interests of different parties and thus might lead to benefits for both, the organization- and the customer as initially shown by [31],
- assessment of the potential laying in residential DR at community scale, differentiating between three different types of energy utilities, which are characterized by distinct generation portfolios. In this research the focus lies low-priced orchestrator (LO), green municipal utility (GMU) and conventional municipal utility (CMU) as introduced by [1],

- design of variable electricity tariffs (TOU and dynamic pricing), balancing both customer and utility preferences. As introduced residential customers and energy utilities have different preferences and requirements when it comes to variable electricity tariffs. In this context, it is necessary that energy utilities complement the introduction of more dynamic electricity tariffs with information on their advantages over the common FT from an energy market and an individual perspective [15].

4. Optimization approach

4.1. Integrated modeling

The optimal matching of the energy flows between energy sources and energy demand is determined using the model IRPopt [8, 10]. This bottom-up techno-economic numerical optimization model, implemented in GAMS/CPLEX, allows for solving mixed-integer problems (MIP) in a quarter-hourly resolution for perennial periods. The model framework mainly expands on different building blocks of the *deeco* model [32, 33], *xeona* model [31, 34] and *Energy Hub* model [35, 36]. The implemented modular model structure enables the configuration of actors, components, connections and transactions under uncertain market developments and undetermined policy interventions if deemed important to the problem at hand.

Parametrization of the model takes place through the configuration of an energy network graph as well as several financial network graphs. An illustrative schematic overview is illustrated in Figure 2. More detailed information are given in [8, 10]. The structural composition of the technical energy system demonstrates the interconnection of the spatially distributed technology processes within a complex societal framework. Since the system comprises several energy sectors, the technical system graph resembles a directed multi-commodity flow network with nodes as engineering components and arcs as flow gateways. The required specification of the technological component nodes is process-dependent. From this perspective, nodes in this research paper represent energy generation or conversion units, storage technologies as well as energy markets. Thereby, energy markets as well as generation technologies but at some points in time also storage units represent sources of a specific commodity within the flow network. At the same time, conversion technologies and demand loads constitute sinks of a certain commodity associated with the sector. An edge in the graph is associated with the energy flow capability between two components, and is thus a single-commodity edge.

Each flow gateway needs to be associated with legal contracts, covering for instance connection and supply or market participation. The system coordination facilitates the commercial interactions between defined market actors and thus represents the financial network graph of the system. Legal contracts at different gateways determine relationships between various actors which are fundamental for operational decisions. They define the exchange of monetary units between actors. The perceived value of their decision depends on the objective function.

The integration of the technical and financial systems is based on the concept of property. In this context, a component sovereignty function indicates which actor has the authority to optimize the engineering component of the energy system model or in other words, the operational management over the optimization variable. The described construct allows the system model to optimize the unit commitment problem from selected actor perspectives by taking into account technical and commercial interactions.

In this sense, the sketched optimization framework builds upon the DEECO model [32] and Energy Hub model [36]. The process formulations of technologies are based on [32, 37–39]. Furthermore, the idea of a multi-level entity-oriented optimization approach has been already presented by the authors of the XEONA model [31, 34].

4.2. Optimization systematic

Based on the design decisions, the MIP is modeled through an objective function taking into account the financial flows of chosen market actors, time points and energy sectors, based on the dispatch energy flows of the engineering components. The major objective is to maximize the total profit of individual actors.

In the framework of this paper, the model works with an actor-related multi-step optimization systematic [31, 34]. The model first optimizes from an aggregated customer perspective, determining the residual energy demand and excess energy supply with all components the customers have regulative access to. With respect

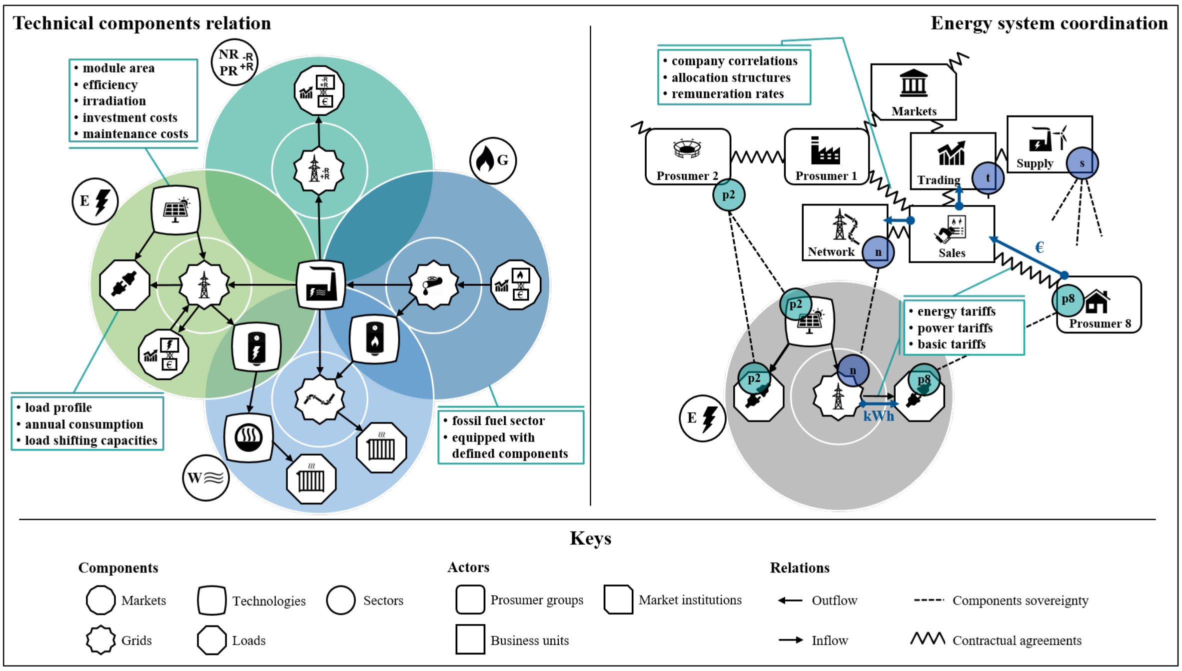

Figure 2: Schematic representation of the interrelations of IRPopt. The energy network graph (left) as well as the actor dependent financial network graphs (right) form the fundamental basis of the multi-step optimization systematic

to the first optimization step (customer optimization), the tariff scheme is of primary importance. The objective function consists of the sum of the electricity and thermal energy purchase costs from the grid as well as the income from energy grid feed in.

In the subsequent step, the model optimizes all other energy and financial flows from the utilities' perspective, considering all residual energy demand and supply. A regional energy deficit might be balanced by generation plant activities and spot market trading. Excess energy is sold or stored. With respect to the second optimization step (organization optimization), the market prices as well as the variable costs of the energy systems are most decisive. In this context, the objective function is restricted by different equality and inequality constraints. These are derived from processes given by the nature of the components. The objective function consists of the sum out of the fuel costs, the electricity energy costs from the market as well as the sales revenues of electricity energy at the market and the sales revenues of electricity and thermal energy to the end customers.

The two-step optimization process is reflected in the operation strategy of the analyzed system as follows:

- customers, able to perform DR, optimize their electricity consumption with regard to their (variable) tariff scheme
- subsequently, utilities provide the electricity demanded by their customers, minimizing their provisioning costs

By summing up variable and fixed cash flows, IRPopt determines the net present value of payment series of individual customer groups as well as business divisions of utilities.

4.3. Shifting mechanism

To investigate the business potential of residential DR for energy utilities in a model-based analysis requires the existence of a suitable residential DR representation in the applied energy system model. To a large part the DR formulation builds on the work of [39], which is outlined in the following section, along with the adaptations made to their proposal for this work. The mathematical formulation is outlined in equations (1-4):

$$DR_t^{up} = \sum_{tt=t-L}^{t+L} DR_{t,tt}^{do} \qquad \forall t \qquad (1)$$

$$DR_t^{up} \leq C^{up} \qquad \forall t \qquad (2)$$

$$\sum_{t=tt-L}^{tt+L} DR_{t,tt}^{do} \leq C^{do} \qquad \forall tt \qquad (3)$$

$$DR_{tt}^{up} + \sum_{t=tt-L}^{tt+L} DR_{t,tt}^{do} \leq max\left\{C^{up}, C^{do}\right\} \qquad \forall tt \qquad (4)$$

The positive variables DR_t^{up} and $DR_{t,tt}^{do}$ are introduced. They represent hourly load shifts in an upward or downward direction. $DR_{t,tt}^{do}$ represents downward load shifts effective in hour tt to compensate for upward shifts in hour t. This formulation directly tags downward load shifts to the respective upward shifts. From equation (1) it follows that every upward load shift is compensated by according downward shifts in due time, taking place either before or after the upward load shift, or both. L represents the load shift horizon. It defines in which interval around hour t downward (upward) load shifts must be compensated by upward (downward) load shifts. Equations (2-3) restrict maximum hourly upward and downward shifts to the predefined levels C^{up} and C^{do}. Depending on which of the restrictions given in these two equations is tighter, only one of the equations is relevant due to equal constraint in equation (1). The other constraint then simply results from equation (4). E.g, in case $C^{do} \leq C^{up}$, equation (2) contains redundant information and can be ignored. On the basis of equation (4) the DR capacity is not fully utilized in both directions at the same time.

The actual implications of the proposal by [39] can be shown by drawing on a stylized example. In this example, customers are equipped with DR resources that are characterized by a load shift horizon L of two hours and a maximum level of hourly upward and downward shifts C^{up} and C^{do} of 20 MWh. The demand without the utilization of DR is constant and the electricity price between the hours 8 to 16 is assumed to be lower than it is during the rest of the day. An illustrative sketch of the example with a DR representation according to equations (1-4) is shown in Fig. 3. Demand is shifted as a reaction to the price signal, with upward shifts in hours 8, 9, 13 and 14 and downward shifts in hours 6, 7, 15 and 16.

The integration of a DR representation into the existing IRPopt model requires both reinterpretation and adaptation of the presented DR formulation:

- Since IRPopt has a quarter-hourly resolution, the indices t and tt do not represent the hour, but the quarter hour, in which a load shift takes place.
- Due to the rolling horizon applied in IRPopt, the formulation is adapted so that the optimization of residential customers with the help of DR measures is restricted to the optimization horizon. Thus, all load shifts have to be balanced out at the end of every day.
- The DR parameters C^{up} and C^{do} are redefined as being load-dependent ($C^{up}(Customer\ load)$ and $C^{do}(Customer\ load)$). Thus, both parameters can be defined as percentage shares of customer loads that serve as input into IRPopt.

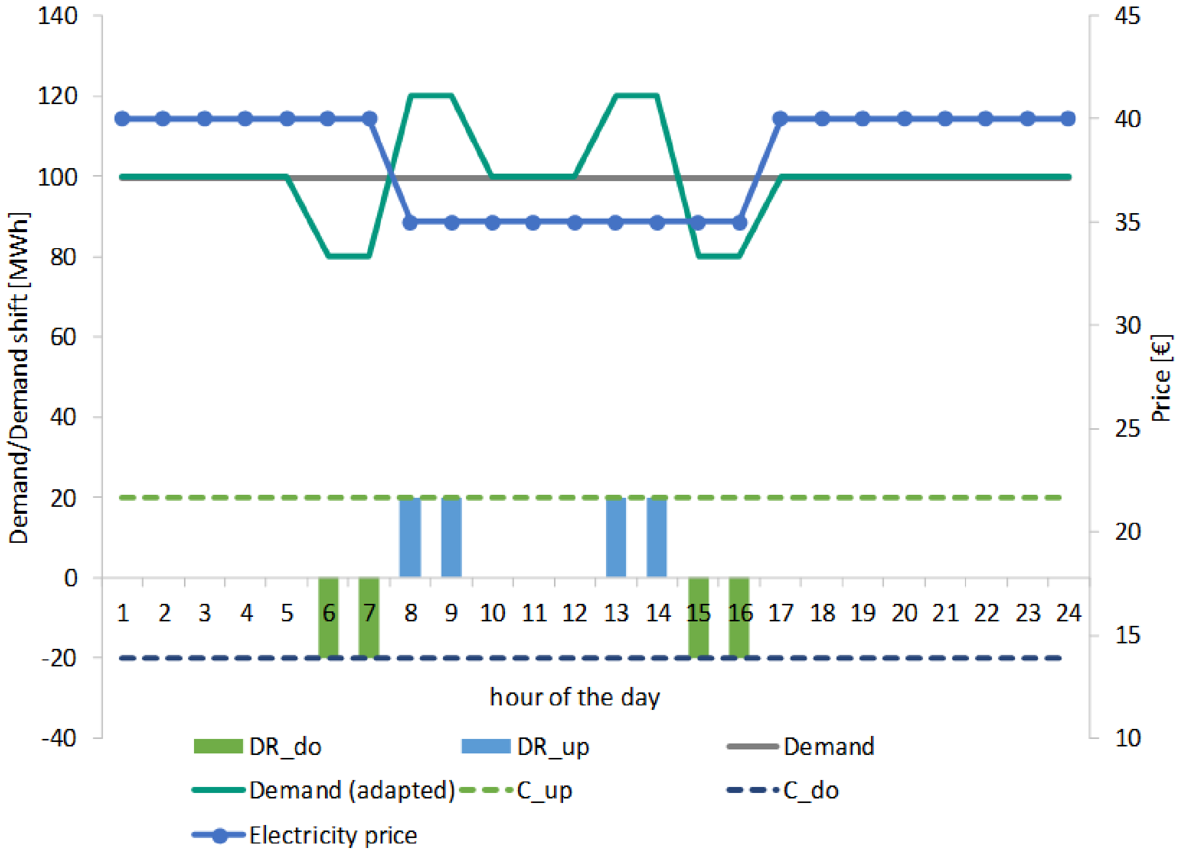

Figure 3: Illustration of the DR mechanism as reaction to a price signal, based on [39]

5. Case studies

5.1. Model inputs

5.1.1. Market foundations

The potential future state of the energy system is investigated by applying a green scenario, where a strong increase of renewables is assumed. The selected scenario set some of the boundary conditions for the assessment. The quarter-hourly data sets are based on German spot market price projections of MICOES-Europe [40, 41]. In addition to the projections for 2025 and 2035, the initial year of 2015 uses historical market data. An overview of average spot market price characteristics is given in Figure4. In this context, the higher projected spot market prices are characterized by a rise of CO_2-prices as well as fuel prices. At the same time, the future merit order effect is visible by the through deep valleys. Additionally, an interest rate of 4 % and a value added tax of 19 % is applied.

5.1.2. Relevant actors

According to [1], four different types of energy utilities with distinct value-added architectures can be distinguished: supra-regional and local (municipal) integrators as well as low-priced and green orchestrators. Based on that, this research paper distinguishes on the utility-side between three different types of energy utilities. Firstly, a LO without any own generation facilities. Secondly, a GMU, which is characterized by

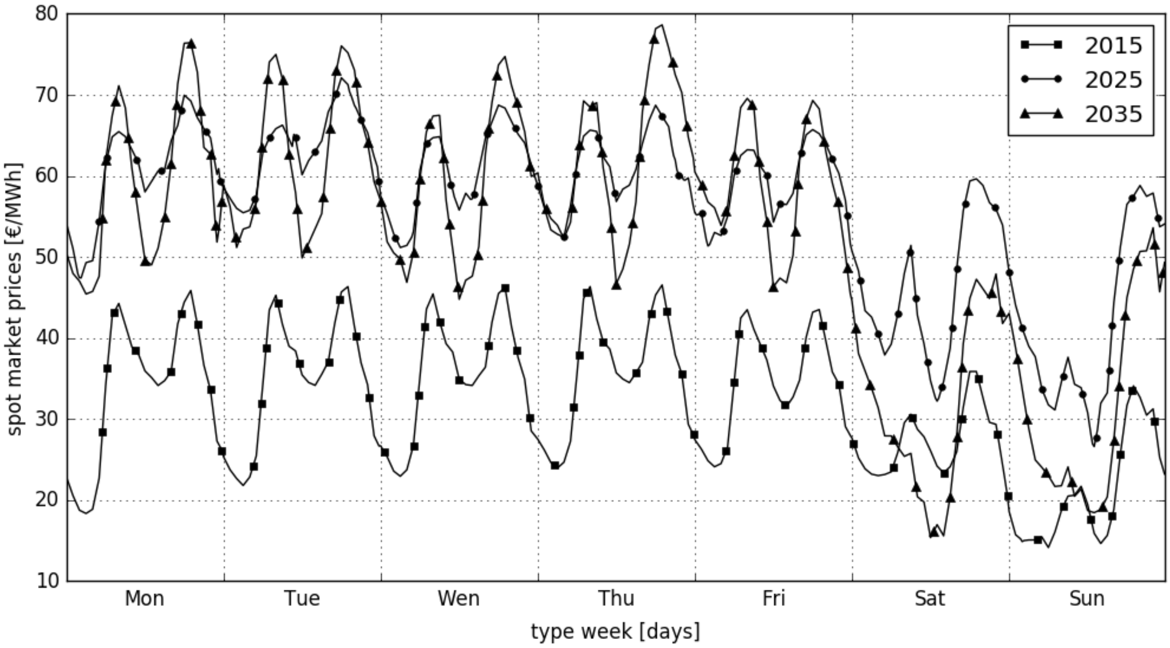

Figure 4: Average week of spot market prices for the years 2015, 2025 and 2035 (green scenario)

a large share of electricity production from wind energy plants. Thirdly, a CMU, whose generation relies largely on cogeneration plants.

The residential customers considered in this research paper can be distinguished by the share of total electricity consumption that they are able to shift over time. For matters of simplification, none of the residential customers under consideration owns a generation facility. The share of total residential electricity consumption shiftable over time depends on the characteristics of appliances owned by residential customers. Thereby, two customer groups are taken into account with respect to the optimization cases as shown in more detail in section 5.2. While in several cases as shown in only a group of five residential customers with distinct electrical load profiles is included (customer group 1 - hereafter abbreviated by CG1), in further cases this group is complemented with a customer group of five distinct types of customers characterized by the same electrical load profiles as their counterparts in CG1 and an additional electricity consumption for the provision of heat and hot water by a system coupling an electrical heat pump with a thermal buffer storage (customer group 2 - hereafter abbreviated by CG2).

5.1.3. Electricity tariffs

The grid electricity FT is one of the most crucial input data. For every time step in 2015, the customer pays 28.81 Ct/kWh$_{el}$ (el for electrical energy) to sales-side, grid-side and political-side, with proportions depending on fees and levies. Table 4 shows the total cost of electricity and its cost components for household customers purchasing their electricity from the electricity grid in 2015. A detailed analysis is outlined in [42]. After deduction of the statutory fees and levies (grid fee, value added tax, concession fee, EEG surcharge, electricity tax, cogeneration levy and other levies) the competitive or sales pricing elements remained (profit margin and supplier's cost of purchasing wholesale power on the market). Given the mean spot market price at the EPEX SPOT in 2015 of 3.16 Ct/kWh$_{el}$, the remaining 3.96 Ct/kWh$_{el}$ of the sales cost component is assumed to be the utility margin. The tariff for the projected scenarios has been determined according to this: while the grid and regulatory components were kept constant in absolute numbers, the sales component was derived from the projected mean spot price and the fixed margin. A similar procedure was applied to the cost components of the gas tariff. Initial price is 6,6 Ct/kWh$_f$ with grid and regulatory fees and levies of 2,4 Ct/kWh$_f$ and a margin of 1,1 Ct/kWh$_f$.

Table 4: Composition of customer electricity costs for grid usage

Cost component	**Costs [Ct/kWh$_{el}$]**
Grid fees	6.760
EEG surcharge	6.170
Cogeneration levy	0.254
Offshore liability	-0.051
Concession fee	1.660
§ 19 StromNEV levy	0.237
Levy for deferrable loads	0.006
Electricity tax	2.050
Sales (competitive pricing)	7.120
Value added tax	4.600
Total costs	28.806

As stated in section 2.3, every variable electricity tariff represents a compromise between the preferences of customers, who prefer less dynamic variable tariffs, and utilities, which, if technically feasible, prefer highly dynamic tariffs. Hence, for the model-based analysis of this research a total of six variable electricity tariffs, consisting of a fixed utility margin of 3.96 Ct/kWh$_{el}$ and a fluctuating price component, are designed, ranging from highly dynamic to very static. Thereby, the most static tariff is given with the FT. Table 5 lists and explains the three dynamic tariffs as well as the three TOU tariffs that are applied in the model-based analysis. Additionally, with the exception of the FT each of the tariffs is illustrated in Fig. 5.

In three of these tariffs the fluctuating price component reflects the average electricity spot market price within the different TZs (dynamic pricing schemes). Consequently, the price levels during the same TZ on two different days are likely to differ from each other. In this context, the one hour (1h) tariff scheme 1h$_{dyn}$ reflects the varying degree of hourly changes of the spot market prices for energy, the four TZ identifier 4TZ$_{dyn}$ reflects the varying degree of four time-zones of every day (morning, midday, evening and night), and the low tariff time (NT) and high-tariff time (HT) identifier NT/HT$_{dyn}$ reflects the varying degree of two price zones every day.

In the remaining tariffs - although having the same TZ as their dynamic counterparts - the fluctuating price component reflects the average electricity spot market prices within the respective TZs over all days of the same type (weekday, Saturday, Sunday) and within the same season (winter, summer, transition season) of the evaluation year (TOU pricing schemes). As mentioned in section 2.2, in real life the price levels for the respective TZs in TOU pricing schemes as given in 1h$_{TOU}$, 4TZ$_{TOU}$, NT/HT$_{TOU}$, are established on the basis of historical or forecasted spot market prices.

Special attention should be paid to the tariffs 4TZ$_{dyn}$ and 4TZ$_{TOU}$, since their TZs are not assigned to the same fixed times over the whole year, as it is done for the other tariffs, but orientate themselves along the average spot market price level during days of the same type/season. The two peak price TZs, one in the morning, the other one in the evening, lasting 4 hours each, are assigned to cover the peak price periods of electricity on the spot market. Therefore, the first TZ - the morning - lasts, for example, from 6:00 to 10:00 on a weekday in winter, while it lasts from 7:00 to 11:00 and from 8:00 to 12:00 on a Sunday in summer. A complete overview of the TZ assignment in tariffs 4TZ$_{dyn}$ and TZ4$_{TOu}$ can be found in the Appendix.

In the second stage of this research (*Model Confiq II*), the presented set of tariffs is reduced to the three tariffs that led to the best results in *Model Confiq I* and is further complemented by modified versions of these three tariffs. The modification is based on the DR pattern of customers and the generation profile of the two municipal energy utilities. More concretely, the customer electricity price is decreased by 0.4

Table 5: Characteristics of applied electricity tariffs$_{el}$

Tariff identifier	Description
FT	FT with constant electricity price (yearly avg. spot market prices + margin)
$1h_{dyn}$	Tariff with hourly changes in price (hourly avg. of spot prices + margin)
$4TZ_{dyn}$	Tariff characterized by four price zones with distinct price levels: morning, mid-day, evening and night (zonally avg. of spot prices + margin)
NT/HT_{dyn}	Tariff having two price zones per day: day (6:00 - 22:00) and night (22:00 - 6:00) (zonally avg. of spot prices + margin)
$1h_{TOU}$	Tariff with hourly seasonal (TZs during days of the same season exhibit the same price levels) changes in price (hourly seasonal avg. of spot prices + margin)
$4TZ_{TOU}$	Tariff characterized by four seasonal price zones with distinct price levels: morning, mid-day, evening and night (zonally seasonal avg. of spot prices + margin)
NT/HT_{TOU}	Tariff having two seasonal price zones per day: day (6:00 - 22:00) and night (22:00 - 6:00) (zonally seasonal avg. of spot prices + margin)

Ct/kWh$_{el}$ in time steps in which:

- the generation from utility owned facilities is 20% higher than the residential electricity demand and
- households do not show any upward demand shifts in the model run applying the unmodified original tariff.

5.1.4. Shifting parameters

As stated in section 2.4, without taking electric heating systems into account, the realistic maximum share of shiftable residential electricity consumption is approximately 30%. Hence, in *Model Confiq I*, the set DR_{LS} of applied values for the parameter *share of total shiftable load* includes elements ranging from 0.1 to 0.3 in steps of 0.05 ($DR_{LS} = \{0.10,\ 0.15,\ 0.20,\ 0.25,\ 0.30\}$). To set an upper boundary for the parameter *load shift horizon* is a more complex task. This is due to the fact that each electric household appliance exhibits a distinct load shift horizon. Since only one single value serves as an input into the model, this value can be regarded as the average load shift horizon, taking the distinct load shift horizons of all DR capable appliances into account. Based on the information presented in section 2.4, the longest load shift horizon that is applied in the scenarios of *Model Confiq I* is three hours. However, it has to be noted that reaching this maximum average value, the insulation of all cooling appliances needs to be optimal and customers need to make use of the DR potential of their semi-automatically controlled appliances. The set DR_{SH} of applied values for the parameter load shift horizon in *Model Confiq I* includes values from 1 h to 3 h in half hour steps ($DR_{SH} = \{1.0\text{h},\ 1.5\text{h},\ 2.0\text{h},\ 2.5\text{h},\ 3.0\text{h}\}$). In *Model Confiq II*, both DR parameters are fixed at realistic specific values; *share of total shiftable load* is set to 0.2, while *load shift horizon* is fixed at 2.0 hours (see section 2.4).

5.1.5. Load profiles

The residential customers of CG1 and CG2 are assigned with slightly different electrical load profiles. These are taken from a household load profile set of HTW Berlin [43] with a temporal resolution of one minute, which are adapted to the quarter-hourly resolution of IRPopt. The load profiles are scaled to a yearly electricity consumption of 3500 kWh$_{el}$. The heating load profiles for customers of CG2 are derived on the basis of the Hellwig methodology [44]. It is assumed that these customers live in new single-family houses with an average heating demand of 13600 kWh$_{th}$ (th for thermal energy) per year.

5.1.6. Technology characteristics

Tables 6 –9 give a comprehensive overview of characteristics of customer-side and utility-side technologies that are applied in the model. In all scenarios in *Model Confiq II*, customers from CG2 are equipped with

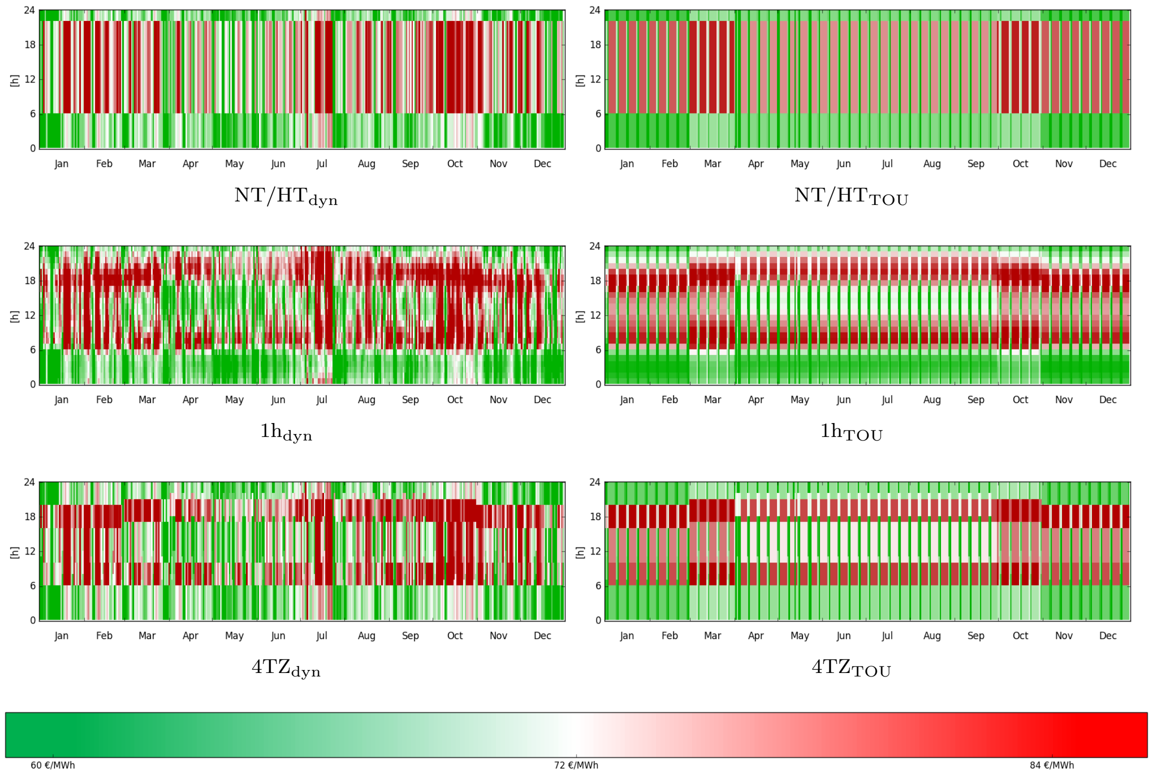

Figure 5: Applied TOU and dynamic electricity tariffs of the year 2015 (competitive pricing elements only)

the identical heat pump system. In contrast, the size and, consequently, the investment cost of the applied thermal buffer storage depends on the selected tariff scheme. In the reference case, in which a FT is applied a thermal buffer storage of 250 l, corresponding to a maximum thermal capacity of approximately 15 kWh_{th}, is used. In all other scenarios, characterized by time-variable tariffs, the applied thermal buffer storage has a size of 500 l, or a thermal capacity of approximately 30 kWh_{th}. The values pertaining to the scenarios with time-variable tariffs are listed in brackets in Table 7.

The applied heat pump is a ground-source heat pump with a constant coefficient of power (COP) of 4. Since this work does not aim at a cost comparison of different heating systems, the investment costs and the technical life time of the heat pump are of no importance. An important characteristic regarding demand shifts is the self-discharge rate, which is assumed to be 0.1 % per time step. The technical lifetime of both technologies is assumed to be 20 years.

On the utility-side, the wind energy plant is scaled via the rotor diameter in such a way that its electricity generation exceeds the demand of the residential customers for a considerable amount of time intervals. In these times, the municipal energy utility has the opportunity to gain additional profit by adapting their electricity tariff to foster demand shifts. Assuming a FT, the designed wind energy plant covers approximately 60 % of the residential demand in 2015. The wind speed data used as input into the model runs is taken from the meteonorm databank [45] and corresponds to data that was recorded in Kiel/Holtenau in the year 2005.

In the design of the combined heat and power (CHP) plant, attention is paid to the fact that the heating demand of the customers connected to the district heating grid can be satisfied at any point. The values of the generation facilities were chosen on the basis of a survey of available information.

Table 6: Heat pump characteristics

Characteristic	Value	Unit
Maximum thermal power	9	kW_{th}
COP	4	

Table 7: Thermal storage characteristics

Characteristic	Value	Unit
Maximum thermal capacity	15 (30)	kWh_{th}
Maximum state of charge	100	%
Minimum state of charge	0	%
Maximum charging capacity	21	kW_{th}
Maximum discharge capacity	21	kW_{th}
Self-discharge rate	0.10	%/15 min
Technical lifetime	20	years
Investment costs	1050 (1200)	€

Table 8: Wind energy plant characteristics

Characteristic	Value	Unit
Maximum capacity	0.76	MW
Power coefficient C_p	0.50	
Generator efficiency	98	%
Drive train efficiency	98	%
Rotor diameter	31.62	m
Hub height	130	m
Air density at hub height	1.20	kg/m^3
Nominal wind speed	15	m/s
Start-up speed	3	m/s
Shut-down speed	25	m/s
Technical lifetime	20	years

Table 9: CHP plant characteristics

Characteristic	Value	Unit
Maximum electric capacity	0.30	MW
Minimum electric capacity	0	MW
Electric efficiency	0.27	
Power to heat ratio	0.50	
Technical lifetime	20	years

5.2. Case overview

To explore challenges and opportunities of residential DR, this research deploys a scenario-based analysis at neighborhood scale, considering different market actors, system processes as well as system relations. Table 10 lists the optimization cases of this research paper with respect to the utility and customer characteristics. The research consists of two stages: *Model Confiq I* and *Model Confiq II*.

Three types of utilities are distinguished: LO, GMU and CMU. Cases in research stages *Model Confiq I* and *Model Confiq II* are characterized by different customer structures. While in scenarios with *Model Confiq I*, only customers from CG1 are included, scenarios with *Model Confiq II* also take customers from CG2

Table 10: Optimization scenarios

Research stage	Utility and customer characteristics			
	Utility type	**Tariff scheme**	**DR parameters**	**CG setting**
MT I	LO	FT	–	CG1
MT I	LO	$1h_{dyn}$	$[DR_{LS}] \times [DR_{SH}]$	CG1
MT I	LO	$4TZ_{dyn}$	$[DR_{LS}] \times [DR_{SH}]$	CG1
MT I	LO	NT/HT_{dyn}	$[DR_{LS}] \times [DR_{SH}]$	CG1
MT I	LO	$1h_{TOU}$	$[DR_{LS}] \times [DR_{SH}]$	CG1
MT I	LO	$4TZ_{TOU}$	$[DR_{LS}] \times [DR_{SH}]$	CG1
MT I	LO	NT/HT_{TOU}	$[DR_{LS}] \times [DR_{SH}]$	CG1
MT II	LO	FT	–	CG1/2
MT II	LO	T1	0.2, 2.0h	CG1/2
MT II	LO	T2	0.2, 2.0h	CG1/2
MT II	LO	T3	0.2, 2.0h	CG1/2
MT II	GMU	FT	0.2, 2.0h	CG1/2
MT II	GMU	T1	0.2, 2.0h	CG1/2
MT II	GMU	T2	0.2, 2.0h	CG1/2
MT II	GMU	T3	0.2, 2.0h	CG1/2
MT II	GMU	$T1_{mod,GMU}$	0.2, 2.0h	CG1/2
MT II	GMU	$T2_{mod,GMU}$	0.2, 2.0h	CG1/2
MT II	GMU	$T3_{mod,GMU}$	0.2, 2.0h	CG1/2
MT II	CMU	FT	–	CG1/2
MT II	CMU	T1	0.2, 2.0h	CG1/2
MT II	CMU	T2	0.2, 2.0h	CG1/2
MT II	CMU	T3	0.2, 2.0h	CG1/2
MT II	CMU	$T1_{mod,CMU}$	0.2, 2.0h	CG1/2
MT II	CMU	$T2_{mod,CMU}$	0.2, 2.0h	CG1/2
MT II	CMU	$T3_{mod,CMU}$	0.2, 2.0h	CG1/2

into account. In this context, each customer group also consists of different individual households equipped with respective loads and decentralized technologies. In this context, the municipality posses a high share of renewables on the basis of a wind turbine of the GMU. Further, while CG1 serves their heating load with gas boilers, CG2 takes heat pumps into account.

Additionally, in *Model Confiq I*, one FT as well as six variable tariffs ($1h_{dyn}$, $4TZ_{dyn}$, NT/HT_{dyn}, $1h_{TOU}$, $4TZ_{TOU}$, NT/HT_{TOU}) serve as input for the different business cases. In contrast, for cases in *Model Confiq II*, only the three tariffs that perform best in *Model Confiq I* are selected. In Table 10, these tariffs are listed as T1, T2 and T3.

Additional tariffs ($T1_{mod,GMU}$, $T2_{mod,GMU}$, $T3_{mod,GMU}$ and $T1_{mod,CMU}$, $T2_{mod,CMU}$, $T3_{mod,CMU}$) are created by modifying these tariffs based on the DR pattern that customers exhibit when being exposed to the original tariffs and the generation profile of the utilities, the GMU and the CMU. The optimization scenarios in which a FT is applied and no DR is performed by the customers, represents the reference case. Next to the economic assessment, this part of the research also investigates the effects of residential DR on the energy autonomy of municipalities, or, in other words, their independence from external electricity production. In this work, the level of energy autonomy is defined as the quotient of the consumption of locally produced electricity and the total electricity consumption of residential customers.

In addition, in *Model Confiq I*, the decisive DR parameters - *share of total shiftable load* DR_{LS} and *load shift horizon* DR_{SH} - demonstrate sensitivity parameters and thus are varied between the individual optimization cases to assess the influence of both parameters on customer savings and utility earnings. Detailed information about the shifting parameters is also given in the next subsection.

Moreover, as described before, while the evaluation in *Model Confiq I* concentrates solely on the year 2015, the evaluation period in *Model Confiq II* is broadened to 2015, 2025 and 2035. This allows an assessment of the overall potential.

6. Optimization results

6.1. Model Confiq I

Fig. 6 depicts the change in customer, utility and combined results per household when applying tariff $1h_{dyn}$ compared to the results of the reference model run for varying values of *load shift horizon* (1.5 h - 3.0 h) and *share of total shiftable load* (10 - 30 %) in the year 2015. The results show that even when residential customers who exclusively perform DR with the help of electric household appliances are exposed to a very dynamic variable electricity tariff, such as $1h_{dyn}$, they are financially worse off than in the reference case, in which they are facing a FT with no opportunity to perform DR. The shorter the load shift horizon and the smaller the share of total shiftable load, the worse the customer results are. However, the results of the utility, a LO in this stage of the research, are higher than in the reference case in every instance in which customers are able to perform DR. Furthermore, it can be observed that a change in the DR parameters has only a minimal effect on the utility result, which decreases slightly with an increase of the share of total shiftable load and stays approximately constant over varying load shift horizons. The combined results, the sum of customer and utility results, is calculated to see if any gains in overall welfare can be achieved by residential DR provoked through a specific variable electricity tariff. For tariff $1h_{dyn}$, the combined results are positive for all model runs with a load shift horizon equal to or longer than 1.5 h and a share of total shiftable load equal or larger than 15 %.

Fig. 7 shows the change in customer, utility and combined results per household for all six variable electricity tariffs and the specific DR parameter combination of 2.0 h and 20 %. While both NT/HT_{dyn} and NT/HT_{TOU} show poor results, the greatest overall welfare gains are achieved by tariff $1h_{dyn}$, followed by tariffs $1h_{TOU}$, $4TZ_{dyn}$ and $4TZ_{TOU}$, all three of which show similar results. Although tariff $1h_{TOU}$ performs slightly better than the other two tariffs at the fixed DR parameter combination, tariffs $4TZ_{dyn}$ and $4TZ_{TOU}$ are selected for the further analysis in stage *Model Confiq II*, along with tariff $1h_{dyn}$. This is justified by the fact that customers prefer variable tariffs with fewer price levels over alternative options with more price levels.

Fig. 8 gives a complete overview of the change in combined results per customer relative to the base case results for all applied variable electricity tariffs over all possible DR parameter combinations. While tariffs NT/HT_{dyn} and NT/HT_{TOU} show hardly any economic potential, the other tariffs have a small economic potential, which is in this stage still exclusively performed by electric household appliances. Naturally, the larger the share of total shiftable load and the longer the load shift horizon, the bigger the economic potential of variable electricity tariffs. Nevertheless, in order to achieve any gains in overall welfare, even in the scenarios with the four best performing tariffs ($1h_{TOU}$, $1h_{TOU}$, $4TZ_{dyn}$ and $4TZ_{TOU}$), households need to reach a share of total shiftable load of at least 20 % and a load shift horizon of two hours.

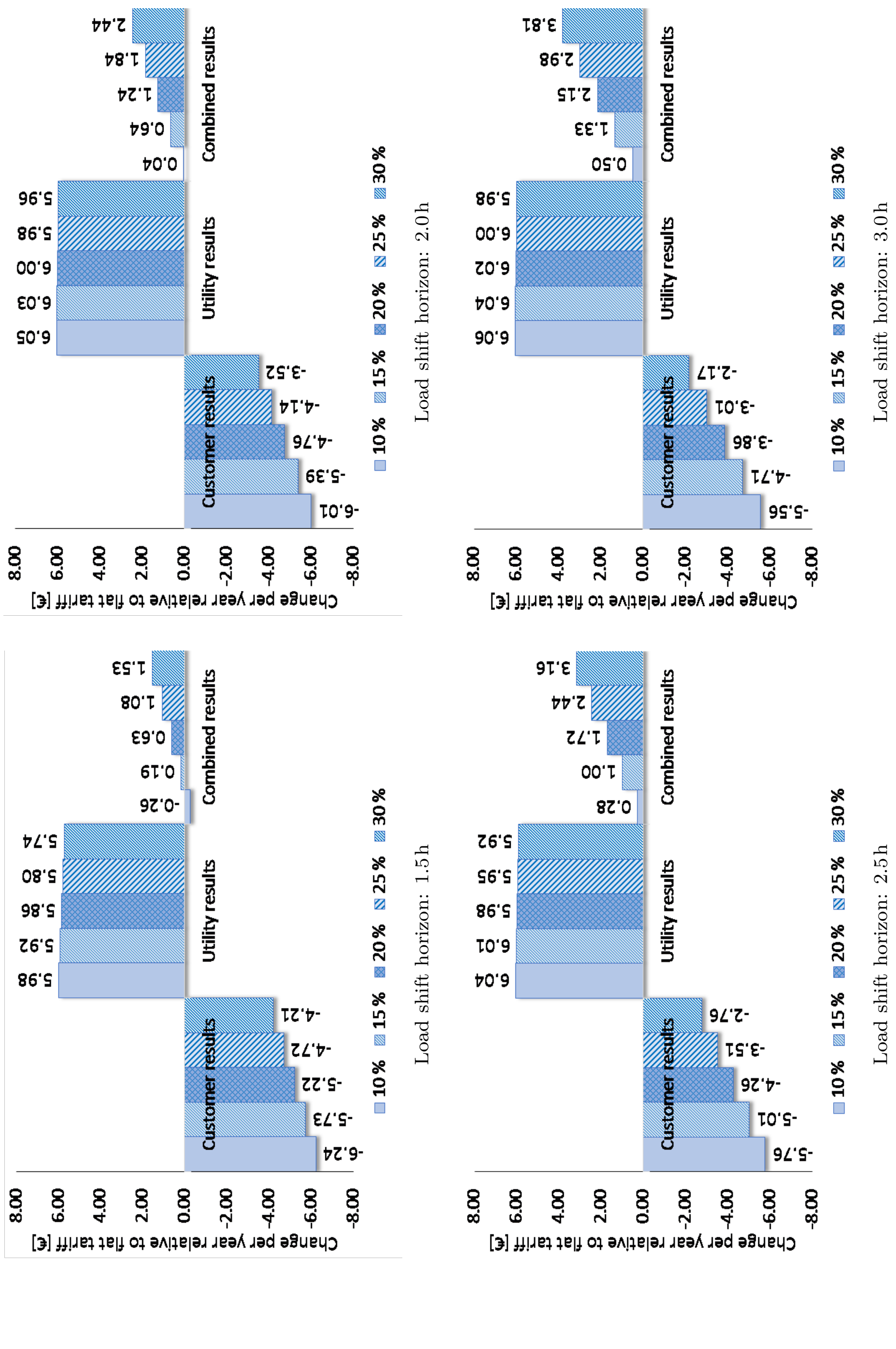

Figure 6: Change in customer, utility and combined results in 2015 when applying tariff $1h_{dyn}$ compared to a FT for varying load shift horizons and shares of total shiftable load of $10-30\,\%$

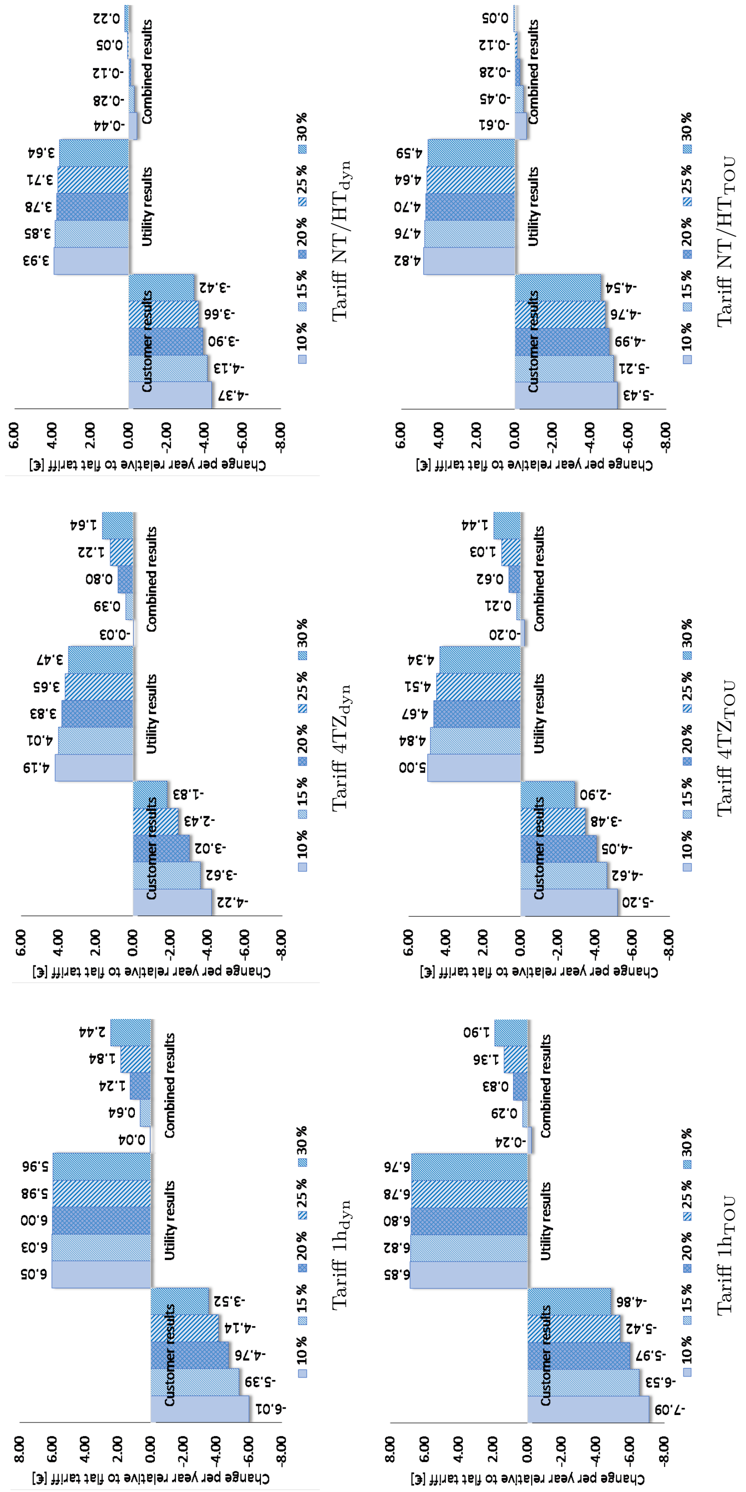

Figure 7: Change in customer, utility and combined results in 2015 when applying a variable tariff compared to a FT for a fixed load shift horizon of 2.0 h and shares of total shiftable load of 10 - 30 %

Share of total load shiftable	Maximum duration of load shifts: 1.0 h	1.5 h	2.0 h	2.5 h	3.0 h
0.10	-0.06%	-0.03%	0.00%	0.03%	0.05%
0.15	-0.03%	0.02%	0.06%	0.10%	0.13%
0.20	0.00%	0.06%	0.12%	0.17%	0.21%
0.25	0.03%	0.11%	0.18%	0.24%	0.30%
0.30	0.06%	0.15%	0.24%	0.31%	0.38%

Tariff $1h_{dyn}$

Share of total load shiftable	Maximum duration of load shifts: 1.0 h	1.5 h	2.0 h	2.5 h	3.0 h
0.10	-0.08%	-0.05%	-0.02%	0.00%	0.02%
0.15	-0.05%	-0.01%	0.03%	0.06%	0.09%
0.20	-0.03%	0.02%	0.08%	0.13%	0.17%
0.25	0.00%	0.06%	0.13%	0.19%	0.24%
0.30	0.02%	0.10%	0.19%	0.26%	0.31%

Tariff $1h_{TOU}$

Share of total load shiftable	Maximum duration of load shifts: 1.0 h	1.5 h	2.0 h	2.5 h	3.0 h
0.10	-0.06%	-0.03%	0.00%	0.02%	0.04%
0.15	-0.04%	-0.01%	0.04%	0.07%	0.10%
0.20	-0.03%	0.02%	0.08%	0.13%	0.17%
0.25	-0.01%	0.05%	0.12%	0.18%	0.23%
0.30	0.00%	0.07%	0.16%	0.23%	0.30%

Tariff $4TZ_{dyn}$

Share of total load shiftable	Maximum duration of load shifts: 1.0 h	1.5 h	2.0 h	2.5 h	3.0 h
0.1	-0.07%	-0.05%	-0.02%	0.00%	0.02%
0.15	-0.06%	-0.02%	0.02%	0.06%	0.09%
0.2	-0.04%	0.00%	0.06%	0.11%	0.15%
0.25	-0.03%	0.03%	0.10%	0.16%	0.21%
0.3	-0.01%	0.06%	0.14%	0.21%	0.27%

Tariff $4TZ_{TOU}$

Share of total load shiftable	Maximum duration of load shifts: 1.0 h	1.5 h	2.0 h	2.5 h	3.0 h
0.10	-0.06%	-0.05%	-0.04%	-0.04%	-0.03%
0.15	-0.05%	-0.04%	-0.03%	-0.02%	0.00%
0.20	-0.05%	-0.03%	-0.01%	0.00%	0.02%
0.25	-0.04%	-0.02%	0.01%	0.02%	0.04%
0.30	-0.03%	-0.01%	0.02%	0.04%	0.07%

Tariff NT/HT_{dyn}

Share of total load shiftable	Maximum duration of load shifts: 1.0 h	1.5 h	2.0 h	2.5 h	3.0 h
0.10	-0.08%	-0.07%	-0.06%	-0.05%	-0.04%
0.15	-0.07%	-0.06%	-0.04%	-0.03%	-0.02%
0.20	-0.06%	-0.05%	-0.03%	-0.01%	0.00%
0.25	-0.06%	-0.04%	-0.01%	0.01%	0.03%
0.30	-0.05%	-0.03%	0.01%	0.03%	0.05%

Tariff NT/HT_{TOU}

Figure 8: Change in combined results per customer relative to base case results for all variable tariffs over all possible DR parameter combinations displayed as share of base case customer electricity costs

6.2. Model Confiq II

Tables 11, 12 and 13 list the economic results of the optimization scenarios of stage *Model Confiq II*. Each table depicts the change in customer groups ($CG1$ / $CG2$), utility earnings of each of the customer groups ($Utility_{\mathrm{CG1}}$ / $Utility_{\mathrm{CG2}}$) and combined results with respect to the base case results for one of the three different types of energy utilities that are included in the analysis. Customer and utility results that can be attributed to customers from CG1, who solely perform DR with electric household appliances, are listed separately from the results that are attributable explicitly to the use of a heating system combining an electric heat pump with a thermal buffer storage system of customers from CG2 (in order to analyze costs for heat pump separately, the CG2 is depicted with $\mathrm{CG2_{HP}}$). As depicted before, all optimization scenarios of this research stage have been optimized on the data basis of 2015, 2025 and 2035.

First of all, the optimized scenarios support the outcomes from *Model Confiq I*. The tariffs $\mathrm{1h_{dyn}}$, $\mathrm{4TZ_{dyn}}$ and $\mathrm{4TZ_{TOU}}$ show a small economic potential in the context of DR performed by customers from CG1 for the LO in the years 2025 and 2035. A very similar picture presents itself when looking at the respective results for the CMU and the GMU. The only exceptions are the optimization scenarios for tariff $\mathrm{4TZ_{TOU}}$ in the year 2025, in which the combined results are negative.

Additionally, it can be observed that variable electricity tariffs exhibit a considerable economic potential in the context of DR performed by heating systems combining an electric heat pump with a thermal buffer storage system. Independent of the type of utility, tariff $\mathrm{1h_{dyn}}$ shows much better combined results than tariff $\mathrm{4TZ_{dyn}}$, which in turn, performs better than tariff $\mathrm{4TZ_{TOU}}$ in this context. It is worth mentioning that tariff $\mathrm{1h_{dyn}}$ is the only one out of the three mentioned tariffs that leads to positive customer results throughout all evaluation years, regardless of the utility. Furthermore, the different tariff schemes lead to similar combined results for the different utility set-ups.

In most cases, the modified tariffs $\mathrm{1h_{dyn,mod,GMU}}$, $\mathrm{4TZ_{dyn,mod,GMU}}$, $\mathrm{4TZ_{TOU,mod;GMU}}$ and $\mathrm{1h_{dyn,mod,CMU}}$, $\mathrm{4TZ_{dyn,mod,CMU}}$, $\mathrm{4TZ_{TOU,mod,CMU}}$ perform equally well or even slightly better than their unmodified counterparts. In addition, Table 14 reveals a further advantage over the unmodified tariffs: they help to increase the level of energy autonomy of municipalities. While in case of the municipality with the GMU the level of energy autonomy is increased by $0.44 - 0.52\,\%$, it is increased by $0.3 - 0.34\,\%$ in the case of the municipality with the CMU.

Table 11: Change in customer, utility (LO) and combined results per household in 2015, 2025 and 2035 when applying variable tariffs compared to a FT (in €)

Tariff	**Year**	**CG1**	**Utility$_{CG1}$**	**Combined CG1/Utility$_{CG1}$**	**CG2$_{HP}$**	**Utility$_{CG2_{HP}}$**	**Combined CG2$_{HP}$/Utility$_{CG2_{HP}}$**
$1h_{dyn}$	2015	-4.76	6.00	1.24	1.14	12.25	13.40
	2025	-3.64	4.78	1.14	0.33	13.88	14.21
	2035	-3.86	6.42	2.56	12.03	29.90	41.93
$4TZ_{dyn}$	2015	-3.02	3.83	0.81	-3.27	9.37	6.10
	2025	-1.52	2.12	0.60	-6.71	9.53	2.82
	2035	-1.40	2.93	1.53	0.16	22.05	22.21
$4TZ_{TOU}$	2015	-4.05	4.67	0.62	-8.29	11.20	2.91
	2025	-2.11	2.56	0.45	-12.94	7.58	-5.36
	2035	-3.51	4.62	1.11	-14.67	21.38	6.71

Table 12: Change in customer, utility (GMU) and combined results per household in 2015, 2025 and 2035 when applying variable tariffs compared to a FT (in €)

Tariff	**Year**	**CG1**	**Utility$_{CG1}$**	**Combined CG1/Utility$_{CG1}$**	**CG2$_{HP}$**	**Utility$_{CG2_{HP}}$**	**Combined CG2$_{HP}$/Utility$_{CG2_{HP}}$**
$1h_{dyn}$	2015	-4.76	5.99	1.23	5.90	6.17	12.07
	2025	-3.54	1.85	-1.69	2.64	13.02	15.66
	2035	-3.86	6.39	2.53	15.89	23.48	39.37
$1h_{dyn,mod,GMU}$	2015	-2.92	4.30	1.38	7.86	3.87	11.73
	2025	-1.55	0.07	-1.48	5.07	10.17	15.24
	2035	-2.08	4.85	2.77	17.73	22.65	39.38
$4TZ_{dyn}$	2015	-3.03	3.76	0.73	-0.24	5.60	5.36
	2025	-1.41	-0.86	-2.27	-6.59	11.47	4.88
	2035	-1.40	2.85	1.45	1.56	19.21	20.77
$4TZ_{dyn,mod,GMU}$	2015	-0.94	2.02	1.08	2.37	2.94	5.31
	2025	0.69	-2.63	-1.94	-3.39	8.70	5.30
	2035	0.59	1.19	1.78	3.95	18.01	21.96
$4TZ_{TOU}$	2015	-4.05	4.61	0.59	-4.24	6.66	2.42
	2025	-2.02	-0.41	-2.43	-12.03	9.03	-3.00
	2035	-3.51	4.54	1.03	-11.21	16.93	5.72
$4TZ_{TOU,mod,GMU}$	2015	-2.00	2.91	0.91	-1.77	3.81	2.03
	2025	0.05	-2.12	-2.07	-9.12	5.90	-3.22
	2035	-1.46	2.83	1.37	-8.92	15.65	6.73

Table 13: Change in customer, utility (CMU) and combined results per household in 2015, 2025 and 2035 when applying variable tariffs compared to a FT (in €)

Tariff	**Year**	**CG1**	**Utility$_{CG1}$**	**Combined CG1/Utility$_{CG1}$**	**CG2$_{HP}$**	**Utility$_{CG2_{HP}}$**	**Combined CG2$_{HP}$/Utility$_{CG2_{HP}}$**
$1h_{dyn}$	2015	-4.76	5.99	1.23	5.90	6.18	12.08
	2025	-3.55	4.69	1.14	2.65	10.18	12.83
	2035	-3.86	6.39	2.53	15.89	23.48	39.37
$1h_{dyn,mod,GMU}$	2015	-2.24	2.65	0.41	8.94	3.83	12.77
	2025	-0.92	2.33	1.41	6.65	5.55	12.20
	2035	-1.62	4.45	2.83	19.00	20.35	39.35
$4TZ_{dyn}$	2015	-3.03	3.76	0.73	-0.24	5.61	5.37
	2025	-1.42	1.98	0.56	-6.58	8.66	2.08
	2035	-1.40	2.85	1.45	1.56	19.21	20.77
$4TZ_{dyn,mod,GMU}$	2015	-0.16	1.40	1.24	3.90	1.18	5.08
	2025	1.46	-0.43	1.03	-1.25	3.60	2.35
	2035	1.16	0.76	1.92	5.52	16.08	21.60
$4TZ_{TOU}$	2015	-1.20	2.25	1.05	-0.37	2.30	1.93
	2025	-2.03	2.43	0.40	-12.02	6.21	-5.81
	2035	-3.51	4.53	1.02	-11.16	16.96	5.81
$4TZ_{TOU,mod,GMU}$	2015	-2.00	2.91	0.91	-1.77	3.81	2.03
	2025	0.75	0.12	0.87	-7.25	0.28	-6.97
	2035	-0.82	2.33	1.55	-7.58	13.56	5.98

Table 14: Change in the level of energy autonomy of the investigated municipality

Utility	Tariff	Year	Change in energy autonomy relative to base cases [%]
GMU	$1h_{dyn}$	2015	-0.03
		2025	-0.09
		2035	-0.56
	$4TZ_{dyn}$	2015	-0.09
		2025	-0.12
		2035	-0.49
	$4TZ_{TOU}$	2015	-0.03
		2025	-0.10
		2035	-0.74
	$1h_{dyn,mod,GMU}$	2015	0.39
		2025	0.48
		2035	-0.23
	$4TZ_{dyn,mod,GMU}$	2015	0.35
		2025	0.39
		2035	-0.10
	$4TZ_{TOU,mod,GMU}$	2015	0.43
		2025	0.35
		2035	-0.10
CMU	$1h_{dyn}$	2015	-0.53
		2025	-0.58
		2035	-0.79
	$4TZ_{dyn}$	2015	-0.28
		2025	-0.40
		2035	-0.77
	$4TZ_{TOU}$	2015	-0.34
		2025	-0.46
		2035	-0.76
	$1h_{dyn,mod,GMU}$	2015	-0.22
		2025	-0.10
		2035	-0.55
	$4TZ_{dyn,mod,GMU}$	2015	0.08
		2025	-0.01
		2035	-0.51
	$4TZ_{TOU,mod,GMU}$	2015	0.03
		2025	-0.15
		2035	-0.51

7. Business implications

The optimization results illustrate that variable electricity tariffs allow to exploit the economic potential lying in residential DR. However, all variable tariffs applied in this analysis put customers that perform DR with electric household appliances in a worse financial position rather than the initial FT scheme. The reason for this lies in the price risk that has to be taken on by the customers in variable pricing schemes as already stated by [15, 16]. Consequently, to make variable electricity tariffs competitive, utilities need to transfer a portion of the gains that they realize due to residential DR to their customers.

A higher economic potential lies in DR performed by customers that run an electric heating system combining an electric heat pump. Both the high amount of electricity and the long effective load shift horizon due to the thermal buffer storage have a positive effect on the results, so that considerable gains can be achieved especially when applying highly dynamic tariffs.

Additionally, electricity tariffs that only take price differences of the spot market into account have a negative impact on the energy autonomy level of municipalities whose electricity generation relies largely on cogeneration in CHP plants. This is due to the fact that the operation of the CHP plants in the model runs is heat- and not power-controlled. The negative impact on the energy autonomy level of municipalities with a large share of electricity production from wind energy plants is less pronounced. Basing variable electricity tariffs not solely on spot market prices, but also on the DR pattern of customers and on the specific generation profiles of municipal energy utilities helps to increase the level of energy autonomy of municipalities.

All in all, municipal energy utilities with their close customer relation and interrelation with the municipality should be especially able to exploit the small, but existing potential if the following aspects are taken into consideration in the design of suitable business models:

- variable tariffs should be designed by taking into account the price structure of the spot market with simultaneous consideration of municipal conditions as municipal vision, generation portfolio, customer structure.
- since the dynamic of variable electricity tariffs needs to be quite high to take advantage of the DR potential of electric household appliances, utilities need to approach their customers and communicate the benefits of more dynamic variable electricity tariffs to them.
- residential customers running a heat pump system might be approached by specific and more variable tariffs and informed about the potential benefits of installing a larger thermal buffer storage.
- in order to attract customers, any business model needs to include a mechanism that regulates the transfer of a portion of the utility gains realized due to residential DR to their customers. For instance, customers could be guaranteed certain electricity cost savings and be further rewarded for reaching specific DR patterns.

Interpreting the results also requires the inclusion of assumptions and limitations of the work. Representative customer load profiles were used as input into the model instead of calculating the customer load profiles based on information about individual electric appliances. For this reason, the specific DR characteristics of individual household appliances could have been taken into account only on an average basis. Furthermore, original variable electricity tariffs were modified based on information about the DR pattern of customers and the generation profile of both municipal energy utilities. In the performed analysis, this modification process was facilitated by the fact that there was perfect knowledge.

8. Concluding remarks

The preceding analysis showed that via variable electricity tariffs energy utilities can benefit from residential DR. This is achieved by adjusting the loads of residential customers to the generation profile of their plants and by taking available DR resources into account in their trading activity. In terms of a common development of the DR business model, also customers of a municipal company are able to profit. An alignment of the business model regarding municipal conditions increases the probability of success. Additionally, DR enables the integration of fluctuating electricity generation in the respective municipality.

Regarding future research the designed tariffs could serve as input for an energy system model in which customer load profiles are calculated based on information about individual electric appliances. This would permit DR characteristics of individual appliances to be taken into account thus strengthening the validity of the results. Additionally, in a further investigation the effects of changing statutory fees and levies need to be incorporated. Beyond, the effect of DR needs to be analyzed in terms of decentralized technologies adopted by the customers. In this context, a load shifting could save costs since the load is shifted to times of energy generation and thus the self-consumption could be increased.

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List of abbreviations

CG1: Customer group 1
CG2: Customer group 2
do: Down
CHP: Combined heat and power
CMU: Conventional municipal utility
COP: Coefficient of power
do: Downwards
DR: Demand response
dyn: Dynamic
el: Electrical
FT: Flat tariff
GMU: Green municipal utility
HT: High tariff time
HP: Heat pump
IRPopt: Integrated Resource Planning and Optimization
LO: Low-priced orchestrator
LS: Load share
MIP: Mixed-integer problems
MTI: Model Confiq I
MTII: Model Confiq II
mod: modified
NT: Low tariff time
RTP: Real-time pricing
SH: Shift horizon
TOU: Time-of-use
TZ: Tariff price zones
th: Thermal
up: Upwards

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Chapter 5

Actor-Oriented Multi-Level Optimization Approach

Towards integrated multi-modal municipal energy systems: An actor-oriented optimization approach ***

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**Further explanations about the model design are outlined in Appendix A and a comprehensive overview of the optimization approach is given in Appendix B.

Towards integrated multi-modal municipal energy systems: An actor-oriented optimization approach

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Abstract

Against the backdrop of a changing political, economic and ecological environment, energy utilities are facing several challenges in many countries. Due to an increasing decentralization of energy systems, the conventional business could be undermined. Yet the reliable integration of small-scale renewable technologies and associated system transformations could represent an opportunity as well. Municipal energy utilities might play a decisive role regarding successful transition. For better decision-making, they need to investigate under which conditions certain novel business cases can become a sustainable part of their future strategy. The development of the strategy is a challenging task which needs to consider different conditions as business portfolio, the customer base, the regulatory framework as well as the market environment. Integrated Multi-Modal Energy System (IMMES) models are able to capture necessary interactions. This research introduces a model-driven decision support system called Integrated Resource Planning and Optimization (IRPopt). Major aim is to provide managerial guidance by simulating the impact of business models considering various market actors. The mixed-integer linear programming approach exhibits a novel formal interface between supply and demand side which merges technical and commercial aspects. This is achieved by explicit modeling of municipal market actors on one layer and state-of-the-art technology components on another layer as well as resource flow relations and service agreement mechanisms among and between the different layers. While this optimization framework provides a dynamic and flexible policy-oriented, technology-based and actor-related assessment of multi-sectoral business cases, the encapsulation in a generic software system supports the facilitation. Based on the actor-oriented dispatch strategy, flexibility potential of community energy storage systems is provided to demonstrate a real application.

Keywords: Actor-oriented optimization, Integrated multi-modal energy system, Mixed-integer linear programming, Model-driven decision systems, Energy utility business portfolio planning

1. Introductory remarks

1.1. Research context

Energy systems face different challenges in coping with future requirements, especially with sustainability challenges [1]. In many countries, the decentralization of the energy system due to an increased usage of renewable energy technologies is driven by various government promotions, declining technology costs and clean technology innovations. This trend entails a changing market environment. As a result, the conventional business of energy utilities could get undermined [2]. Yet the reliable integration of decentralized

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small-scale renewable technologies and associated system transformations could represent an opportunity as well. Storage systems, sector coupling, demand response, plant flexibility or any combination of these might represent economically attractive options. Municipal energy utilities might play a decisive role regarding successful transition as they represent the linkage of supply and demand [3] and as they are locally embedded with direct customer relations [4]. Despite significant efforts of utilities to define their future role, the main hindrances to innovation yet prevail: uncertainties in unpredictable policy frameworks, lacking profitability of projects, and insufficient investment volume, to name but a few [5]. For better decision-making, they need to investigate under what conditions certain business cases can become a sustainable part of the future municipal system.

The development of a sustainable and successful future strategy is a challenging task which needs the inclusion of both internal and external conditions [6]: First, utilities need to cope with their existing business portfolio and energy generation structures on the supply side. For a sustainable strategy it is beneficial to exploit resulting synergy effects. Second, arising regulatory frameworks, market mechanisms and technological capabilities are decisive on municipal and national levels. In some countries, the energy policy landscape nowadays is changing continuously. Third, the nature and dynamics of the customer base need to be taken into account. Customer orientation is seen as a key lever. Accordingly, both parties should benefit of new business models. "Innovative numerical energy models will necessarily play a central role in this overall endeavor, if only because the interactions are too complex for intuitive analysis." [7].

Various conditions have been already incorporated in different optimization models and studies related to municipal solutions. This requires not only a comprehensive view of transmission and distribution, but also on different energy sectors. The optimization model *deeco* [8] enables the exploration of competition and synergies of different technologies in a municipality. Even though, different energy sectors are included, the main focus is on high temporal and topological resolution modeling in order to capture network effects as shown in [9] and [10]. In contrast, the *EnergyHub* concept in [11] focuses on multi-energy carrier coupling and management. A comprehensive review of different case studies regarding the optimal design and utilization of infrastructure components is outlined by [12]. Additionally, applying a linear optimization model, [13] analyze the benefits of the integration of complementary technologies at neighborhood scale. The model *urbs* has been applied for storage sizing at a municipality in Germany in combination with a network model [14]. Furthermore, [15] presents and applies a multi-modal energy system design for large building complexes, such as airports or university campuses.

To harness local potential, it is also necessary to find business models that provide an opportunity for market actors as utilities and households [16]. This requires the modeling of individual actors. From a conceptual point of view, an optimization approach has been presented by the authors of the model *xeona* [17]. Applied research with similar purposes including multi-node optimization without aggregation by incorporating various buildings of a site is presented in [18] on the basis of the *EnergyHub* framework [19]. Besides, [20] use this model for optimal electric distribution system expansion planning, differentiating between utility- and customer-owned hubs. Reference [21] use a further development of the *EnergyHub* to evaluate integration of distributed energy systems amongst various consumers and producers at a neighborhood scale. Thereby, also business cases as direct marketing and community energy storage systems are investigated. Reference [22] model an optimum community energy storage system for photovoltaic energy time-shift as a function of the community size and its photovoltaic penetration. Reference [23] assesses the optimal composition of both demand and supply portfolios for an economically efficient implementation of demand response. For this purpose, optimal tariffs are defined via a bi-level optimization model that takes both the aggregators' and customers' objective into account.

Nomenclature

Scalars

Δt	length of a time step
T	number of periods of the optimization horizon

Functions

$\mathfrak{u}$	sector association
$\mathfrak{n}$	components sovereignty
$\mathfrak{q}$	power connections sovereignty
$\mathfrak{e}$	energy flow [MWh]
$\mathfrak{p}$	power measurement [MW]
$\mathfrak{r}$	relative status code
$\mathfrak{a}$	absolute status code
$\mathfrak{w}$	energy tariff [€/MWh]
$\mathfrak{x}$	power tariff [€/MW]
$\mathfrak{y}$	absolute status cost [€]
$\mathfrak{z}$	relative status cost [€]
$\mathfrak{f}$	system objective [€]
$\mathfrak{f}^{\text{energy}}$	energy system [€]
$\mathfrak{f}^{\text{power}}$	power system objective [€]
$\mathfrak{f}^{\text{status}}$	status system objective [€]
$\mathfrak{g}$	equality constraint
$\mathfrak{h}$	inequality constraint

Graphs

C	relative status tariff graph
E	energy system graph
G	tariff graph
G^A	absolute status tariff graph
G^E	energy tariff graph
G^P	power tariff graph
G^R	relative status tariff graph
P	power connection system

Indices

$t \in T$	(quarter-hourly) time periods
$m \in M$	monthly time periods
$u \in U$	system sectors
$s \in S$	market actors
$n \in N$	engineering components
$k \in K$	status components
$i \in J$	connection points
$q \in Q$	power connections
$a \in A$	system graph links
$c \in C$	tariff graph links

Vectors & Matrices

$\eta(u,n)$	efficiency matrix
$\mathrm{L}(t,u,n)$	energy demand [MWh]
$A(n)$	surface area [m^2]
$C^{dn}(t)$	downward shifting [MWh]
$C^{up}(t)$	upward shifting [MWh]
$DR^{dn}(t)$	downward load shift [MWh]
$DR^{up}(t)$	upward load shift [MWh]
$I^0(t,n)$	irradiation conditions [W/m^2]
M	load shift horizon [period]
$SOC(t,n)$	state of charge [MWh]
$SOC^{max}(t,n)$	maximum state of charge [MWh]
$SOC^{min}(t,n)$	minimum state of charge [MWh]
$T^{on}(n)$	block bid length [period]
$P^{max}(u,n)$	maximum power output [MW]
$P^{min}(u,n)$	minimum power output [MW]

Sets

A	energy system arcs
A^s	energy system arcs associated with an actor
C	tariff system arcs
C^A	status tariff system arcs
C^E	energy tariff system arcs
C^P	power tariff system arcs
C^R	status tariff system arcs
M	monthly optimization horizon
N	engineering components
N^{coll}	collector components
N^{conv}	conversion components

N^{dem}	demand components
N^{port}	import-export components
N^{store}	storage components
N^{s}	engineering components associated with an actor
N^{trans}	transmission components
N^{u}	engineering components associated with a sector
Q	power connections
Q^{s}	power connections associated with an actor
S	system actors
S^{inst}	market institutions
S^{orga}	business units
S^{pros}	prosumer groups
T	quarter-hourly or hourly optimization horizon
U	energy sectors

1.2. Research scope

Even though the incorporation of different actors is increasingly gaining attention, a centralized planning approach still underlines most of the models and studies. However, usually not one single actor contains all relevant components for distribution, conversion, and the storing of energy. Instead, individual actors are spatially distributed over a municipal area and are equipped with respective components. Specifically, model design is lacking with regards to the role different market actors play [24].

An integrated view of supply side and demand side is necessary for optimal investigation [25]. As main contribution, this research paper develops and applies a modular model interface between supply and demand side in order to enable an actor-oriented dispatch. The model design facilitates the allocations when costs and benefits do not boil down to the same actor as posed by [24]. This multi-level actor approach is referred to as *integrated optimization*. At the same time, the model framework called Integrated Resource Planning and Optimization (IRPopt) allows a flexible and scalable configuration of business cases. New business strategies need to be analyzed under different municipal conditions in order to determine competition effects. For a systematic processing, the research intends to accomplish the following objectives:

- Design an integrated model framework to evaluate business model strategies under differing municipal system conditions.
- Propose a multi-level entity-oriented optimization approach to facilitate flexible analysis from different market actor perspectives.
- Demonstrate the applicability of the system by analyzing the flexibility potential of community energy storage systems at differing municipal system conditions.

The rest of this research paper is organized as follows: Section 2 describes the framework of the integrated multi-layer model. Section 3 proposes the multi-level entity-oriented optimization problem. Section 4 demonstrates the embedded software workflow. Section 5 presents the case study and the optimization results. Section 6 summarizes main conclusions and sketches future work.

2. Model design

The energy system model IRPopt is designed around an innovative *multi-layer framework* as sketched in Figure 1. An illustrative representation of different approaches of different layers is given in Figure 2.

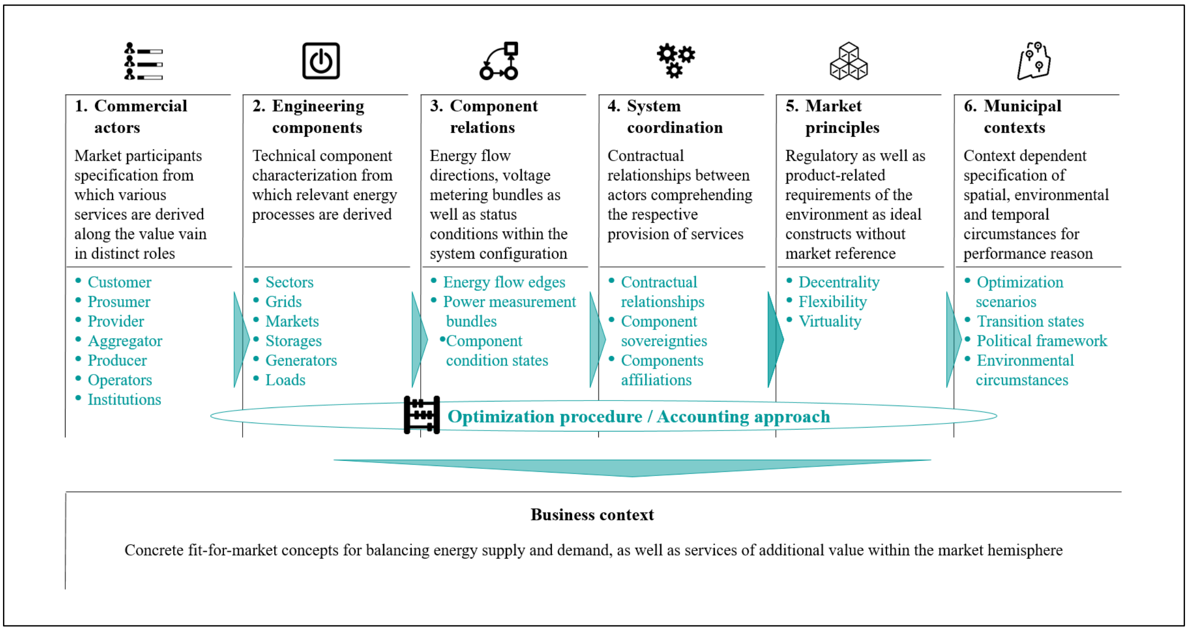


Figure 1: Multi-layer IMMES modeling framework of IRPopt consisting of five coordinated layers

The layers itself combine retrieved system entities and dynamics of reviewed municipal energy system definitions. While [26] attach importance to the optimal combination of energy processes of a certain area in general, [27] specify the benefits in finding environmentally friendly, social acceptable and cost-effective solutions in particular. [28] explicitly stress the importance of the linkage between local government, provider and end users. According to [29] four perspectives are decisive in multi-energy systems: the spatial, the multi-fuel, the multi-service, and the network. The interplay of the perspectives is described by the definition of multi-modal energy management [30]. Besides, integrated community systems should be seen as "multi-source multi-product complex socio-technical systems consisting of different decision-making entities and technological artefacts" [24]. Thus, technology interrelations but also social relationships are fundamental [24].

The issues raised are summarized with *Integrated Multi-Modal Energy Systems (IMMES)* in this research paper: An IMMES enables the integrated operational optimization of technical and environmental energy chain processes of multiple energy carriers and services in a multi-energy system by simultaneous consideration and coordination of the social, economic and institutional network of relationships of market actors in a spatial context.

Taking into account the required entities and dynamics of the system definition, the development of *IRPopt* is mainly guided by the following model approaches: the graph theoretical concept of *deeco* [8] serves as foundation to interconnect processes. Furthermore, high resolution modeling in terms of the processes is also inspired by *deeco* and the *DER-CAM* [31]. A similar multi-carrier approach in terms of multi-vectors as initially presented by the *EnergyHub* framework [11] has been also adopted. Additionally, commercial association networks based on individual commerical actors as implemented by the *xeona* [17] have been taken into account.

2.1. Commercial actors

The energy model comprises *commercial actors* that provide various services along the system value chain. Not one single actor contains all relevant components for distribution, conversion, and storing of energy, but

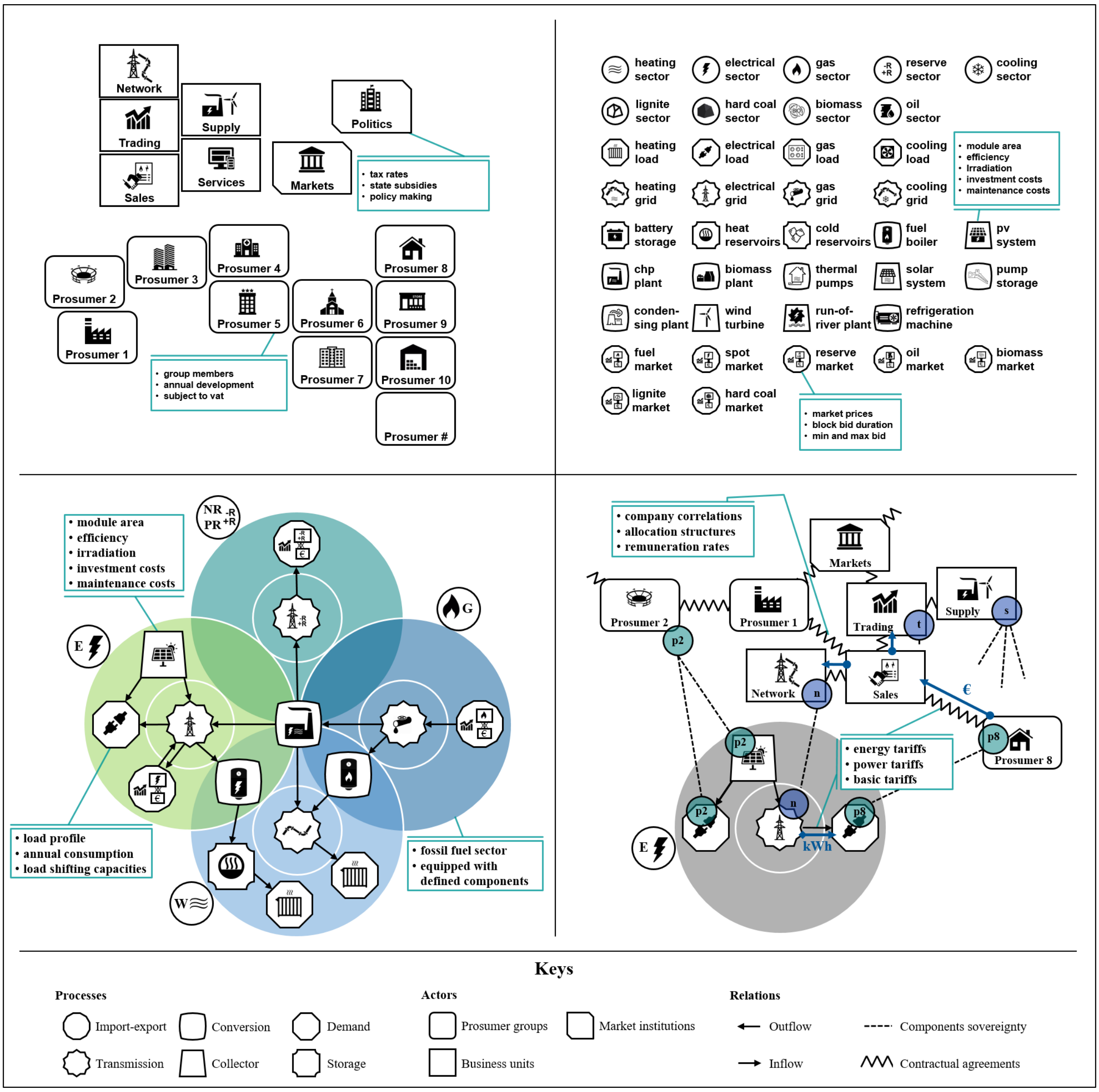


Figure 2: Schematic representation of the commercial actors (top left; section 2.1) and the engineering components (top right; section 2.2) as well as the energy system graph (bottom left; section 2.3) and the energy tariff graph (bottom right; section 2.4) of IRPopt

rather individual actors are spatially distributed over a municipal area and are equipped with respective components.

The actor-oriented approach forms the basis for an integrated multi-perspective analysis. A specific actor is denominated by $s \in S$. Relevant actors might be prosumer groups ($S^{pros} \subset S$), utility business units ($S^{orga} \subset S$) and public institutions ($S^{inst} \subset S$) as outlined in Figure 2. Each of them represent a possible *contractual partner* regarding various commercial interactions.

2.2. Engineering components

In addition to the commercial actors, an energy system consists of several interconnected engineering components (e.g. energy grids and generation facilities) with respect to various energy sectors or rather energy carriers (e.g. electricity and heating). From a functional perspective, these components realize certain processes within the energy system. While [11] focuses on conversion ($N^{conv} \subset N$), storage ($N^{store} \subset N$) and transmission processes ($N^{trans} \subset N$), [8] additionally introduces demand ($N^{dem} \subset N$), collector ($N^{coll} \subset N$) and import-export ($N^{port} \subset N$) processes. An overview of available processes of *IRPopt* is outlined in Figure 2.

The set of processes is denoted by $n \in N$. The set of energy sectors is given by $u \in U$. Each component $n \in N$ is associated with a sector $u \in U$ via the sector association function $\mathfrak{u} : U \to Pot(N)$. Besides, the optimization component sovereignty function $\mathfrak{n} : S \to Pot(N)$ indicates which actor has the authority to operate the component n, meaning that the variables associated with it are free to dispatch variables. $Pot(N)$ describes the power set of any set N. Mathematical restrictions of selected processes are outlined in section 3.3.

2.3. Component relations

The *structural composition* of the technical system demonstrates the interconnection of the spatially distributed processes. In this model, real-world characteristics have been abstracted with the help of an *energy system graph* (section 2.3.1), a *power connection measurement subsystem* (section 2.3.2) as well as a *status component condition subsystem* (section 2.3.3). Each of the technical systems provides decisive criteria for the optimal dispatch decision based on of various endogenously determinable functions[1].

2.3.1. Energy system graph

The energy system graph constitutes the basis. It resembles a *commodity flow graph*; the set of engineering processes N as nodes and the set of energy links A as arcs. In this context, the *energy system graph* $E = (N, A)$ needs to be seen as multiple source multiple sink flow network with $A \subset U \times N \times N$. Arcs as system links are represented by $a = (u, n, n')$ as ordered 3-tuple with source node $n \in N$, target node $n' \in N$, and sector index $u \in U$. While a formal example graph is given in Figure 3, an illustrative representation is depicted in Figure 2.

The energy flow in [MWh] through each arc $a \in A$ is described through the energy flow function $\mathfrak{e} : T \times A \to \mathbb{R}_{\geq 0}$ representing the flow of energy through arc $a \in A$ at time $t \in T$. Taking into account the possession of the individual processes $n \in N$, the specific actor $s \in S$ may only operate the energy flow along arcs adjacent to a node n they have optimization sovereignty over ($n \in N^s$ with $N^s = \mathfrak{n}(s) \subset N$). The set of energy links an actor can operate during the optimization run is denoted by $A^s = \{a = (u, n, n') \in A : n \in N^s \vee n' \in N^s\}$.

In order to express directed energy flows between processes, the sets $\overrightarrow{A}^{u,n}$ and $\overleftarrow{A}^{u,n}$ are introduced. While $\overrightarrow{A}^{u,n}$ represents the set of arcs in the energy system graph E with component $n \in N$ being the source flow in the respective sector $u \in U$ ($\overrightarrow{A}^{u,n} = \{a = (u, n, n') \in A : n' \in N, n \neq n'\}$), $\overleftarrow{A}^{u,n}$ represents the set of arcs with component $n \in N$ being the target ($\overleftarrow{A}^{u,n} = \{a = (u, n', n) \in A : n' \in N, n \neq n'\}$).

[1]An endogenous function describes the construct of endogenous variables or rather decision variables.

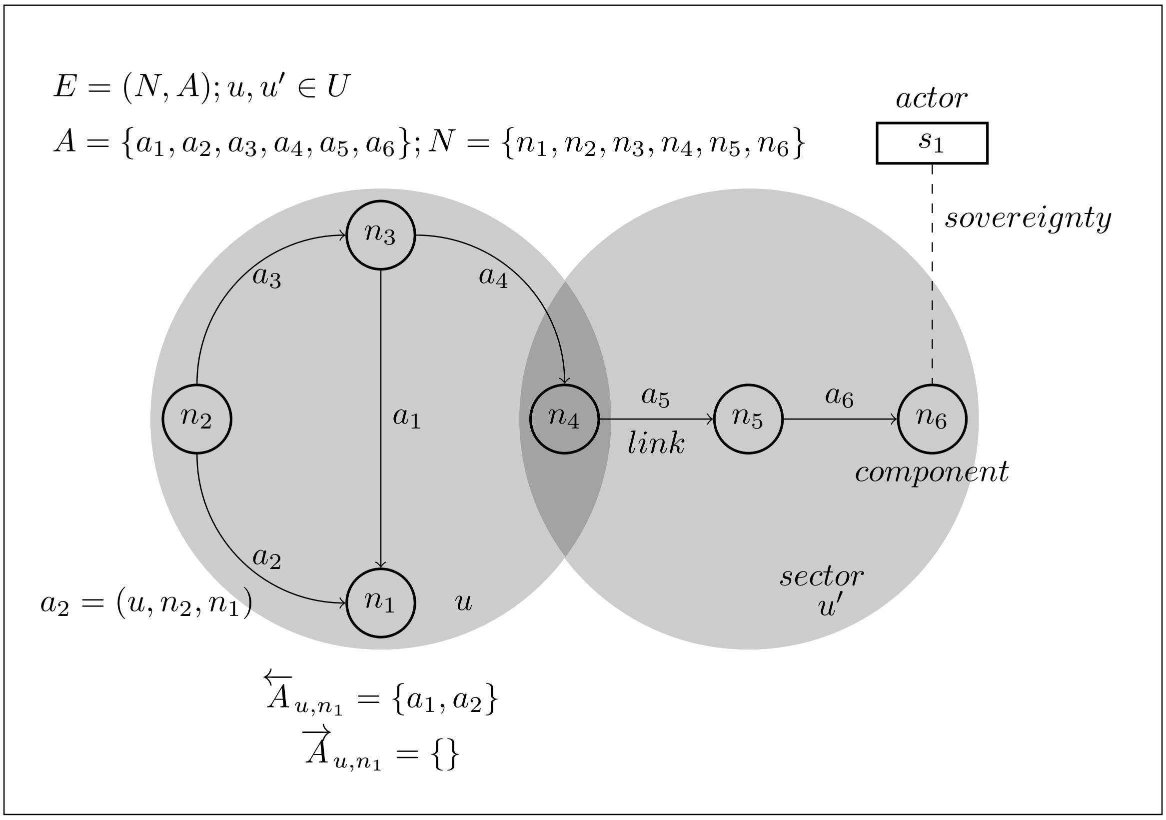


Figure 3: Schematic representation of some important principles of the energy system graph $E = (N, A)$ in order to determine the energy flow function $\mathfrak{e}$

2.3.2. Power connection measurement bundles

In the context of *smart metering*, innovative future business models might also give more weight to a capacity charge instead of energy rate. The *power connection measurement subsystem* $P = (Q, A)$ models the capacity measurement of a set of power connections Q and the set of system links A. A connection $q \in Q$ is formalized as 2-tuple $q = (i, u)$ with $i \in I$ as definable connection points and $u \in U$ as sector affiliation. Similar to the engineering components and the system links, the power connections are also assigned to an actor in order to define operation sovereignty ($\mathfrak{q} : S \to Pot(Q)$ with $Q^s = \mathfrak{q}(s) \subset Q$).

The introduced subsystem is directly build up on the energy system graph. A specific power connection q is freely bundled with relevant arcs $a, a' \in A$ to a specific power sub-system $p \in P$. Arcs which increase the capacity of the power connection are summarized under the set p^+ and arcs which decrease the capacity of the power connection are summarized under the set p^-. In terms of the optimal operation of energy flows, the power flow function $\mathfrak{p} : Q \times M \to \mathbb{R}_{\geq 0}$ determines the capacity at each defined connection for every monthly time step $m \in M$ on the basis of the following condition $\left(\sum\limits_{a \in p^+} \mathfrak{e}_{t,a} - \sum\limits_{a \in p^-} \mathfrak{e}_{t,a} \right) \leq \mathfrak{p}_{m,q} \cdot \Delta t, \quad \forall t \in T^M$.
A formal example configuration of such a subsystem is given in Figure 4.

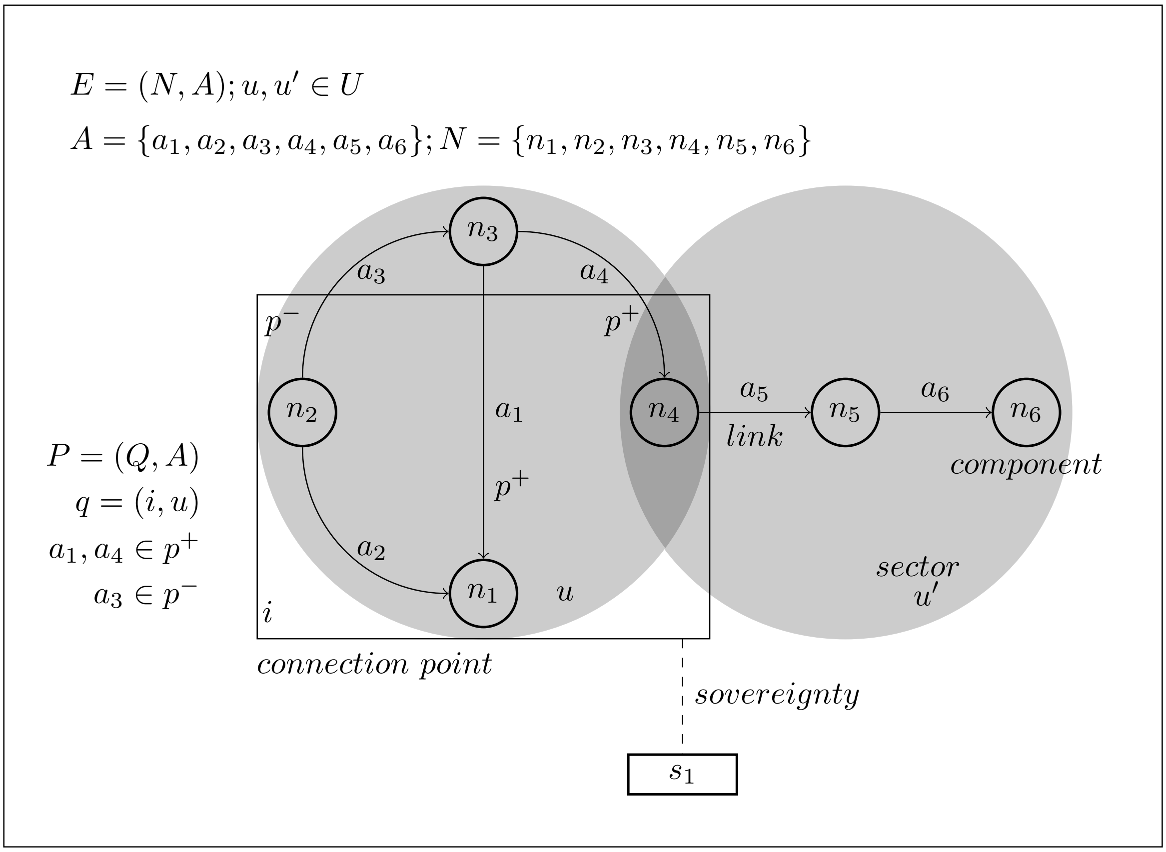


Figure 4: Schematic representation of some important principles of the power measurement subsystem $P = (Q, A)$ in order to measure the power $\mathfrak{p}$

2.3.3. Component condition status system

In addition to the energy flows and the power measurements, the optimal operation policy depends also on the *operating mode* of such single processes. In this sense, e.g. the dynamics of start-up modeling as well as of types of wear modeling of different processes might be integrated in the *component status system.*

To model such cases, two simple status condition functions are implemented. Previously, to ensure a sector specific $u \in U$ operation strategy of the individual processes ($n \in N$), a 2-tuple of $k = (u, n)$ is introduced with $k \in K$. Depending on the particular usage context, the function can be given by an absolute condition function $\mathfrak{a} : T \times K \to \{0, 1\}$ or by a relative condition function $\mathfrak{r} : T \times K \to [0, 1]$. As outlined, the absolute and relative status can be determined for each sector specific component $k \in K$ and time step $t \in T$ separately.

2.4. System coordination

The system coordination facilitates the *commercial interactions* between market actors and thus represents the economic module of IRPopt. Integrated systems are "multi-source multi-product complex socio-technical systems consisting of different decision-making entities and technological artefacts [...]." [24]. In this context, each presented technical graph or subsystem is interrelated with one of the following economic graphs: *energy system tariff network* (section 2.4.1), *power connection tariff network* (section 2.4.2) and the *status condition tariff networks* (section 2.4.3).

2.4.1. Energy flow tariff network

Since actors optimize energy flows from an economic perspective, energy flows in E (see section 2.3.1) need to be related to financial flows between actors. This is done through associating each energy flow (through arc $a \in A$ in the energy system graph at time $t \in T$) with a set of energy tariffs.

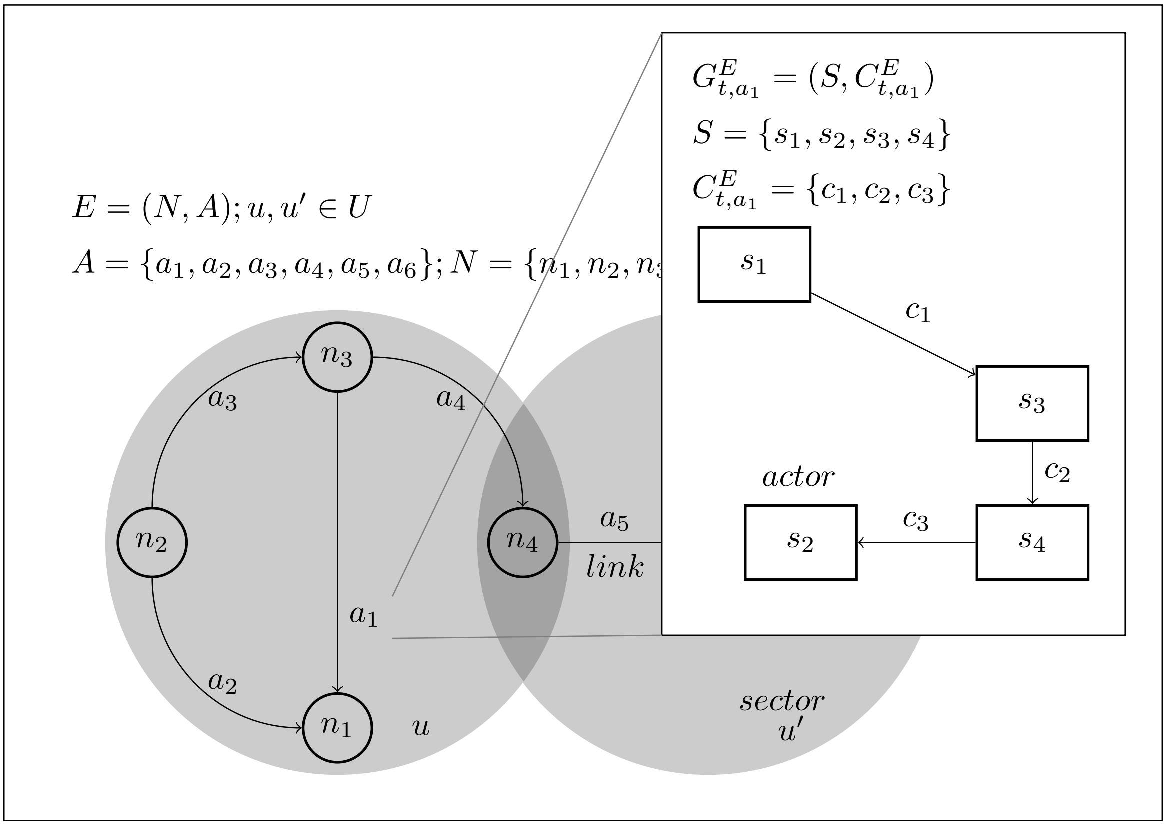


Figure 5: Schematic representation of some important principles of the energy flow tariff network $G^E_{t,a} = (S, C^E_{t,a})$. For a determined energy flow $\mathfrak{e}$ along arc a_1 the energy tariff function $\mathfrak{w}$ defines the financial flows between the actors. According to the contractual agreement, s_1 needs to pay to s_3 while s_3 needs to pay to s_4, and s_4 needs to pay to s_2

Contractual tariff relationships between actors for these energy flows are depicted through energy tariff graphs. Since a multitude of contractual relationships can exist for a given energy flow and these can differ in their dependence of the flow of energy and the point in time, energy tariffs are formalized through a set of energy tariff graphs $G^E = \bigcup_{a \in A} \bigcup_{t \in T} G^E_{t,a}$. A schematic representation is given in Figure 5.

Each *energy tariff graph* $G^E_{t,a}$ is a directed graph $G^E_{t,a} = (S, C^E_{t,a})$ describing the contractual relationships between actors $s \in S$ for the given energy flow along arc $a \in A$ in the energy system graph E at time $t \in T$ with $C^E_{t,a} \subset S \times S$. Each energy tariff graph arc $c \in C^E_{t,a}$ is associated with a corresponding tariff in [€/MWh] via the energy tariff function $\mathfrak{w} : T \times A \times S \times S \rightarrow \mathbb{R}_{\geq 0}$. The function specifies the contractual relationship between actors $s \in S$ for the flow of energy from component $n \in N$ to component $n' \in N$ at a time $t \in T$ for a given sector $u \in U$.

2.4.2. Power measurement tariff network

Similar to the energy subsystem, financial flows in the power subsystem are modeled through *capacity tariff graphs*. A power tariff graph $G^P_{m,q}$ describes the effective tariffs between actors for a power bundle

$q \in Q$ net capacity measurement at month of interest $m \in M$.

The power tariff graph $G^P_{m,q} = (S, C^P_{m,q})$ is parametrized through the tariffs in [€/MW] between the set of actors S for each capacity measurement in $q \in Q$ at time $m \in M$. The (partial) power tariff function is given by $\mathfrak{x} : Q \times M \times S \times S \rightarrow \mathbb{R}_{\geq 0}$. The principles are illustrated in Figure 6.

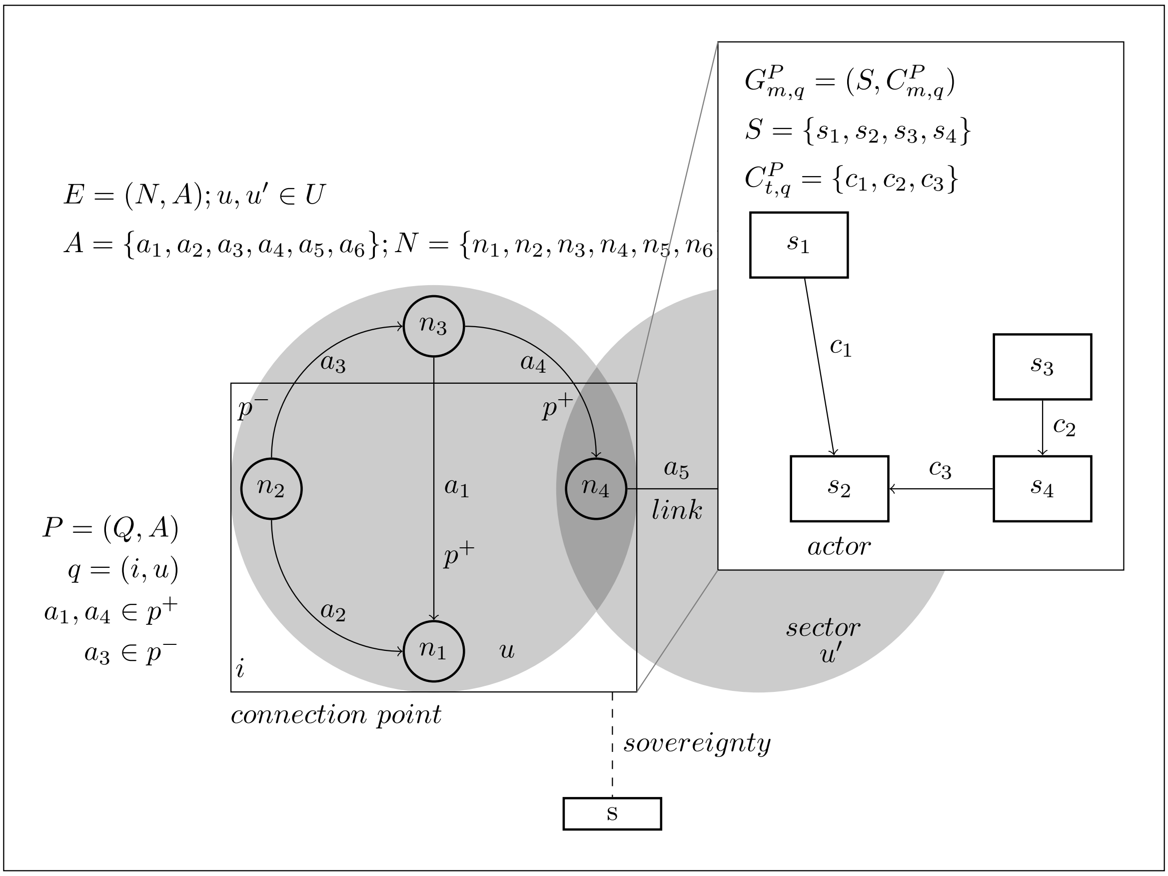


Figure 6: Schematic representation of some important principles of the power measurement tariff network $G^P_{m,q} = (S, C^P_{m,q})$. For a determined power measurement $\mathfrak{p}$ regarding connection point i the power measurement tariff function $\mathfrak{x}$ defines the financial flows between the actors. According to the contractual agreement, s_1 needs to pay to s_2, s_3 needs to pay to s_4, and s_4 needs to pay to s_2

2.4.3. Component condition status tariff network

The absolute and relative status cost graph, formalized by $G^A_{t,k} = (S, C^A_{t,k})$ or rather $G^R_{t,k} = (S, C^R_{t,k})$, describe the financial flows between actors regarding the status costs. For each actor $s \in S$, an arc $c \in C^A_{t,k}$ can be defined representing the share of the cost in [€] s has to pay to s' for the part of the cost of sector component k at time t. An arc $c \in C^A_{t,k}$ is associated with the absolute status tariff function $\mathfrak{y} : T \times K \times S \times S \rightarrow \mathbb{R}_{\geq 0}$. The same applies for the relative status tariff function $\mathfrak{z}$.

2.5. Market principles

The development of innovative business models requires the implementation of *advanced market aspects*. This is especially attributable to the potential counteraction effects between individual technologies and business [10]. Noticeable concepts are among others multi-energy conversion, aggregation and system service modeling, microgrids control scheduling as well as virtual power plant coordination and balancing service provision [29]. Major concepts might be classified by *decentralization*, *flexibilization* and *virtualization*. A summary of available concepts of *IRPopt* is given in Figure 7. A comparison of different building blocks is presented in [32].

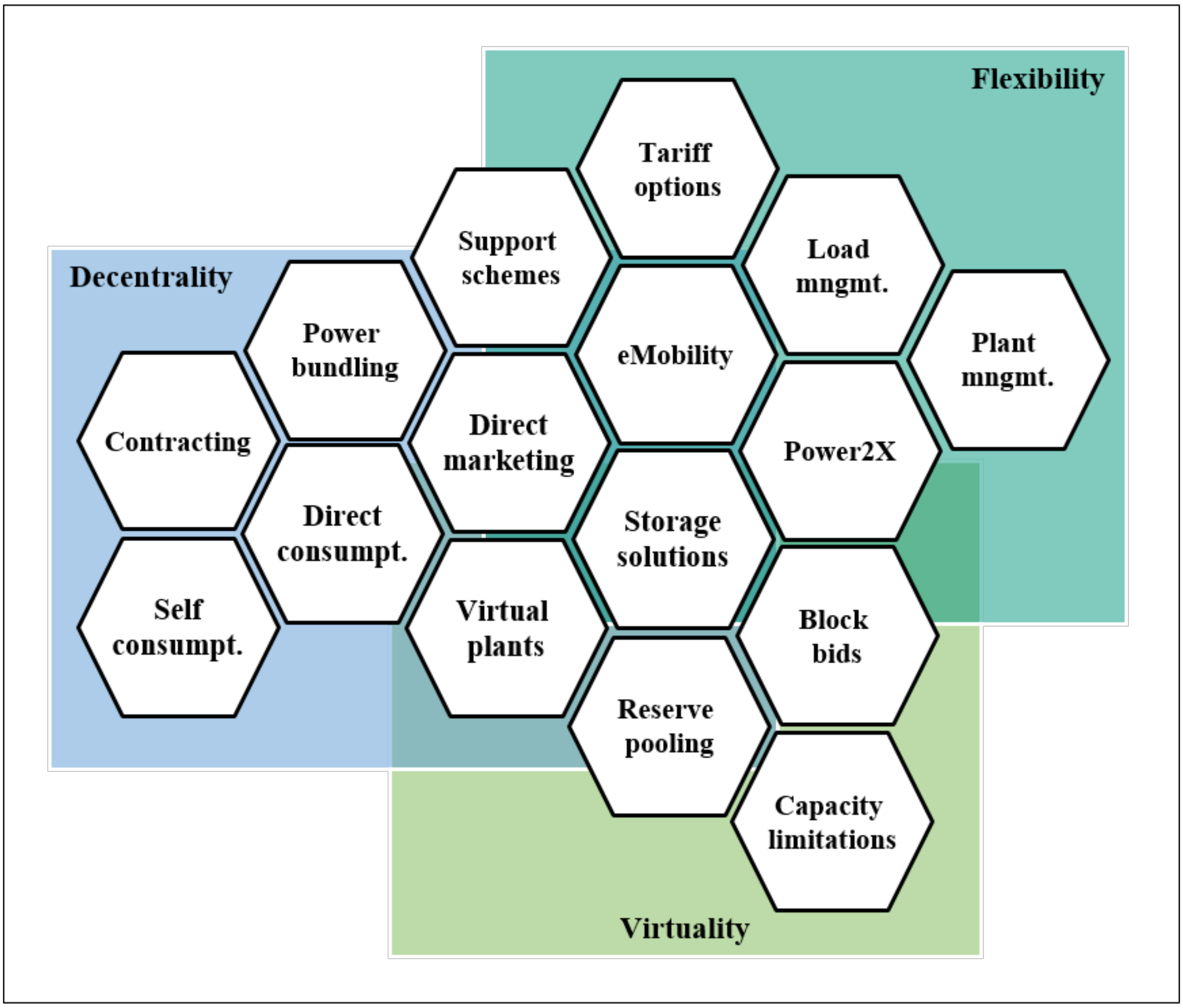


Figure 7: Overview of available building blocks of IRPopt

2.6. Municipal contexts

Finally, each strategy assessment is associated with *context dependent specifications*. In *IRPopt*, these prevailing physical, commercial, legal, institutional and regional conditions are comprised with the *municipal contexts*. Thus, this layer comprises specifications of public policy interventions, optimization scenario assumptions, time-frame specifications as well as environmental circumstances.

3. Optimization approach

At its core, IRPopt is a bottom-up techno-economic numerical optimization model, implemented in GAMS/CPLEX, for solving mixed-integer problems (MIP) in different time resolutions for perennial periods.

3.1. Objective function

The mathematical objective function of IRPopt $\mathfrak{f}$ is based on the determination of the optimal operating policy of the designed technical systems (unit commitment problem) taking into account the financial flows of chosen market actors, time points and energy sectors.

The major objective of IRPopt is to maximize revenues over the whole optimization horizon (*max* $\mathfrak{f}$) as expressed in equation (1a). This corresponds to the sum of the optimized revenues of the energy model $\mathfrak{f}^{energy}$ in equation (1b), of the power model $\mathfrak{f}^{power}$ in equation (1c), and the status model $\mathfrak{f}^{status}$ in equation (1d). For completion, $\mathfrak{f}$ is restricted by different equality constraints $\mathfrak{g} \in \{\mathbb{R}_{\geq 0}, \mathbb{Z}_{\geq 0}\}$ and inequality constraints $\mathfrak{h} \in \{\mathbb{R}_{\geq 0}, \mathbb{Z}_{\geq 0}\}$ as outlined in section 3.3.

$$\begin{aligned} \text{maximize} \quad & \mathfrak{f} = \mathfrak{f}^{\text{energy}} + \mathfrak{f}^{\text{power}} + \mathfrak{f}^{\text{status}} \\ \text{subject to} \quad & \mathfrak{g} = 0 \\ & \mathfrak{h} \geq 0 \end{aligned} \tag{1a}$$

$$\mathfrak{f}^{\text{energy}} = \sum_{t \in T'} \sum_{s \in S'} \sum_{a \in A^s} \left(\sum_{s' \in S} \mathfrak{e}_{t,a} \cdot \mathfrak{w}_{t,a,s',s} - \sum_{s' \in S} \mathfrak{e}_{t,a} \cdot \mathfrak{w}_{t,a,s,s'} \right) \tag{1b}$$

$$\mathfrak{f}^{\text{power}} = \sum_{m \in M'} \sum_{s \in S'} \sum_{q \in Q^s} \left(\sum_{s' \in S} \mathfrak{p}_{m,q} \cdot \mathfrak{x}_{m,q,s',s} - \sum_{s' \in S} \mathfrak{p}_{m,q} \cdot \mathfrak{x}_{m,q,s,s'} \right) \tag{1c}$$

$$\mathfrak{f}^{\text{status}} = \sum_{t \in T'} \sum_{s \in S'} \sum_{k \in K^s} \left(- \sum_{s' \in S} \mathfrak{a}_{t,k} \cdot \mathfrak{y}_{t,k,s,s'} - \sum_{s' \in S} \mathfrak{r}_{t,k} \cdot \mathfrak{z}_{t,k,s,s'} \right) \tag{1d}$$

A set of time points of interest $T^{'} \subset T$ and its derived set $M^{'} \subset M$ as well as a set of actors of interest $S^{'} \subset S$ need to be specified in order to define the optimization period as well as optimization perspective. According to the design decision taken, associated energy links ($\bigcup_{s \in S'} A^s \subset A$ of the actor $s \in S^{'}$), power connections ($\bigcup_{s \in S'} Q^s \subset Q$ of the actor $s \in S^{'}$) and engineering processes ($\bigcup_{k \in K'} K^s \subset K$ of the actor $s \in S^{'}$) are determined. The optimal operation strategy is determined by maximizing the profits from the chosen actor perspective by taking into account the incoming and outgoing financial flows. For the energy profit model (equation (1b)), the energy flows $\mathfrak{e}$ associated with the actor(s) of interest are dispatched on the basis of the energy tariffs $\mathfrak{w}$. For the power profit model (equation (1c)), financial flows are determined through the product of the measured capacity $\mathfrak{p}$ within a power connection associated with an actor of interest and any relevant financial demands as specified in the respective power tariff graph $\mathfrak{x}$. Additional cost modeling in terms of absolute $\mathfrak{a}$ and relative status $\mathfrak{r}$ changes of engineering processes, contribute through the status cost model $\mathfrak{n}$ and $\mathfrak{z}$ (equation (1d)). The general integrated optimization procedure is shown in Figure 8.

3.2. Optimization strategy

IRPopt aims to be an actor-based multi-carrier optimization model in order to reflect process dispatch at various municipal conditions. By default, the model initially optimizes from an aggregated prosumer' perspective ($S^{'} = S^{pros}$), determining the residual energy demand and excess energy supply with all processes the customers have regulative access to. With respect to the first optimization step (prosumer optimization), the tariff scheme as well as the variable costs of decentralized energy systems are of primary

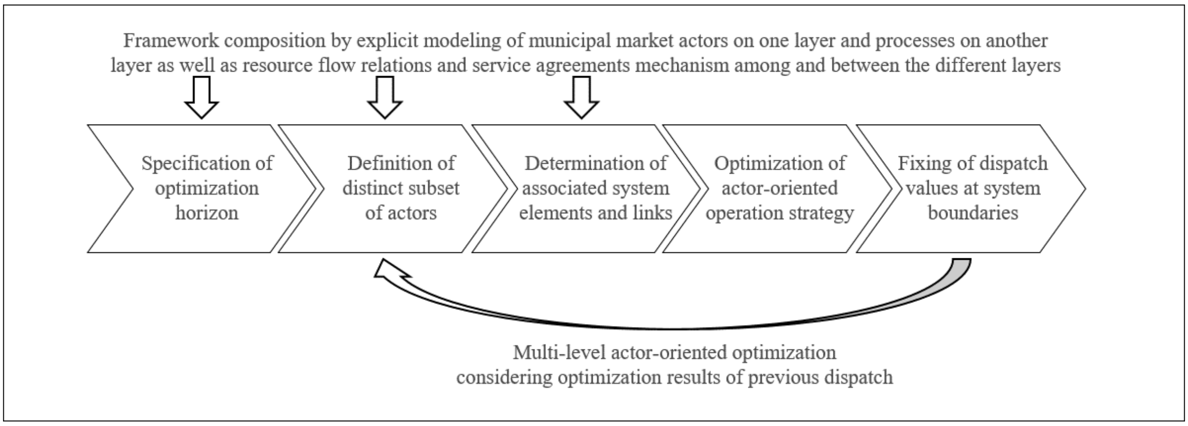


Figure 8: Multi-level actor-oriented optimization procedure

importance. Subsequently, the model optimizes all other energy and financial flows from the utilities' perspective ($S^{'} = S^{orga}$), considering the total residual energy demand and supply. With respect to the second optimization step (utility optimization), the market prices as well as the variable costs of the energy systems are most decisive. This idea of a multi-level entity-oriented optimization approach has already been sketched by [17].

The entire optimization year $T = \{1, ..., 35040\} \subset \mathbb{N}$ for Δt of quarter-hourly time steps $t \in T$, and $M = \{1, ..., 12\} \subset \mathbb{N}$ for monthly time steps $m \in M$ is not optimized in one piece, but rather in a recursive dynamical way. In course of this, various time-local problems of the whole scheduling horizon are optimized. To reduce computational complexity, in each optimization step, the optimal operation strategy is determined over an horizon comprising 48 hours while only the results of 24 hours are saved.

3.3. Process restrictions

Constraint functions $\mathfrak{g}$ and $\mathfrak{h}$ of equation (1a) describe the technical nature of the engineering processes as introduced in section 2.2. In the following, equations relevant for the demonstration case of section 5 are outlined.

3.3.1. Demand processes

Demand processes as electrical demand ($n \in N^{el} \subset N^{dem}$) or heating demand ($n \in N^{hl} \subset N^{dem}$) only absorb energy. The energy demand is specified by a exogenous load curve $L_{t,u,n} \in \mathbb{R}_{\geq 0}$ [MWh], which has to be satisfied by the sum of branch energy flows to the respective load of the respective energy sector. A formalization of the electrical ($u_{el} \in U$) demand coverage including a generic load shifting representation is given by equations (2a-2d). The equations are also applicable for the heating sector ($u_{th} \in U$).

$$\sum_{a \in \overrightarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} = L_{t,u_{el},n} + DR^{up}_{t,n} - \sum_{t_t = t-M}^{t+M} DR^{dn}_{t,t_t,n} \quad ,\forall t \in T^{'}, \forall n \in N^{el} \tag{2a}$$

$$DR^{up}_{t,n} = \sum_{t_t = t-M}^{t+M} DR^{dn}_{t,t_t,n} \quad ,\forall t \in T^{'}, \forall n \in N^{el} \tag{2b}$$

$$DR^{up}_{t,n} \leq C^{up} \quad ,\forall t \in T^{'}, \forall n \in N^{el} \tag{2c}$$

$$\sum_{t=t_t-M}^{t_t+M} DR^{dn}_{t,t_t,n} \leq C^{dn} \quad ,\forall t_t \in T^{'}, \forall n \in N^{el} \tag{2d}$$

$$DR^{up}_{t_t,n} + \sum_{t=t_t-M}^{t_t+M} DR^{dn}_{t,t_t,n} \leq max\left\{C^{up}, C^{dn}\right\} \quad ,\forall t_t \in T^{'}, \forall n \in N^{el} \tag{2e}$$

For load shifting in accordance with [33], the variables $DR^{up}_{t} \in \mathbb{R}_{\geq 0}$ [MWh] and $DR^{dn}_{t,t_t} \in \mathbb{R}_{\geq 0}$ [MWh] represent hourly load shifts in upward or downward direction. From equation (2b) it follows that every upward load shift is compensated by downward shifts. $M \in \mathbb{R}_{\geq 0}$ defines the interval in which the load shifts must be compensated. Equation (2c) and equation (2d) restrict maximum hourly shifts to the predefined levels $C^{up} \in \mathbb{R}_{\geq 0}$ [MWh] and $C^{dn} \in \mathbb{R}_{\geq 0}$ [MWh]. Equation (2e) prevents that the DR capacity is not fully utilized in both directions at the same time.

3.3.2. Conversion processes

The dispatch of the natural gas boilers ($\forall n \in N^{fb} \subset N^{conv}$) are first bounded by specified maximum capacity $P^{max}_{u,n} \in \mathbb{R}_{\geq 0}$ [MW] - in case of the maximum heating output $u_{th} \in U$ by $P^{max}_{u_{th},n}$. Secondly, the sum of all fuel energy inflows ($u_{fu} \in U$) is converted by the engineering component into the sum of all heating outflows ($u_{th} \in U$) by considering the efficiency ($0 \leq \eta_{u_{fu},n} \leq 1$).

$$\sum_{a \in \overrightarrow{A}^{u_{th},n}} \mathfrak{e}_{t,a} \leq P^{max}_{u_{th},n} \cdot \Delta t \quad ,\forall t \in T^{'}, \forall n \in N^{fb} \tag{3a}$$

$$\sum_{a \in \overrightarrow{A}^{u_{th},n}} \mathfrak{e}_{t,a} = \sum_{a \in \overleftarrow{A}^{u_{fu},n}} \mathfrak{e}_{t,a} \cdot \eta_{u_{fu},n} \quad ,\forall t \in T^{'}, \forall n \in N^{fb} \tag{3b}$$

The main function of a *heat pump* ($\forall n \in N^{hp} \subset N^{conv}$) is to provide heat from low temperature heat sources to high temperature heat sinks. It is assumed that the thermal coefficient of performance $COP_{t,u_{th},n} \in \mathbb{R}_{\geq 0}$ is gradually dependent on the temperature. Furthermore, the heat pump is operated by electricity including a heat rod as a backup. Equation (4a) demonstrates the combined heating outflows ($u_{th} \in U$) as the endogenously determinable sum of the generated heat of the temperature dependent heating pump $P^{hp}_{t,u_{th},n} \in \mathbb{R}_{\geq 0}$ [MW] and the heating rod backup $P^{hr}_{t,u_{th},n} \in \mathbb{R}_{\geq 0}$ [MW]. While the maximal power boundary of the overall system is limited by the maximum thermal capacity $P^{max}_{u_{th},n} \in \mathbb{R}_{\geq 0}$ [MW] in equation (4b), the maximum output of the temperature dependent part is bounded by the temperature dependent capacity $P^{max,temp}_{u_{th},n} \in \mathbb{R}_{\geq 0}$ [MW] in equation (4c). The electrical inflow ($u_{el} \in U$) is given in equation (4d).

$$\sum_{a \in \overrightarrow{A}^{u_{th},n}} \mathfrak{e}_{t,a} = (P^{hp}_{t,u_{th},n} + P^{hr}_{t,u_{th},n}) \cdot \Delta t \quad ,\forall t \in T^{'}, \forall n \in N^{hp} \tag{4a}$$

$$P^{hp}_{t,u_{th},n} + P^{hr}_{t,u_{th},n} \leq P^{max}_{u_{th},n} \quad ,\forall t \in T^{'}, \forall n \in N^{hp} \tag{4b}$$

$$P^{hp}_{t,u_{th},n} \leq P^{max,temp}_{u_{th},n} \quad ,\forall t \in T^{'}, \forall n \in N^{hp} \tag{4c}$$

$$\frac{P^{hp}_{t,u_{th},n} \cdot \Delta t}{COP_{t,u_{th},n}} + \frac{P^{hr}_{t,u_{th},n} \cdot \Delta t}{\eta_{u_{el},n}} \leq \sum_{a \in \overleftarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} \quad ,\forall t \in T^{'}, \forall n \in N^{hp} \tag{4d}$$

3.3.3. Collector processes

Collector processes ($n \in N^{coll}$) regarding *electrical photovoltaic panels* ($n \in N^{pv} \subset N^{coll}$) depend on insulation time series $I^0_{t,n} \in \mathbb{R}_{\geq 0}$ [W/m^2]. The energy output of the processes is equal or lower than the product of the electrical efficiency $0 \leq \eta_{u_{el},n} \leq 1$, the surface area $A_n \in \mathbb{R}_{\geq 0}$, the length of the time step Δt, as given by equation (5).

$$\sum_{a \in \overrightarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} \leq I^0_{t,n} \cdot \eta_{u_{el},n} \cdot A_n \cdot \Delta t \quad ,\forall t \in T^{'}, \forall n \in N^{pv} \tag{5}$$

3.3.4. Storage processes

The state of charge $SOC_{t,n} \in \mathbb{R}_{\geq 0}$ [MWh] of the electrical storage system ($n \in N^{es} \subset N^{store}$) is calculated according to equation (6a) based on the constraints of equations (6b-6d). While the charging and discharging efficiency is equal and given by $0 \leq \eta_{u_{el},n} \leq 1$, the self-discharging rate in Δt is given by $0 \leq \eta^{self}_{u_{el},n} \leq 1$. The $SOC_{t,n}$ is bounded by $SOC^{min}_n \in \mathbb{R}_{\geq 0}$ [MWh] and by $SOC^{max}_n \in \mathbb{R}_{\geq 0}$ [MWh] as shown in equation (6b). Additionally, the discharging and charging is restricted by the maximum (dis)charging power $P^{max}_{u_{el},n} \in \mathbb{R}_{\geq 0}$ [MW] as outlined in equation (6c) and (6d). Previously, the initial state of charge $SOC_{t^0,n}$ needs to be specified.

$$\begin{aligned} SOC_{t,n} = & SOC_{t-1,n} + \sum_{a \in \overleftarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} \cdot \eta_{u_{el},n} - \sum_{a \in \overrightarrow{A}^{u,n}} \mathfrak{e}_{t,a}/\eta_{u_{el},n} \\ & - SOC_{t-1,n} \cdot \eta^{self}_{u_{el},n} \quad ,\forall t \in T^{'}, \forall n \in N^{es} \end{aligned} \tag{6a}$$

$$SOC^{min}_n \leq SOC_{t,n} \leq SOC^{max}_n \quad ,\forall t \in T^{'}, \forall n \in N^{es} \tag{6b}$$

$$\sum_{a \in \overleftarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} \cdot \eta_{u_{el},n} \leq P^{max}_{u_{el},n} \cdot \Delta t \quad ,\forall t \in T^{'}, \forall n \in N^{es} \tag{6c}$$

$$\sum_{a \in \overrightarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a}/\eta_{u_{el},n} \leq P^{max}_{u_{el},n} \cdot \Delta t \quad ,\forall t \in T^{'}, \forall n \in N^{es} \tag{6d}$$

Electricity storage systems are also able to provide load-frequency control. On the one hand, the provision is restricted by the maximum charging or discharging capacity. This is stated in equation (6e) for the positive reserve and in equation (6f) for the negative reserve. On the other hand, the provision is restricted by the current state of charge as shown in equations (6g) and (6h).

$$\sum_{a\in \overrightarrow{A}^{u_{pr},n}} \mathfrak{e}_{t,a} \leq P^{max}_{u_{el},n} \cdot \Delta t - \sum_{a\in \overrightarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} \quad ,\forall t \in T^{'}, \forall n \in N^{es} \tag{6e}$$

$$\sum_{a\in \overrightarrow{A}^{u_{nr},n}} \leq P^{max}_{u_{el},n} \cdot \Delta t - \sum_{a\in \overleftarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} \quad ,\forall t \in T^{'}, \forall n \in N^{es} \tag{6f}$$

$$\begin{aligned} SOC^{min}_{n} \leq & SOC_{t-1,n} + \sum_{a\in \overleftarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} \cdot \eta_{u_{el},n} - \sum_{a\in \overrightarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a}/\eta_{u_{el},n} \\ & - \sum_{a\in \overrightarrow{A}^{u_{pr},n}} \mathfrak{e}_{t,a}/\eta_{u_{el},n} \quad ,\forall t \in T^{'}, \forall n \in N^{es} \end{aligned} \tag{6g}$$

$$\begin{aligned} SOC^{max}_{n} \geq & SOC_{t-1,n} + \sum_{a\in \overleftarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} \cdot \eta_{u_{el},n} - \sum_{a\in \overrightarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a}/\eta_{u_{el},n} \\ & - \sum_{a\in \overrightarrow{A}^{u_{nr},n}} \mathfrak{e}_{t,a}/\eta_{u_{el},n} \cdot \eta_{u_{el},n} \quad ,\forall t \in T^{'}, \forall n \in N^{es} \end{aligned} \tag{6h}$$

3.3.5. Transmission processes

The transmission process of the *electrical grid* ($n \in N^{eg} \subset N^{trans}$) is kept deliberately simple. As formulated in equation (7a), the sum of all branch energy flows out of a certain electrical grid u_{el} must be equal to the sum of all branch electrical energy flows into this grid. The same applies for the *fuel grid* ($n \in N^{fg} \subset N^{trans}$).

$$\sum_{a\in \overrightarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} = \sum_{a\in \overleftarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} \cdot \eta_{u_{el},n} \quad ,\forall t \in T^{'}, \forall n \in N^{eg} \tag{7a}$$

3.3.6. Import-export processes

Different energy markets as the spot market ($n \in N^{em} \subset N^{market}$), the fuel market ($n \in N^{fm} \subset N^{market}$) or the reserve market ($n \in N^{rm} \subset N^{market}$) are implied in terms of the import-export processes. In this context, only the reserve market processes exhibit different restrictions. For modeling reason, next to the positive and negative reserve sectors ($u_{pr} \in U, u_{nr} \in U$), components like primary, secondary and tertiary reserve markets ($n \in N^{rm} = prm, srm, trm$) as well as primary, secondary and tertiary reserve pools ($n \in N^{rp} = prp, srp, trp$) are implemented.

To integrate reserve pooling and block bids, processes which are able to provide load frequency control are not directly connected to the reserve market but rather to specific reserve pool elements which are again connected with the associated reserve market elements. $\forall x \in \mathbb{N}$ with $\forall t_x \in t_{x \cdot T^{on}(x)+1}, ..., t_{(x+1)\cdot T^{on}}$ equation (8a) formulates the n-th block bid. For every block bid x, the ingoing flows to the reserve pools need to be greater or equal at every timestep t than the outgoing flows of the reserve pools to the reserve market at the intial timestep of the block bid t_x. T^{on}_{n} specifies the corresponding block length of the tender period of the reserve market offering. The symmetric bids are realizable with the help of equation (8b). The presented equations are also applicable for positive reserve u_{pr}.

$$\sum_{a\in \overleftarrow{A}^{u_{nr},n}} \mathfrak{e}_{t,a} \geq \sum_{a\in \overrightarrow{A}^{u_{nr},n}} \mathfrak{e}_{t_x,a} \quad ,\forall t \in \{x \cdot T^{on}(x)+1, ..., (x+1)\cdot T^{on}(x)\}, \forall n \in N^{rp} \tag{8a}$$

$$\sum_{a \in \overrightarrow{A}^{u_{nr}, n_{prp}}} \mathfrak{e}_{t,a} = \sum_{a \in \overrightarrow{A}^{u_{pr}, n_{prp}}} \mathfrak{e}_{t,a} \quad , \forall t \in T' \tag{8b}$$

4. Software infrastructure

The model implementation is embedded in a software infrastructure. Taken together they form a decision system for municipal energy utilities. A screenshot of the graphical user-interface is shown in Figure 9.

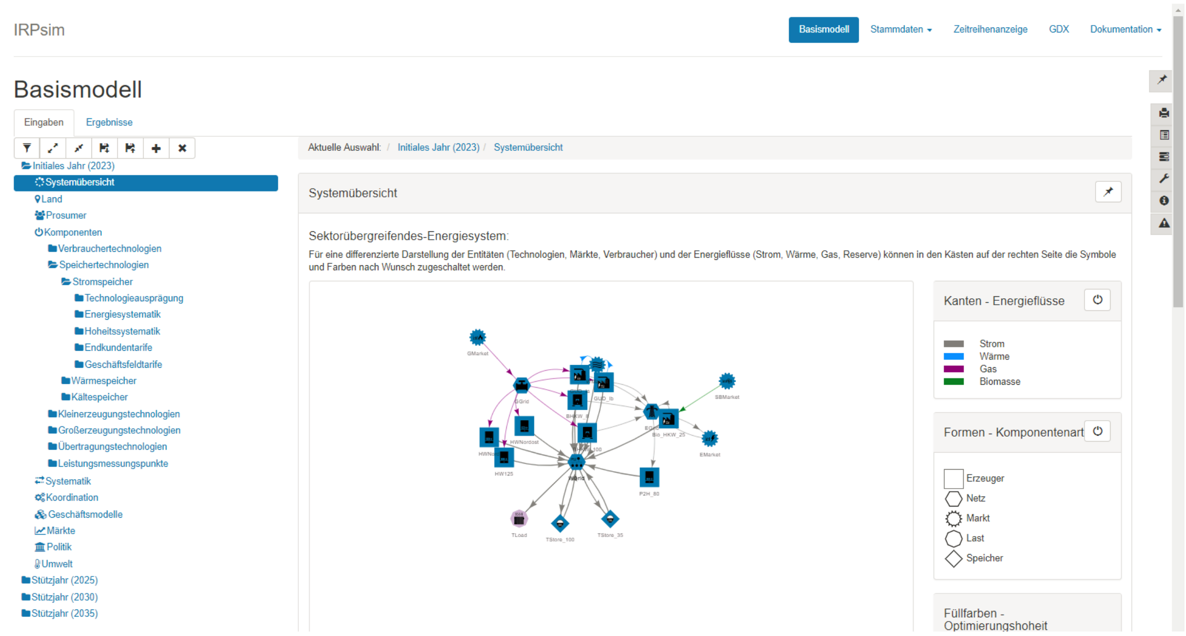


Figure 9: Screenshot of the graphical user interface

A major emphasis was placed on usability. The client provides a hierarchical structure of input and output categories. In addition to manual input and file-based import, users can load parameter values from a corresponding database. Moreover, the so-called energy system model graphs provide an intuitive way to check and validate overlapping relationships of parameter settings.

With various of input parameters in practice the model requires a considerable amount of configuration efforts to evaluate real business scenarios. A major aspect of reducing the configuration effort is the reuse of configuration knowledge. For this purpose, the IRPopt software infrastructure provides a master data management.Based on the master data management content related subsets of predefined parameter settings can be combined to so-called business scenarios.

The IRPopt software infrastructure is technically realized as a distributed system. The software consists of a web-based presentation layer, an integration layer for the GAMS/CPLEX environment and a data layer for managing different database systems. These layers represent different logical units, which can be deployed on different physical server nodes. As a result, the computing and storage load can be scaled horizontally according to computational requirements.

5. Demonstration case

The model-driven decision support system IRPopt can unfold its value in the context of *corporate strategy* or *business strategy adjustments* and *business development processes.* The following energy network-related case study with the introduced actor-oriented approach is based on the case of [34]

5.1. Case study design

IRPopt has been applied to an illustrative synthetic municipal community under German framework conditions. As part of an increased diffusion of decentralized renewable energy technologies, an additional need for flexibility arises. This case study analyzes the profitability of community electricity storage systems (CES) by simultaneous application of demand response (DR).

5.1.1. Applied flexibility options

A CES is a power bank that stores excess energy generated by decentralized energy systems of individual prosumers in a central electrical storage to bridge the temporal and quantitative gap of electricity supply and demand. Each participating household is located in spatial proximity to the CES and connected via the public grid. The CES system is managed by an operator [22]. Charging and discharging the CES system for self-consumption is assumed to be exempted from both the EEG (German Renewable Energy Sources Act) surcharge and electricity tax according to a recommendation of the German Energy Storage Association [35]. A CES would not be utilized at all in terms of the existing legal specifications of Germany due to grid-related levies [36].

Revenue potential for a CES includes energy arbitrage (approx. 17.7 €/kW p.a. (per annum) [37]), optimization of self-consumption and reserve market offerings (approx. 156 €/kW p.a. for primary, 170 €/kW p.a. for secondary, and 57 €/kW p.a. for tertiary control reserve [38]). [39] concludes that the highest revenues can be achieved through a combination of spot market and reserve market participation. Additional revenue streams could arise from local markets for grid services that are currently implemented in several research projects in Germany.

CES for multiple uses increases the utilization ratio (UR) [38]. While the UR is 62 % for the multi-tasking system, it is only 26 % (storing surplus PV) for the single-tasking applications. Investment costs of a CES are currently around 800 €/kWh to 1000 €/kWh [40]. The International Renewable Energy Agency also states reference costs of 577 €/kWh for the cells and 155 €/kW for the inverter. At the same time, a yearly price drop of CES investment costs of approximately 4 % is expected [41].

Since other flexibility options could reduce the market size for storage applications [22], participating households also have the possibility to apply DR. The concept of DR is defined as the changes in electricity consumption in response to changes in the price [42]. Thereby, only load shifting is adopted. The competing effects between DR options and CES solutions is taken into account by carrying out various sensitivity analysis.

5.1.2. Demand side parameters

The community consists of six individual households. The prosumers demonstrate differing electrical (el) load profiles based on the highly-resolved profile set of [43]. The average energy consumption per year varies between 2900 kWh_{el} and 4500 kWh_{el}. The heating (th) load profiles are derived on the basis of [44]. The average demand per year varies from 15300 kWh_{th} to 18300 kWh_{th}. Since DR is associated with a level of discomfort, it is assumed that a maximum of 40% of residential load can be shifted for 4 h (DR_{max}). A realistic average share of shiftable load (DR_{avg}) is given by 20% for 2 h [45].

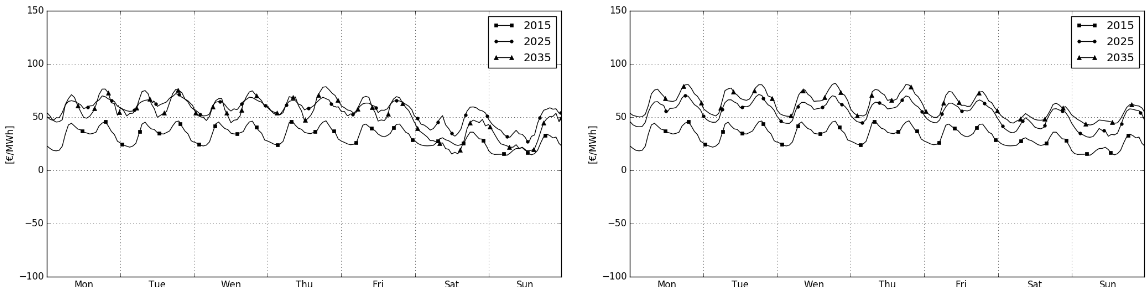
Moreover, each prosumer might be equipped with conversion processes and is connected to the storage process via the electrical grid (EG). Technology specification for the photovoltaic system (PV), the heat pump system (HP), the community electrical storage system (CES), the natural gas boiler system (NGB) are outlined in Table 1. The given data is broken down to one single customer. Additionally, the CES demonstrates a power- and energy capacity ratio of one (measured in kW inverter power divided by kWh storage capacity).

Table 1: Technology specifications for case study assessment.*Electric efficiency for the backup heater

	PV	**HP**	**CES**	**NGB**
Capacity	0-30 m^2		0-10 kWh_{el}	
Power		9 kW_{th}	0-10 kW_{el}	9 kW_{th}
Efficiency	18 $\%_{el}$	95 $\%_{el}$*	90 $\%_{el}$	95 $\%_{th}$
COP		3,9		

5.1.3. Scenario assumptions

The evaluation period is set to twenty years (2015-2035). The potential future state of the energy system is investigated by applying a green and a fossil scenario. The quarter-hourly data sets are based on historical market data 2015 of Germany. Spot market projections for 2025 and 2035 has been determined with MICOES-Europe [46]. The price characteristics are presented in Figure 10 and Figure 11.



(a) Green scenario

(b) Fossil scenario

Figure 10: Spot market price characteristics for the applied scenarios of the years 2015, 2025 and 2035

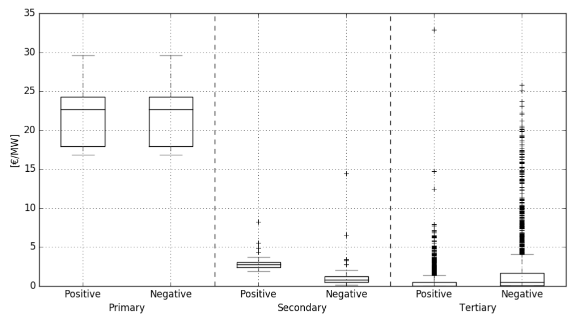
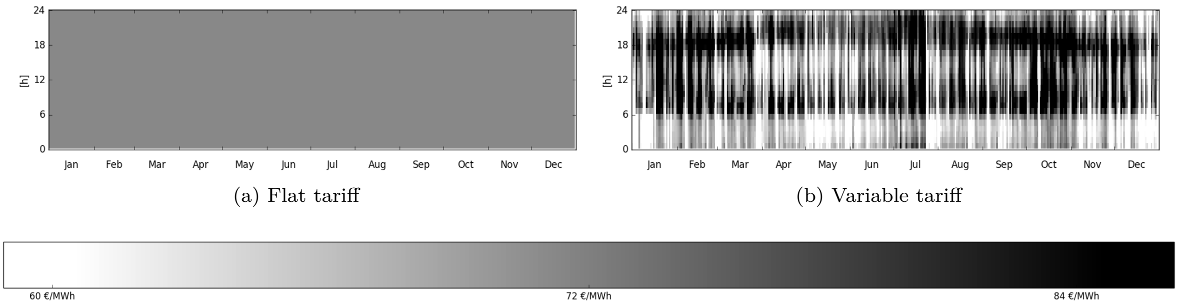


Figure 11: Reserve market price characteristics for the applied scenarios of the years 2015

The scenarios are, furthermore, completed for different tariff schemes for grid consumption as well as feed-in remuneration. The tariffs are composed of competitive pricing elements as well as statutory fees and levies as elaborated for Germany in [36]. In terms of the flat tariff (constant price) the mean spot market price in 2015 of 3.16 Ct/kWh_{el} states the basis and another 3.96 Ct/kWh_{el} of the sales cost component is added as the utility margin. In contrast, the variable electricity tariff (dynamic price) has besides the same constant utility margin a variable hourly spot price component. An exemplary depiction of the tariffs is given in Figure 12.



(a) Flat tariff (b) Variable tariff

Figure 12: Applied electricity tariffs_{el} of the year 2015 (competitive pricing elements only)

5.1.4. Case configurations

Taking into account flexibility options as well as the technical processes, different community structures are conceivable. All six residential prosumers are arranged in the same way. An overview of applied cases are outlined in Table 2. In case $\#1_{\text{flat}}$ using flat tariffs and $\#1_{\text{variable}}$ using variable tariffs, the prosumers are connected to the EG to cover their EL. The HL is satisfied by a NGB. A FG connection is necessary. In the other case the sectors are coupled. For case $\#2_{\text{flat}_{\text{avg}}}$, the NGB is replaced by a HP. Different sensitivities are conducted for the PV size and the CES capacity.

Table 2: Community layout for case study assessment

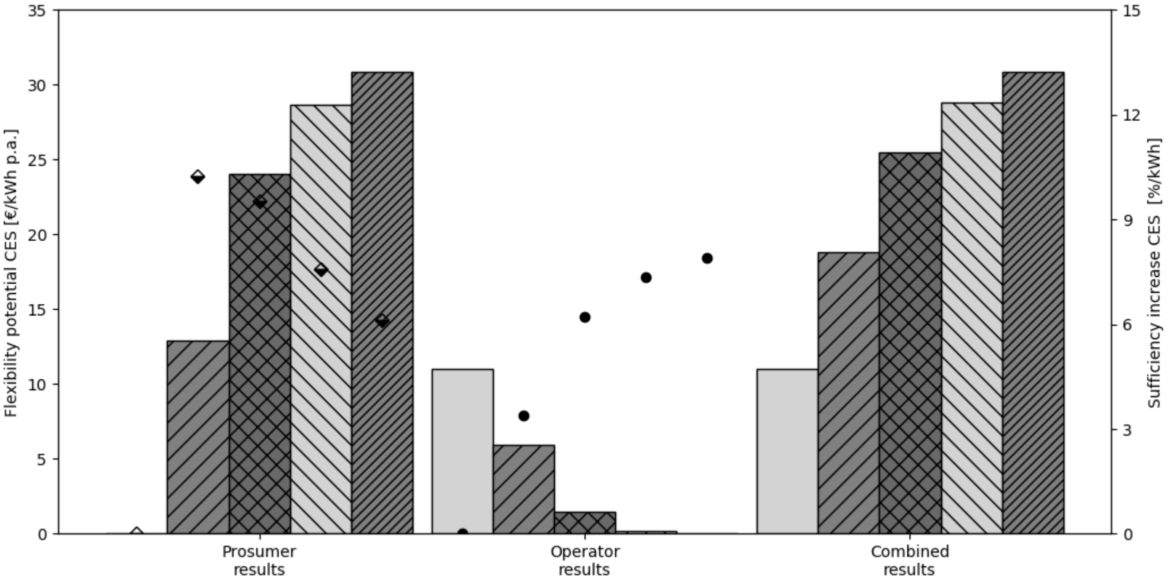
	$\#1_{\text{flat}}$	$\#1_{\text{variable}}$	$\#2_{\text{flat}}$
Prosumer	PV, EG, FG, NGB	PV, EG, FG, NGB	PV, EG, HP
Operator	CES	CES	CES
Sensitivities	PV size (0-30 m^2) and CES capacity (0-10 kWh_{el}), DR possibility ($DR_{\text{n.a.}}$,$DR_{\text{avg.}}$,$DR_{\text{max.}}$)		

5.2. Optimization results

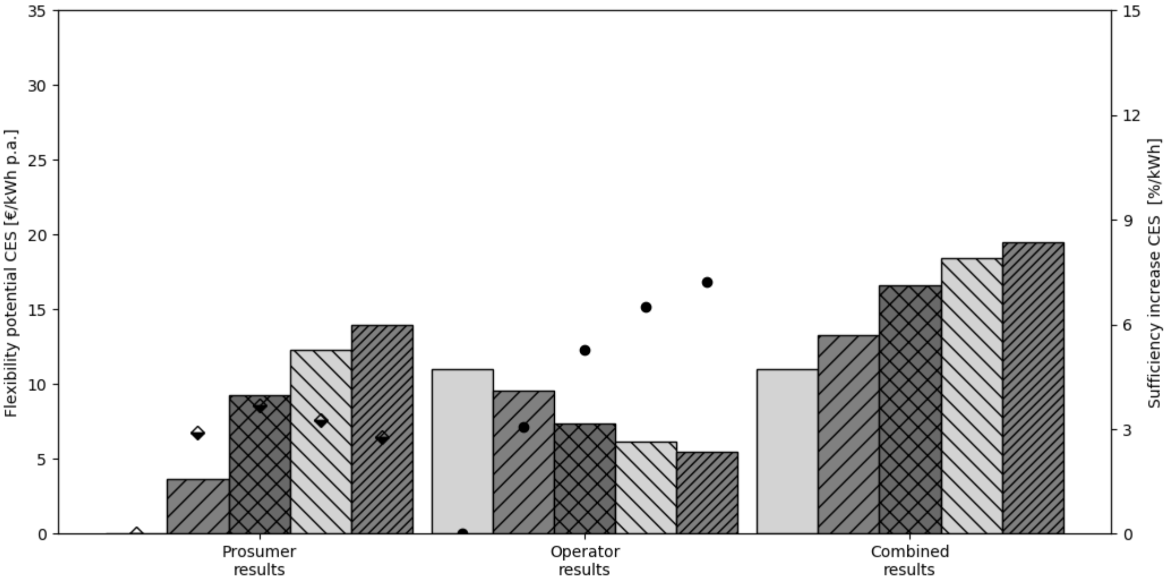
The CES has been optimized in terms of the actor-oriented approach as outlined in section 3.2: firstly, the model optimizes from an aggregated prosumer' perspective and subsequently from the operators' perspective. An exemplary flexibility potential of each stage is depicted in Figure 13. Cost savings on the prosumer side accrue from the utilization of the CES instead of sole grid consumption. Budgetary surplus on the operator side can be achieved by spot market trading of the available CES capacity with simultaneous consideration of losses regarding grid consumption. Investment costs of the CES are not considered yet. Additionally, the UR of the CES [38] is outlined in Table 3.

Considering the individual and combined dispatch results of the applied cases presented in Figure 13 and Figure 14, the following conclusions can be drawn:

- CES flexibility potential for the operator is dependent on the utilization by the prosumers as visible in terms of the arbitrages. Multi-level actor optimization show these correlations .
- In terms of a small CES account size and an average PV size as shown in Figure 13 the operator is only able to cover the financial losses of grid consumption by spot market trading. However, due to the prosumer flexibility potential, the highest combined flexibility potential arises in these cases per kWh. The ratio of the operator regarding the combined flexibility amounts in average 28 % for times self-consumption is possible.
- The variable tariff scheme in case $\#1_{\text{variable}}$ without $DR_{\text{n.a.}}$ leads to slightly higher annual prosumers costs. The reason is that the spot market price fluctuations are directly passed to the prosumers.



(a) CES 2.5 kWh per account



(b) CES 10 kWh per account

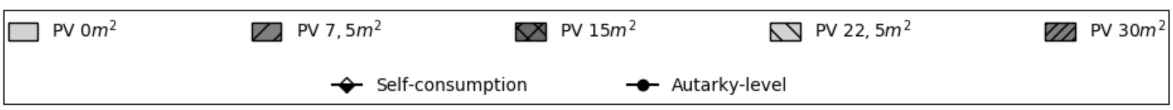


Figure 13: Average CES flexibility potential for prosumer and operator in [€/kWh p.a.] of case #1_{flat} without $\text{DR}_{\text{n.a.}}$ in the optimization year 2015

However, if the prosumers are able to adapt their consumption pattern ($DR_{avg.}$ and $DR_{max.}$) the benefits of the CES are marginally higher.

- By incorporating a further flexibility option in terms of heat pumps in case $\#2_{flat}$, the CES offers a lower flexibility potential even in the best cases. In this case, the prosumers utilize the flexibility of the heat pump first, the DR flexibility second, and the CES at the end.
- Even though the combined flexibility results of the CES are only slightly reduced by simultaneous application of $DR_{avg.}$ and $DR_{max.}$, the contribution share attributable to the prosumers decreases by up to 10 %. In this context, the CES is more intensively exploited by the operator as shown in Table 3.
- Related to single utilization, the CES is hardly used as shown in Table 3. Even the multiple usage reaches the peak by around 61 %, this again demonstrates the importance of shared usage of the CES. Reserve offerings might also increase the utilization.

PV [m^2] \ CES [kWh]	0	2,5	5	7,5	10
0	n.a.	11 €/kWh	11 €/kWh	11 €/kWh	11 €/kWh
7,5	n.a.	19 €/kWh	15 €/kWh	14 €/kWh	13 €/kWh
15	n.a.	26 €/kWh	21 €/kWh	18 €/kWh	17 €/kWh
22,5	n.a.	28 €/kWh	24 €/kWh	21 €/kWh	18 €/kWh
30	n.a.	30 €/kWh	25 €/kWh	22 €/kWh	19 €/kWh

(a) Case $\#1_{flat}$ with $DR_{n.a}$

PV [m^2] \ CES [kWh]	0	2,5	5	7,5	10
0	n.a.	11 €/kWh	11 €/kWh	11 €/kWh	11 €/kWh
7,5	n.a.	18 €/kWh	15 €/kWh	14 €/kWh	13 €/kWh
15	n.a.	24 €/kWh	20 €/kWh	18 €/kWh	16 €/kWh
22,5	n.a.	27 €/kWh	23 €/kWh	20 €/kWh	18 €/kWh
30	n.a.	29 €/kWh	24 €/kWh	21 €/kWh	19 €/kWh

(b) Case $\#1_{flat}$ with $DR_{avg.}$

PV [m^2] \ CES [kWh]	0	2,5	5	7,5	10
0	n.a.	11 €/kWh	11 €/kWh	11 €/kWh	11 €/kWh
7,5	n.a.	17 €/kWh	14 €/kWh	13 €/kWh	13 €/kWh
15	n.a.	23 €/kWh	19 €/kWh	17 €/kWh	16 €/kWh
22,5	n.a.	26 €/kWh	22 €/kWh	19 €/kWh	17 €/kWh
30	n.a.	28 €/kWh	23 €/kWh	20 €/kWh	18 €/kWh

(c) Case $\#1_{flat}$ with $DR_{max.}$

PV [m^2] \ CES [kWh]	0	2,5	5	7,5	10
0	n.a.	11 €/kWh	11 €/kWh	11 €/kWh	11 €/kWh
7,5	n.a.	18 €/kWh	15 €/kWh	14 €/kWh	13 €/kWh
15	n.a.	26 €/kWh	21 €/kWh	18 €/kWh	17 €/kWh
22,5	n.a.	29 €/kWh	24 €/kWh	21 €/kWh	19 €/kWh
30	n.a.	30 €/kWh	25 €/kWh	22 €/kWh	20 €/kWh

(d) Case $\#1_{var}$ with $DR_{n.a}$

PV [m^2] \ CES [kWh]	0	2,5	5	7,5	10
0	n.a.	11 €/kWh	11 €/kWh	11 €/kWh	11 €/kWh
7,5	n.a.	17 €/kWh	14 €/kWh	13 €/kWh	13 €/kWh
15	n.a.	24 €/kWh	20 €/kWh	18 €/kWh	16 €/kWh
22,5	n.a.	27 €/kWh	23 €/kWh	20 €/kWh	18 €/kWh
30	n.a.	29 €/kWh	24 €/kWh	21 €/kWh	19 €/kWh

(e) Case $\#1_{var}$ with $DR_{avg.}$

PV [m^2] \ CES [kWh]	0	2,5	5	7,5	10
0	n.a.	11 €/kWh	11 €/kWh	11 €/kWh	11 €/kWh
7,5	n.a.	16 €/kWh	14 €/kWh	13 €/kWh	12 €/kWh
15	n.a.	23 €/kWh	19 €/kWh	17 €/kWh	15 €/kWh
22,5	n.a.	26 €/kWh	21 €/kWh	19 €/kWh	17 €/kWh
30	n.a.	28 €/kWh	23 €/kWh	20 €/kWh	18 €/kWh

(f) Case $\#1_{var}$ with $DR_{max.}$

PV [m^2] \ CES [kWh]	0	2,5	5	7,5	10
0	n.a.	11 €/kWh	11 €/kWh	11 €/kWh	11 €/kWh
7,5	n.a.	11 €/kWh	11 €/kWh	11 €/kWh	11 €/kWh
15	n.a.	15 €/kWh	13 €/kWh	13 €/kWh	12 €/kWh
22,5	n.a.	19 €/kWh	16 €/kWh	15 €/kWh	14 €/kWh
30	n.a.	22 €/kWh	18 €/kWh	17 €/kWh	15 €/kWh

(g) Case $\#2_{flat}$ with $DR_{n.a.}$

PV [m^2] \ CES [kWh]	0	2,5	5	7,5	10
0	n.a.	11 €/kWh	11 €/kWh	11 €/kWh	11 €/kWh
7,5	n.a.	11 €/kWh	11 €/kWh	11 €/kWh	11 €/kWh
15	n.a.	15 €/kWh	13 €/kWh	13 €/kWh	12 €/kWh
22,5	n.a.	19 €/kWh	16 €/kWh	15 €/kWh	14 €/kWh
30	n.a.	21 €/kWh	17 €/kWh	16 €/kWh	15 €/kWh

(h) Case $\#2_{flat}$ with $DR_{avg.}$

	CES [kWh] 0	2,5	5	7,5	10
0	n.a.	11 €/kWh	11 €/kWh	11 €/kWh	11 €/kWh
7,5	n.a.	11 €/kWh	11 €/kWh	11 €/kWh	11 €/kWh
15	n.a.	14 €/kWh	13 €/kWh	12 €/kWh	12 €/kWh
22,5	n.a.	18 €/kWh	15 €/kWh	14 €/kWh	13 €/kWh
30	n.a.	20 €/kWh	17 €/kWh	15 €/kWh	14 €/kWh

(i) Case $\#2_{flat}$ with $DR_{max.}$

Figure 14: Average combined CES flexibility potential in [€/kWh p.a.] of various applied cases without and with simultaneous DR possibility in the optimization year 2015.

Table 3: Average UR [%] of CES without $DR_{n.a}$ and with $DR_{max.}$ for the case $\#1_{flat}$. The results of the different applied PV sizes has been averaged.

CES	UR (Prosumer) $DR_{n.a}$	UR (Prosumer) $DR_{max.}$	UR (Combined) $DR_{n.a}$	UR (Combined) $DR_{max.}$
2.5 kWh	27 %	25 %	58 %	57 %
5 kWh	36 %	33 %	60 %	59 %
7.5 kWh	39 %	35 %	61 %	60 %
10 kWh	40 %	36 %	61 %	60 %

By taking the two scenario price projections into account (see section 5.1.3) the CES shows a better flexibility potential over the years. Since the condition change in favor of CES business model, small CES could be covered by the combined flexibility potential in 2035 in terms of the assumed green scenario. Figure 15 displays the coverage of the annualized investment cost of CES with respect to $\#1_{flat}$ without considering $DR_{n.a}$. Simultaneous reserve market offerings besides the spot market arbitrage leads already to positive results in the year 2015 as shown in Figure 16. From the optimal dispatch results, the following conclusions can be drawn:

- While in the fossil scenario the combined flexibility potential stays nearly constant, the green scenario shows a rise over the years. In this context, the average share of the operator changes quite a bit between the years. Thereby, the share of the operator also increases from 19 % in 2025 to 42 % in 2035. This is not as pronounced in the fossil scenario (21 % in 2025, 28 % in 2035).
- The advantages of a multi-tasking storage application both with respect to capacity utilization as well as realized flexibility potential is apparent. Multi-stage optimization show the differential impact.
- In terms of self-consumption and spot arbitrage, flexibility potential might cover the annual investment costs of the CES in the best cases in 2035. Since the revenues from the spot market arbitrage play a minor role as shown for 2015, revenues from the reserve market offerings should lead to an earlier positive contribution of a CES.

		CES [kWh]				
		0	2,5	5	7,5	10
PV [m²]	0	n.a.	-63 €/kWh	-63 €/kWh	-63 €/kWh	-63 €/kWh
	7,5	n.a.	-55 €/kWh	-58 €/kWh	-60 €/kWh	-60 €/kWh
	15	n.a.	-48 €/kWh	-53 €/kWh	-55 €/kWh	-57 €/kWh
	22,5	n.a.	-45 €/kWh	-50 €/kWh	-53 €/kWh	-55 €/kWh
	30	n.a.	-44 €/kWh	-48 €/kWh	-52 €/kWh	-54 €/kWh

(a) Case $\#1_{\text{flat}}$, Fossil, 2015

		CES [kWh]				
		0	2,5	5	7,5	10
PV [m²]	0	n.a.	-39 €/kWh	-39 €/kWh	-39 €/kWh	-39 €/kWh
	7,5	n.a.	-30 €/kWh	-34 €/kWh	-36 €/kWh	-37 €/kWh
	15	n.a.	-22 €/kWh	-27 €/kWh	-31 €/kWh	-33 €/kWh
	22,5	n.a.	-19 €/kWh	-24 €/kWh	-28 €/kWh	-30 €/kWh
	30	n.a.	-17 €/kWh	-22 €/kWh	-26 €/kWh	-29 €/kWh

(b) Case $\#1_{\text{flat}}$, Fossil, 2025

		CES [kWh]				
		0	2,5	5	7,5	10
PV [m²]	0	n.a.	-22 €/kWh	-22 €/kWh	-22 €/kWh	-22 €/kWh
	7,5	n.a.	-14 €/kWh	-18 €/kWh	-19 €/kWh	-20 €/kWh
	15	n.a.	-8 €/kWh	-12 €/kWh	-15 €/kWh	-16 €/kWh
	22,5	n.a.	-5 €/kWh	-10 €/kWh	-13 €/kWh	-15 €/kWh
	30	n.a.	-4 €/kWh	-8 €/kWh	-11 €/kWh	-14 €/kWh

(c) Case $\#1_{\text{flat}}$, Fossil, 2035

		CES [kWh]				
		0	2,5	5	7,5	10
PV [m²]	0	n.a.	-63 €/kWh	-63 €/kWh	-63 €/kWh	-63 €/kWh
	7,5	n.a.	-55 €/kWh	-58 €/kWh	-60 €/kWh	-60 €/kWh
	15	n.a.	-48 €/kWh	-53 €/kWh	-55 €/kWh	-57 €/kWh
	22,5	n.a.	-45 €/kWh	-50 €/kWh	-53 €/kWh	-55 €/kWh
	30	n.a.	-44 €/kWh	-48 €/kWh	-52 €/kWh	-54 €/kWh

(d) Case $\#1_{\text{flat}}$, Green, 2015

		CES [kWh]				
		0	2,5	5	7,5	10
PV [m²]	0	n.a.	-39 €/kWh	-39 €/kWh	-39 €/kWh	-39 €/kWh
	7,5	n.a.	-29 €/kWh	-34 €/kWh	-36 €/kWh	-37 €/kWh
	15	n.a.	-21 €/kWh	-26 €/kWh	-30 €/kWh	-32 €/kWh
	22,5	n.a.	-17 €/kWh	-23 €/kWh	-27 €/kWh	-30 €/kWh
	30	n.a.	-14 €/kWh	-21 €/kWh	-25 €/kWh	-28 €/kWh

(e) Case $\#1_{\text{flat}}$, Green, 2025

		CES [kWh]				
		0	2,5	5	7,5	10
PV [m²]	0	n.a.	-14 €/kWh	-14 €/kWh	-14 €/kWh	-14 €/kWh
	7,5	n.a.	-8 €/kWh	-11 €/kWh	-12 €/kWh	-13 €/kWh
	15	n.a.	-2 €/kWh	-6 €/kWh	-8 €/kWh	-10 €/kWh
	22,5	n.a.	1 €/kWh	-4 €/kWh	-6 €/kWh	-8 €/kWh
	30	n.a.	3 €/kWh	-2 €/kWh	-5 €/kWh	-7 €/kWh

(f) Case $\#1_{\text{flat}}$, Green, 2035

Figure 15: Average coverage of CES investment costs [€/kWh p.a.] for the green and fossil scenarios for the years 2015, 2025, 2035 considering case $\#1_{\text{flat}}$ and self-consumption and spot market trading

		CES [kWh]				
		0	2,5	5	7,5	10
PV [m²]	0	n.a.	-24 €/kWh	170 €/kWh	122 €/kWh	98 €/kWh
	7,5	n.a.	-18 €/kWh	151 €/kWh	109 €/kWh	88 €/kWh
	15	n.a.	-12 €/kWh	137 €/kWh	99 €/kWh	80 €/kWh
	22,5	n.a.	-10 €/kWh	130 €/kWh	94 €/kWh	76 €/kWh
	30	n.a.	-9 €/kWh	126 €/kWh	90 €/kWh	74 €/kWh

Figure 16: Average coverage of CES investment costs [€/kWh p.a.] for the year 2015 considering case $\#1_{\text{flat}}$ as well as self-consumption, spot market trading and reserve market offerings

6. Concluding remarks

Business portfolio decisions should be supported by optimization studies taking into account the current business portfolio, the customer base, the regulatory framework as well as the market environment. Optimization is necessary, because potentials for reducing energy inputs and emissions of pollutants, as well as applicable costs, depend significantly on the municipal circumstances present. This research presents a novel mathematical optimization framework. The flexible multi-level actor-oriented dispatch approach is able to coordinate prosumers and operators to detect competitive effects in a municipal community. First the multiple processes owned by prosumers can be optimized. Subsequently, the maximal profit of operator can be determined taking into account the behavior of other actors. Future work is intended to be grounded on *business model assessments*.

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Chapter 6

Multi-Model Vision

*IRPsim: A techno-socio-economic energy system model vision for business strategy assessment at municipal level**

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IRPsim: A techno-socio-economic energy system model vision for business strategy assessment at municipal level

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Abstract

Decision makers of municipal energy utilities responsible for future portfolio strategies are confronted with making informed decisions within the scope of continuously evolving systems. To cope with the increasing flexibility of customers, and their autonomous decision-making processes, determining newly established municipal energy-related infrastructure has become a challenge for utilities, which are struggling to develop suitable business models. Even though business portfolio decisions are already supported by energy system models, models only considering rational choices of economical drivers seem to be insufficient. Structural decisions of different market actors are often related to bounded rationality and thus are not fully rational. A combined analysis of sociological and technological dynamics might be necessary to evaluate new business models by providing insights into the interactions between the decision processes of market actors and the performance of the supply system. This research paper outlines a multi-model vision called IRPsim (Integrated Resource Planning and Simulation) including bounded and unbounded rationality modeling approaches. The techno-socio-economic model enables the determining of system impacts of behavior patterns of market actors on the business performance of the energy supply system. The mutual dependencies of the coupled models result in an interactive and dynamic energy model application for multi-year business portfolio assessment. The mixed-integer dynamic techno-economic optimization model IRPopt (Integrated Resource Planning and Optimization) represents an adequate starting point as a result of the novel actor-oriented multi-level framework. For the socio-economic model IRPact (Integrated Resource Planning and Interaction), empirically grounded agent-based modeling turned out to be one of the most promising approaches as it allows for considering various influences on the adoption process on a micro-level. Additionally, a large share of available applied research already deals with environmental and energy-related innovations.

Keywords: Techno-socio economic modeling, Bounded and unbounded rationality, Business model assessment, Empirically grounded agent-based modeling of innovation diffusion

1. Introductory remarks

Techno-economic optimization models are one of the main streams in modeling energy systems and supporting informed decision making within the scope of continuously evolving systems. Sophisticated numerical energy system models at the municipal level have to account for the current business portfolio, technological progress, customer behavior, regulatory framework as well as the market environment. However, in a liberalized market, actors along the energy value chain might assess challenges and opportunities from different actor perspectives and apply various criteria, since every single consumer and operator, due to their positioning, contracts, and instruments, has a differing technology-mediated relationship [1]. A successful introduction of innovative business models needs to be accompanied by an appropriate pricing, distribution, and communication strategy [2]. Existing energy system models often neglect the roles different actors play

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in an existing system architecture [3] and the resulting impact their characteristics, attitude, and behavior might have on the consumer acceptance of specific diffusion processes.

Thus, to valuate future strategies that include business model innovations, which might also have an effect on the system infrastructure, it is crucial to account for the technological restrictions of system units. In addition to this, business models should also encompass the dynamics of the market setting by including the commercial processes that arise between multiple market participants in general and in particular those involving customers or more precisely prosumers in order to determine newly established municipal infrastructure. Mental decision structures can be decisive regarding the evaluation and acceptance of an innovation and for any consequences arising from it. A socio-economic bounded rationality approach recognizes that individuals have incomplete knowledge, as well as limited information gathering and processing abilities [4]. Consequently, coupled modeling of technical infrastructure and interacting actors provides decision makers with a supportive analysis of commercial competition and technical counteraction effects for future business models to be investigated [1].

This paper outlines a multi-model vision called *IRPsim* (Integrated Resource Planning and Simulation) of sociological and technological dynamics. A combination of an unbounded rationality model, as well as a bounded rationality model, enables the simulation of feedback effects that decisions of market actors have on the performance of a certain energy supply network as initially described by [5]. In addition to the existing techno-economic modeling approach *IRPopt* (Integrated Resource Planning and Optimization), a socio-economic modeling approach called *IRPact* (Integrated Resource Planning and Interaction) needs to not only consider the heterogeneity of behavioral patterns, but also the communication and interaction structures of market participants [6]. Empirically grounded agent-based modeling turned out to be one of the most promising approaches for socio-economic modeling as it allows for considering various influences on the adoption on a micro-level [7]. The multi-model vision is in line with the proposed energy policy roadmap of [1] and the long-term objective of combining the various strands into a single assessment package.

This paper is organized as follows: Section 2 introduces the coupled techno-socio-economic model concept. Section 3 outlines theoretical foundations of the socio-economic modeling domains and introduces the concepts of empirically grounded agent-based modeling of innovation diffusion. Section 4 gives an overview of suggested future work to develop the multi-model vision. Finally, section 5 concludes with a recapitulation.

2. Techno-socio-economic model vision

Future energy-related business portfolio decisions should be supported by energy system models considering the current business portfolio, technological progress, customer behavior, regulatory framework as well as the market environment. The techno-economic mathematical optimization framework *IRPopt* (Integrated Resource Planning and Optimization) [8] supports decision makers of municipal energy utilities regarding future portfolio management. The mathematical optimization model allows for a policy-oriented, technology-based and actor-related assessment of varying energy system conditions in general, and innovative business models in particular. The integrated multi-modal approach is based on a novel six-layer modeling framework built on existing high-resolution modeling building blocks.

The optimization model, which has been implemented in GAMS/CPLEX (General Algebraic Modeling System), allows for solving mixed-integer problems in a quarter-hourly resolution for perennial periods. The major objective is to maximize revenues from different actor perspectives. Thereby, *IRPopt* provides a novel actor-oriented multi-level optimization framework. This is achieved by an explicit modeling of municipal market actors on one layer and state-of-the-art technology processes on another layer as well as resource flow interrelations and service agreements mechanism among and between the different layers. Individual participating market actors and the spatially distributed load, storage and generation technologies are modeled separately. Furthermore, multi-party cooperation is incorporated. Individual actors hold bilateral contracts with each other that handle the business transactions. Due to the chosen approach, decision making of different modeled market actors can be described using the term unbounded rationality [4]. In mathematical programming systems, designers define rules and procedures to engineer outcomes. This falls in line with the statement of [4] that "the operational decisions of local utilities and large independent energy producers are assumed to close to individually fully rational, because of the sophisticated software tools already used to support these decisions. Within the approach presented here, operational decisions, therefore, are made using an optimization model similar to the models applied by utilities." Additionally, due to the novel framework, *IRPopt* permits to determine the optimal operation dispatch and thus the optimal *profitability index* from different market actor perspectives, such as prosumer households, and not only from the municipal utility.

With this in mind, the model-driven decision support system IRPopt will be valuable in the context of strategy adjustments and business development processes of utilities. Potential use cases originate from the core business of its departments, supporting, in particular, the day-to-day business of the strategy and sales unit. Questions the model is particularly suited to address are as follows:

- What effects of customer technology adoption on sales and margins are visible in terms of different scenarios?
- Which company-wide impact of a business model implementation, as well as customer migration flows, can be determined?
- What are optimal community layouts in the context of decentralized autarky system trends and differing municipal conditions?
- What is the value of flexibility regarding balancing and spot markets as well as peak load curtailment for different participating actors?

Initial model applications and business model assessments of IRPopt are presented in [9, 10]. The focus has been on decentralized autarky enhancement solutions like self-consumption, direct consumption, direct marketing, demand response, net metering and community storage systems.

Scenario and sensitivity analysis is applied to detect the consequences of parameter changes [11]. For this, uncertain environmental conditions, prosumer operations as well as market developments represent a crucial aspect. Since the quality depends on the procedure, a techno-economic multi-method approach seems useful to cover the issues raised. In order to describe the economic boundary conditions, spot market and reserves market prices need to be consider which might be determined or rather projected by employing the optimization model MICOES-Europe (Mixed Integer Cost Optimization of Energy Systems) and the optimization model MICOES-Reserve. While the fundamental model MICOES-Europe uses marginal costs to determine future spot market prices of selected European countries [12], the fundamental model MICOES-Reserve uses opportunity costs to calculate future control power prices [13, 14]. In this context, LICOES-Europe [15] is able to determine the possible future power plant park. Additionally, the investment decision tool MicroGrid [16] might be applied to assess prosumer technology adoption behavior. An overview of the interplay of different optimization models to parameterize *IRPopt* is outlined in Figure 1.

Techno-economic modeling can capture technological interactions, but it cannot endogenize the commercial processes that arise between multiple market participants [1]. "The structural decisions faced by local utilities, independent energy producers, and house owners exhibit increasing levels of ambiguity and mathematical intractability. The orthodox assumptions of unbounded rationality and perfect foresight reduce the set of potential behaviors that require investigation to those that are defined as optimal in some sense. Bounded rationality, on the other hand, introduces the challenge of extracting realistic behavior patterns from an almost unlimited set of possible alternatives." [4]. Different incentives can influence the heterogeneous market actors and might cause a change in their decision behavior in a different way. If certain customers decide to invest in decentralized energy technologies or to shift their load, this might influence the technical infrastructure and the system performance. Additionally, strategies of competitors may also have a relevant effect on the decision behavior of customers. Even if the competitor is not directly influencing the individual actors, their business offers may induce customers to change their provider or make an investment. During the design and implementation of sustainable business portfolios, this can lead to synergy effects or increasing peer pressure, which needs to be subject to closer examination.

In this context, it is important to understand how investment decisions of individual market actors are conducted, since even good innovations might fail or diffuse at a slow rate [18]. For many companies it is hard to predict how business model innovations will diffuse in the dynamic energy-economic environment,

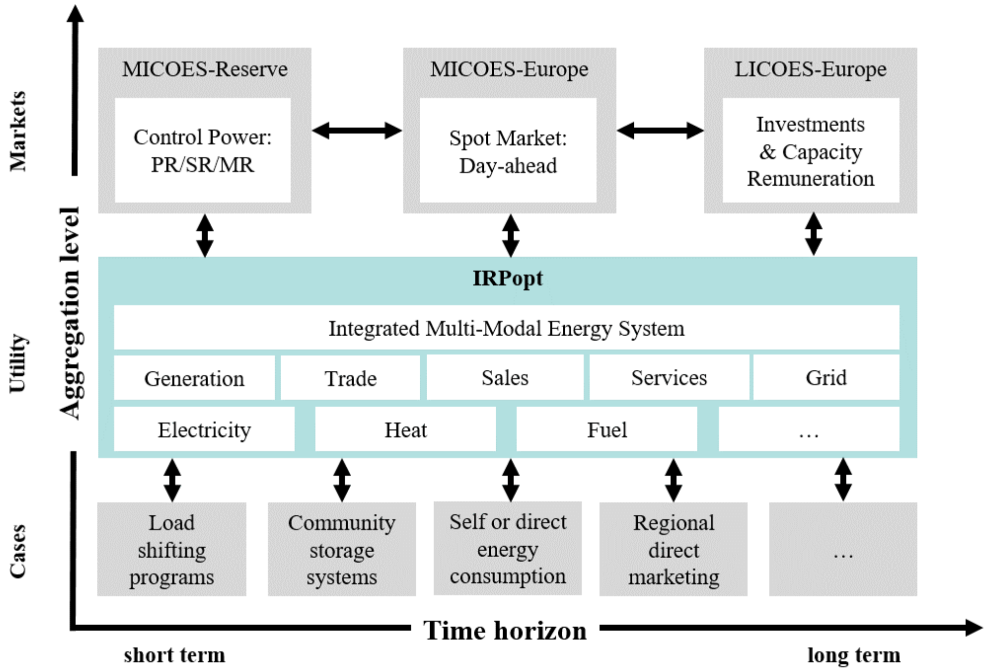

Figure 1: Overview of the interplay of various techno-economic energy system optimization models to parametrize the integrated multi-modal modeling approach IRPopt (MICOES-Reserve [13, 14], MICOES-Europe [12, 14], LICOES-Europe [15], IRPopt [8–10, 17])

resulting in uncertainty about whether an innovation is fit to become a sustainable business model. This may be to a large part because the adoption of these innovations by the intended target groups is not always given, and as [19] shows, doesn't just depend on the qualities of the innovation. Instead, it takes place within a complex social system, in which the diffusion of the respective innovations depends on many factors and mechanisms [20]. Business models and innovations need to encompass the dynamics of the market setting by including the mental decision structures, such as personal characteristics, behavioral attitudes as well as conscious and subconscious purchase decisions, of market participants in general and of customers in particular. As [21] points out, "[...] the diffusion of innovation paradigm postulates that markets are in fact dominated by social influences [...]."

By extending the techno-economic model *IRPopt* with the socio-economic model *IRPact* (Integrated Resource Planning and Interaction), it is possible to consider various energy-economic system drivers as a whole as shown by [4, 5]. Socio-economic modeling does not only account for the heterogeneity of bounded-rational mental behavior patterns, which are not only based on economic thinking but also considers the social structures of market actors [6]. This approach makes it possible to simulate acceptance and diffusion of innovations by various customer types and utilities considering different decision-making and network models, as well as the temporal and regional differences in the diffusion process. The simulated *adoption rate* of individual market actors regarding energy-related business models, in turn, directly affects the energy supply network and process technologies of the techno-economic system model *IRPopt*. In contrast, the optimized *profitability index* of individual actors in terms of a given supply network can be considered a single influencing aspect of the decision behavior of the socio-economic system model *IRPact*.

A multi-model system called *IRPsim* (Integrated Resource Planning and Simulation) of an unbounded technical infrastructure optimization and a bounded interacting actors simulation enables the determination of system impacts of socio-economic behavior patterns of market actors on the techno-economic business performance of the energy supply system. A schematic representation of the interplay of the two models is outlined in Figure 2. While *IRPact* includes simulated adoption decisions of the individual market actors (*adoption rate*), *IRPopt* considers the optimized operation dispatch (*profitability index*). This results in an interactive and dynamic energy multi-model application for multi-year business portfolio assessment.

As outlined in Figure 2, *IRPopt* requires parametrization of the system infrastructure. Thereby, market actors and corresponding engineering processes as well as resource flow interrelations and coordination mechanism among and between them need to be defined. Additionally, market principles need to be specified to model realistic issues at the municipal level. Since *IRPact* takes the same market actors into account as *IRPopt*, mental models and social dynamics between them need to be parametrized first. Furthermore, the social network design, as well as the theoretical and empirical grounding, is required for a realistic adoption behavior modeling. While optimization results of a certain system infrastructure provide costs and revenues for each of the participating actors in terms of operational management, the simulation results of a certain social system shows the adoption rate for each of the participating actor. This, in turn, affects the system infrastructure and changes the parametrization of *IRPopt*. At the same time, the reevaluated profitability of the adoption decision influences the decision making of the participating actors and thus the adoption process of *IRPact*. The integration layer of *IRPsim* provides the necessary interfaces and mechanisms to enable the information exchange of the multi-model approach and allows to analyze the dependencies of the techno-economic and socio-economic system dynamics. In this sense, a multi-model system of coordinated and matched components as outlined above can demonstrate its great benefits and achievement of robust answers.

From a scientific point of view, the multi-model framework aims to analyze the interrelations between customer behavior and system performance. It can give an answer to the question what synergy and competition effects certain socio-economic customer structures evoke within a techno-economic energy system. The main focus of the research in this context is how and to what extent the adoption behavior of different customer groups regarding innovative business models show competition and counteraction effects on the current and emerging energy supply network. In practice, achieving the vision will provide answer a number of management questions, such as:

- What costs and revenues for market actors occur in terms of business model implementation at the municipal level?
- Which product attributes and market dynamics are necessary for customers to adopt business model innovations?
- What are the interrelations between the innovation diffusion among different customer types and the supply network infrastructure?
- What feedback effects along the value chain of the company and its business units will the innovation initiate?
- Which business model innovations do both have a positive effect on the business performance and are adopted by the customers?

3. Socio-economic modeling approach

Decision makers of municipal energy utilities responsible for product or service innovations are confronted with making informed decisions about complex matters. Insights into the diffusion of innovations can help to detect weak areas in business models and innovation marketing. Particularly quantitative socio-economic models of innovation diffusion analysis that account for the social complexity of the modeled system might assist in the investigation of potential measures and in the development of effective strategies. One promising

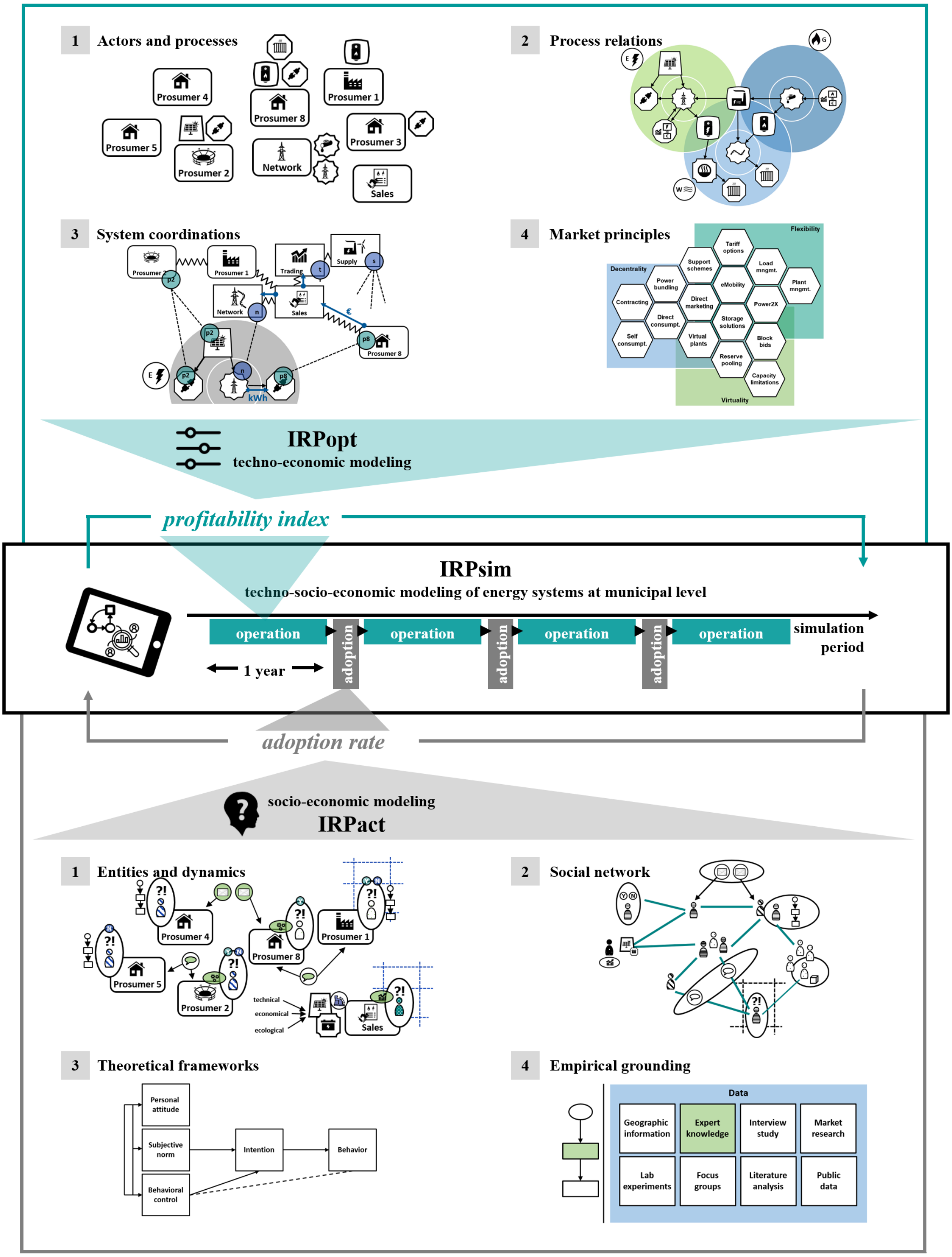

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Figure 2: Schematic relation of the energy model vision IRPsim consisting of the techno-economic modeling approach IRPopt and the socio-economic modeling approach IRPact

socio-economic modeling approach for describing diffusion processes is to employ empirically grounded agent-based models [7]. A general overview of the covered research domains and relevant intersections is given in the following.

3.1. Innovation diffusion modeling

Although the roots of innovation diffusion research lie in the late 19th century, studying the diffusion of innovations can generally be traced back to the seminal study of Ryan and Gross in the 1940s in rural sociology about the diffusion of hybrid corn [20, 22]. This might be due to the fact that the "study advanced theoretical exploration of the diffusion process." [22], or because the study "[...] was driven by scholarly interest in the relative influence of economic versus social factors in the adoption of a technological innovation." [22].

A fundamental aspect of innovation diffusion Ryan an Gross identified was the interpersonal communication between farmers. "The hybrid corn study established diffusion as essentially a social process. A farmer typically adopted the innovation because of interpersonal communication with other farmers who already had adopted it [...]." [22]. Through this social process "[...] subjective evaluations of an innovation spread from earlier to later adopters rather than one of rational, economic decision making." [22].

Rogers defines the *diffusion of an innovation* as "[...] the process in which an innovation is communicated through certain channels over time among the members of a social system." [18]. This definition exemplifies the four major elements, namely innovation, communication channels, time, and the social system. Each one of these elements is identifiable in nearly every diffusion research or diffusion campaign [18]. In other words, diffusion can be seen as a "special kind of communication in which the messages are about a new idea. [...] Diffusion is a kind of social change, defined as the process by which alteration occurs in the structure and function of a social system." [18]. Thereby, "[a]n *innovation* is an idea, practice or object that is perceived as new by an individual or other unit of adoption." [18]. The perception of newness matters, but not the absolute newness as described by [23]. "*Adoption* is a decision to make full use of an innovation as the best course of action available. Rejection is a decision not to adopt an innovation." [18]. The units of adoptions could be individuals, households, institutions or other entities. A summary of operational definitions of presented key concepts is outlined in Table 1.

Table 1: Key concepts of innovation diffusion modeling

Concept	**Definition**
Product innovation	"Innovation is an idea, practice, or object perceived as new by an individual or other unit of adoption. It can also be an impulse to do something new or bring some social change." [18]. In this work, a perception of newness matters, but not the absolute newness [23].
Innovation adoption	"Adoption is a decision to make full use of an innovation as the best course of action available. Rejection is a decision not to adopt an innovation." [18]
Innovation diffusion	Innovation diffusion is "the process by which an innovation is communicated through certain channels over time among the members of a social system." [18]

Starting from the 1960s, innovation diffusion processes have been investigated using models, which aim at empirical generalizations of prototypical diffusion patterns at *aggregate levels* [21]. As Ryan and Gross stress, social contacts, social interaction and interpersonal communication are important influences on the adoption of new behaviors. Kiesling emphasizes that innovations are not evaluated objectively, but instead, the dynamic formation of attitudes and subjective perceptions are transmitted through communication at *disaggregated levels* [21].

A large amount of *aggregated innovation diffusion models* are refined versions of the Bass model [24], a parsimonious, aggregated innovation diffusion model, based on models of epidemiological spread. The *Bass* *model* as described in [24] is theoretically based in (epidemiological) contagion models and is based upon the assumption that the timing of initial purchases is related linearly to the number of previous buyers. The goal of the model is to develop a theory of timing of initial purchases for new classes of products. Its key characteristic is that the adoption behavior of imitators is influenced in timing through social pressure. In this context, the following sentence characterizes the theory: "The probability that an initial purchase will be made at T given that no purchase has been made is a linear function of the number of previous buyers." [24]. Thus, the Bass model intends to formalize literary analysis of Rogers in terms of the likelihood of the number of purchases $P(T)$ at time T given that no purchase has yet been made. On the one hand, this is dependent on the constant p at $T = 0$ which represents the probability of an initial purchase (coefficient of innovation). On the other hand, the number of purchases is dependent on the product $(\frac{q}{m})$ times $Y(T)$. This product reflects the pressures operating on imitators in terms of an increasing number of previous buyers. Thereby, $(\frac{q}{m})$ represents a scaling constant (where m is the number of total initial purchases and q the coefficient of imitation) and $Y(T)$ represents the number of previous adopters. If $Y(0) = 0$, the constant p and thus the probability of an initial purchase remains. All in all, $P(T)$ can be calculated as follows:

$$P(T) = p + \frac{q}{m}Y(T)$$

From this, Bass [24] derives the sales $S(T)$ at time T as follows:

$$S(T) = P(T)(m - Y(T)) = \Big(p + q\int_0^T S(t)\frac{dt}{m}\Big)\Big(m - \int_0^T S(t)dt\Big) = pm + (q-p)Y(T) - \frac{q}{m}(Y(T))^2$$

This adoption behavior exemplifies the exponential growth of initial purchases to a peak, followed by exponential decay. This form shows the aggregated nature of the model, which describes total adoption or rather adoption per time period in a closed form and aggregates the agents into a 'macro' variable.

Despite their popularity, these aggregate models have several shortcomings [20, 21]. The most fundamental shortcomings of aggregated innovation diffusion models are their assumption of a homogeneous population. Furthermore, aggregate models cannot differentiate between the social network of one potential adopter and the other, so they have to impose the assumption of a fully connected social network. Additionally, these models require information about events they ought to predict, and lack predictive power.

To overcome these limitations, many approaches employ *disaggregate models*, most notably *agent-based models*. Disaggregated models are models that avoid aggregating model entities individually. They focus on micro-behavior instead of macro behavior and are grounded in complexity science. In contrast to macro simulations, where the entire system is described directly and 'phenomenologically', societal phenomena of interest are modeled bottom-up based on the underlying processes. The phenomena then emerges from the behavior and micro-level interactions of the agents [21].

3.2. Agent-based modeling

As the name suggests, agent-based models are conceptualized from the perspective of disaggregated units, so-called agents or actors[1], instead of modeling the system on the aggregate level. As noted in [25], no single universally accepted definition of an agent exists. Instead Wooldridge [25] enumerates abilities actor entities need to exhibit in order to be called agents. In their general definition, agents need to exhibit four abilities: autonomy, social ability, reactivity, and pro-activeness. In this, *autonomy* is the ability to act without being directly controlled or manipulated by humans or others, as well as having some control over their actions and internal state. *Social ability* means the use of an agent-communicative language to interact with other agents, where *reactivity* represents the perception of and response to their environment. Finally, *proactiveness* is the

[1]Many publications from the sociological, ecological or socio-economic perspective use the term *agent* to refer to these units, publications in computer science often try to avoid this term, since it might be confused with the concept of software agents, and rather use the term *actor*. In this publication, they will be used interchangeably, and where the distinction between actors and software agents is meaningful, this will be made explicit.

ability to take initiative in goal-directed behavior instead of solely responding to stimuli [25]. Most crucially, agent-based models allow for modeling heterogeneity of potential adopters. Since this approach describes actors on the level of their entity, actors can be designed differently from one another. The characterization of agents is proposed which considers interaction between agents but also puts interaction with and immersion in an environment at the heart of the models [26]. A summary of operational definitions of presented key concepts is outlined in Table 2.

Table 2: Key concepts of agent-based modeling

Concept	**Definition**
Software agent	"An agent is a computer system that is situated in some environment, and that is capable of autonomous action in this environment in order to meet its design objectives." [25].
Multi-agent model	"A multi-agent system is one that consists of a number of agents, which interact with one another [. . .]. [T]he agents in a multi agent system will be representing or acting on behalf of users or owners with very different goals and motivations." [27].
Model procedure	Model procedures poses step-wise guidelines for the designing and modeling of complex systems in terms of scientific purposes. This covers activity lists, building blocks, structural items, best practices, design choices, methodological issues as well as functional protocols and frameworks.
Model component	Model components represent the functional elements of complex systems. Master categories are model strategies, model entities and model dynamics [21].

3.3. Empirically grounded modeling

The level of detail with respect to the data and information incorporated into agent-based simulations varies from "Picasso" to "Photograph" models [28]. "An obvious difference relates to the representation of space, ranging from empty and simple artificial landscapes [...] to very detailed, realistic representations of the environment." [28]. At first, more abstract models (so-called "Picasso" models) were widely used to show general mechanisms rather than to make exact predictions. Since *IRPact* aims to predict innovation diffusion processes, the following research needs to focus on detailed models (so-called "Photograph" models).

In this context, different aspects as actor heterogeneity can enter agent-based innovation diffusion models through different values of characteristics such as income or preference [28], various sources of knowledge [29], different types of agents that differ in decision rules and interaction with other agents and the environment [28]. This is due to the fact that the behavior of the modeled agents "[...] can be empirically informed using a combination of different kinds of data (e.g. qualitative and quantitative) and data collection methods [...] that support multiple approaches to represent actor decision making in an agent (e.g., heuristic decision trees, utility functions)." [26]. Through this they "[...] can go beyond the typical representation of a population or average individual in EBMs [equation based models] and capture the heterogeneity of individual actors, their characteristics, and decision-making structures." [26]. Thus, empirically grounded agent-based models of innovation diffusion can reproduce and explain complex non-linear diffusion patterns observed in the real world as a result of simple local micro-level interactions [21]. A summary of operational definitions of presented key concepts is outlined in Table 3.

Table 3: Key concepts of empirically grounded modeling

Concept	**Definition**
Grounded theory	Grounded theory is defined as "discovery of theory from data systematically obtained from social research." [30]. The derived constructs constitute the grounding of the models. In this work, it refers to theoretical grounding as well as empirical grounding.
Theoretical grounding	Theoretical grounding describes the characterization of the model. It "aims at surfacing the intended model as an artifact: qualifying its contours and interfaces." [31].
Empirical grounding	Empirical grounding describes the parametrization of the model. It "aims at connecting model and target system, through giving values to the set of parameters in order to enable simulation." [31].
Micro-level approach	Micro-level approach describes a "bottom-up" or "microscopic" modeling [6]. "Rather than describing the whole system directly and phenomenologically, macro-scale dynamics in [system models] are emergent phenomena that arise from micro-level interactions between agents when the model is executed." [7].
Case-based applications	Case-based applications "have an empirical space-time circumscribed target domain. [. . .] The goal [. . .] is to find a micro-macro generative mechanism that can allow the specificity of the case [. . .]. [32]. They are usually built "to provide forecasts, decision support, and policy analysis [. . .]." [7].

3.4. Empirically grounded agent-based case studies

Given the advantages, the described models are losing their niche character and gaining importance as a valuable methodology for describing diffusion processes [7]. Since empirically grounded agent-based models are foremost applied to reflect real market issues, papers with real-world case studies to support decision makers are increasing [33]. Case-based applications "have an empirical space-time circumscribed target domain." [32]. They are usually built "to provide forecasts, decision support, and policy analysis [. . .]." [7]. In this context, the application domain of empirically grounded agent-based models of innovation diffusion is very versatile. With respect to various relevant research papers, the approach has been applied to the following major substantive domains: mobility and logistics, consumption and retail, energy and utilities, nature and environment as well as public and education. An overview of reviewed and classified papers is given in Table 4.

Table 4: Identified application domains of empirically grounded agent-based models

Domain	**Example**	**Source**
Mobility and logistics	[34] "introduce an empirically grounded, spatially explicit, agent-based model, InnoMind (Innovation diffusion driven by changing MINDs), to simulate the effects of policy interventions and social influence on consumers' transport mode preferences."	[35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [2], [34]
Consumption and retail	[45] aim "to gain insights on how social influences can affect the market inequalities in the motion picture market."	[46], [47], [48], [45], [49], [50], [51], [52]
Energy and utilities	[53] "propose an agent-based model to simulate how changes to the Italian support scheme will affect the diffusion of PV [photovoltaic] systems among single- or two-family homes."	[54], [37], [55], [56], [57], [58], [59], [53]
Nature and environment	[56] "develop an agent-based simulation model linked to Geographic Information System (GIS) data in order to investigate the spatial–temporal diffusion of agricultural biogas plants, given constraints on the local availability of feedstock resources."	[60], [61], [62], [63], [64], [65], [66], [67]
Public and education	[28] apply "a data-driven case study [. . .] of residential mobility [in a medium-sized town in Germany] to systematically explore the role of model detail on model performance."	[68], [69], [70], [71], [72], [28]

It is obvious that a large share of the surveyed research papers deal with environmental and energy-related innovations. Product innovations are analyzed ranging from hybrid or electric cars [34, 36, 38, 40] to biofuels [2] and photovoltaic panels [59]. Moreover, smart meter diffusions have also been analyzed [37]. One reason might be the high societal relevance of these innovations. Promoting consumer choices with respect to environmental technologies is crucial to meet the challenge of climate change and its associated impacts since the adoption of such environmental-friendly products generally only occurs slowly [36]. This also falls in line with the statement of [34] that environmentally-friendly technologies require influencing the demand side to diffuse on a larger scale. Another reason is the need for an individually-based modeling approach. They claim that "the key strength of agent-based-models is that they overcome the homogeneity assumption of traditional aggregate diffusion models." [7]. Environmental innovations oftentimes polarize and divide consumers between proponents and opponents. To overcome this homogeneity assumption, agent-based models seem to be appropriate in environmental and energy-related innovations. Because of this, basing *IRPact* on empirically grounded agent-based models seems to be the natural choice due to the focus of IRPsim on energy and environmental assessments.

4. Future research

In view of the key question *how energy utilities can and need to shape their business portfolio to manage and survive in a highly dynamic environment*, the system model vision *IRPsim* aims to provide managers with a multi-model decision support system for innovative business model assessments of differing system conditions of interest like business portfolio, legal framework as well as customer behavior and market environment. The model environment intends to match highly stylized modeling for theoretical inquiries as well as highly specific modeling for practical applications.

In this context, *IRPact* aims to investigate the level of adoption of business model innovations and detect success factors by including mental and social dynamics. The development of a case-based empirically grounded agent-based model allows for depicting the heterogeneous agents and social dynamics and to examine their interactions in various scenarios. While *IRPopt* is already in a mature state, the focus of the research needs to be on designing and developing *IRPact* in order achieve the outlined multi-model vision. For this, the following objectives need to be addressed:

- *Examine and determine the innovation environment and the agent structure:* Examine and structure the market, products, and actors and identify the main characteristics of the environment and the innovation chosen.
- *Analyze and characterize the behavior of agents:* Theoretical and empirical analysis of the mental and social dynamics in terms of the factors that drive adoption and diffusion of innovations by households and business enterprises.
- *Model and implement the recursive socio-economic simulation software as „experimental lab“:* Model and implement the multi-agent model based on interacting agents with mental decision structures, social dynamics and respective environmental influences.
- *Integrate the socio- and techno-economic energy system model approach:* Determine interfaces and combine the techno-economic model with the socio-economic model using a technical integration layer.
- *Identify innovative business models and derive implications for business units:* Simulate and evaluate market scenarios using an agent- and optimization-based modeling approach and derive suggestions.

5. Concluding remarks

Business portfolio decisions should be supported by energy system models considering the current business portfolio, the customer base, the regulatory framework as well as the market environment. The combination of sociological and technological dynamics within the energy system simulation *IRPsim* might provide some unique benefits for both theory and practice. In addition to the existing techno-economic modeling approach *IRPopt*, a socio-economic modeling approach called *IRPact* would not only consider the heterogeneity of behavioral patterns but also the communication and interaction structures of market participants [6]. An empirically grounded agent-based model makes it possible to simulate acceptance and diffusion of innovations by various customer types and municipal utilities considering different decision-making and network models, considering the temporal and regional differences in the diffusion process [21].

The presented combination of the multi-model approach enables the simulation of feedback effects that decisions of market actors have on the performance of a certain energy supply network [5]. Thus, the realization of the suggested research roadmap might further yield insights into how policy measures are applied regarding different techno-economic and socio-economic structures of municipalities. In this context, the development process of *IRPact* should be guided by a number of existing case-based models. Before and after coupling, the models ought to be applied to real-world scenarios at the municipal level in order to provide decision support.

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Appendix A

Model Design

The *optimization model IRPopt* has been completely developed from the ground up as outlined in this doctoral thesis. The actor-oriented multi-modal energy system model *IRPopt* is designed to support decision makers with integrated assessment of innovative business models. In this context, *IRPopt* is designed around an innovative *multi-layer framework* which allows a policy-oriented, technology-based and actor-related configuration of varying energy system conditions in general, and innovative business models in particular. Even though an initial representation of the model design has already been given in chapter 4 and chapter 5, the following paragraphs will provide additional information. This will contribute a better understanding of the model framework and aims to emphasize the range of modeling possibilities.

As outlined in chapter 1 and chapter 5, the development of *IRPopt* is mainly guided by the following model approaches: the graph theoretical concept of *deeco* [1] serves as a foundation to interconnecting processes. Furthermore, the high-resolution modeling in terms of the engineering processes is inspired by *deeco* and the *DER-CAM* [2]. A similar multi-carrier approach in terms of multi-vectors as initially presented by the *EnergyHub* framework [3] has been also adopted. Additionally, commercial association networks based on individual commercial actors as implemented by the *xeona* [4] have also been taken into account.

The fundamental *design approach* for the individual layers is presented as follows:

- *commercial actors* are described in section A.1 (first layer),
- *engineering components* are described in section A.2 (second layer),
- *component relations* are described in section A.3 (third layer),
- *system coordination* are described in section A.4 (fourth layer),

- *market principles* are described in section A.5 (fifth layer),
- *municipal contexts* is described in section A.6 (sixth layer).

Previously, a brief introduction into the *graph theory* is given since it underpins the fundamental concept of the mathematical modeling approach. A *directed graph* is a 2-tupel $G = (V, E)$ of a set of vertices V (or nodes in network terminology) and a set of edges E (or arcs in network terminology) between these vertices $E \subset V^2$. In a flow network, each arc is assigned a capacity c (formalized as a non-negative function $c : E \to \mathbb{R}_{\geq 0}$) and is associated with an energy flow, with the restriction that the flow f along arc e at time t cannot exceed capacity of the edges ($f_{t,e} \leq c_e \; \forall t \in T$, with $f : E \times T \to \mathbb{R}_{\geq 0}$). A *directed multi-graph* is an ordered pair $G = (V, E, A)$ with A being a multi-set of an ordered triple. In contrast to a directed graph, a directed multi-graph is permitted to have multiple edges between nodes [5, 6].

Next, in its basic form, a *flow network* distinguishes between two nodes, a source and a sink with the source having only outgoing flows and the sink having only incoming flows. In the network of interest, however, multiple components often dispatch or absorb a certain commodity in terms of various energy sectors. Thus, multiple nodes are to serve this role. Additionally, for different commodities, the same node can serve as a (net) sink for one commodity and a (net) source for the other commodity. For consistency with the theory of flow networks, a *supersource* [7] and a *supersink* [8] can be introduced. The energy flow graph is rather used to establish the structure of the graph and does not employ flow network theory, however, in this work we will refer to nodes that dispatch energy as sources and nodes that consume energy as sinks. This means that a single node can be a sink as well as a source according to the net flow of different time steps. In contrast to the theory of flow networks, the used flow networks are modeled as *lossy networks*, and as such they are not flow conserving. Furthermore, since conversion between sectors is possible, even in loss-free nodes, conservation of flow for a given commodity cannot be guaranteed, since one commodity might be converted into another. As such, the municipal energy system approach following merely borrows terminology from network theory.

A.1 Commercial actors

The energy model comprises municipal *market participants* that provide various services along the value chain. In this sense, not one single actor contains all relevant components for distribution, conversion, and the storing of energy. Instead, individual actors are spatially distributed over a municipal area and are equipped with respective components. Relevant actors are

- *utility business units* (section A.1.1),
- consumer or *prosumer groups* (section A.1.2),
- and *public institutions* (section A.1.3).

Each one represents a possible *contractual partner* regarding various commercial interactions. Available commercial options are commodity market sales, supply contract conclusions, technical contract agreements or third-party services.

This actor-oriented approach forms the basis for an integrated multi-perspective embedding and analysis. To formulate the mathematical model, the set of actors is denominated by S. Thereby, one specific actor $s \in S$ might represent a contract partner node of various tariff graphs as further described in the following.

A.1.1 Business units

The municipal energy utility organization ($S^{orga} \subset S$) is incorporated based on the classical business divisions as a trading unit, a network unit, a supply unit as well as a sales unit. In addition, an emerging business division called smart service unit is available. In line with the progressive liberalization, this breakdown of business divisions constitutes a core element since it enables unique or joint optimization possibilities from a business point of view.

A.1.2 Prosumer groups

The different consumer or prosumer groups ($S^{pros} \subset S$) as prospective clients in the classical sense are freely definable depending on the business model to be studied. The model allows the determination of the initial number of customers for each group. Besides this, the relative or absolute growth rates of the prosumer base over the years can be specified. This way a range of different customers, from building to the community level, be it private, commercial or industrial, can be flexibly defined.

A.1.3 Public institutions

The remaining actor groups are established through political or market institutions ($S^{inst} \subset S$). These allow the scenario-based integration of public policy interventions as well as external events. With this in mind, the effect of different assumptions regarding market development as well as legal framework conditions might be investigated.

A.2 Engineering components

In addition to the actor groups, an energy system consists of several interconnected *engineering components* (e.g. grids, markets, technologies and loads) with respect to various energy sectors or rather energy carriers (e.g. electricity, positive and negative reserve, heating, cooling, natural gas, lignite, hard coal, oil, hydrogen). From a functional perspective, these components realize certain processes within the energy system. *IRPopt* distinguishes between

- *demand processes* (section A.2.1),
- *conversion processes* (section A.2.2),
- *collector processes* (section A.2.3),
- *storage processes* (section A.2.4),
- *import-export processes* (section A.2.5),
- and *transmission processes* (section A.2.6).

This is done through components like energy grids, energy markets, generation facilities, storage systems, and load profiles.

To formulate the mathematical modeling, the set of processes is denoted by $n \in N$. The set of energy sectors is given by $u \in U$. Each component $n \in N$ is associated with a sector $u \in U$ via the sector association function $\mathfrak{u} : U \to Pot(N)$. Besides, the optimization component sovereignty function $\mathfrak{n} : S \to Pot(N)$ indicates which actor has the authority to operate the component n in the energy system model, meaning that the variables associated with it are free to dispatch variables in the optimization procedure. In this context, $Pot(N)$ describes the power set of any set N. The set of components associated with a defined sector u is denoted by $N^u = \mathfrak{u}(u) \subset N$, and the set of components assigned to a defined actor s is denoted by $N^s = \mathfrak{n}(s) \subset N$. In the context of this paper, nodes in the energy system graph corresponding to engineering components will be identified with these, and are also denoted by $n \in N$. The processes themselves are primarily characterized by input-output relationships which comprise the contained engineering processes plus any internal flow splitting and joining balances that may be needed. These relations yield information about the associations between commodity flows entering and exiting individual processes. These informations are used to resolve the unit commitment problem. Functional characteristics of the engineering components are outlined hereinafter. The mathematical equations of the processes are formulated in section B.3.

A.2.1 Demand processes

Demand processes ($N^{dem} \subset N$) are the last link in the chain of the processes of energy conversion, reaching from the generation of primary power to the allocation of energy services. As such, demand processes are situated at the very interface between providers and prosumers. Since demand processes only consumed energy and do not dispense any, their corresponding nodes in the energy flow graph are sinks. The demand of these nodes is determined through gathered load curves of electrical, heating, cooling and fuel energy. The restriction they impose is that their demand has to be satisfied exactly at every time step. However, generic load shifting is also possible. The mathematical equations of the demand processes are outlined in section B.3.1.

A.2.2 Conversion processes

In this modeling framework, conversion processes ($N^{conv} \subset N$) serve to create heating or cooling energy, electrical energy or mechanical energy from chemical energy or electrical energy. This comprises, amongst others combined heat and power plants ($N^{chp} \subset N^{conv}$), thermal power plants ($N^{tp} \subset N^{conv}$), heat pumps ($N^{hp} \subset N^{conv}$) and electrical ($N^{eb} \subset N^{conv}$) or fossil-fired boilers ($N^{fb} \subset N^{conv}$). Therefore, processes with single input and single output, single input and multiple outputs, multiple inputs and single output as well as multiple inputs and multiple outputs have been considered. Within the graph, components implementing these processes are nodes at the intersection of energy flow networks of different sectors. Since they generate one form of energy and consumer another, they simultaneously are sinks in the respective sector flow network of the energy carrier they consume as well as sources within the respective sector flow network of the energy carrier they produce. The mathematical equations of the conversion processes are outlined in section B.3.2.

A.2.3 Collector processes

In IRPopt, collector processes ($N^{coll} \subset N$) absorb energy from regenerative energy sources, convert these and transfer them to other processes as electrical energy and/or heating energy. This is done with the help of processes like photovoltaic systems ($N^{pv} \subset N^{coll}$), thermal solar panels ($N^{sp} \subset N^{coll}$), wind turbines ($N^{wt} \subset N^{coll}$), as well as biomass ($N^{bm} \subset N^{coll}$) and run of river plants ($N^{rp} \subset N^{coll}$). From a physical perspective, regenerative energy enters the storage process. The data required to calculate the energy output is given with the environment vector. Thus, collector processes demonstrate sources in the flow network since they provide energy without using non-renewable resources. The mathematical equations of the collector processes are outlined in section B.3.3.

A.2.4 Storage processes

Within this framework, storage processes ($N^{store} \subset N$) serve the storage of heat ($N^{hs} \subset N^{store}$), electrical ($N^{es} \subset N^{store}$), or fuel energy ($N^{fs} \subset N^{store}$). They comprise not just the actual storage expressed by the respective state of charge, but also the loading and unloading constraints as well as auxiliary facilities. Depending on their use, their role within the graph can change over time. For some time steps they might be sinks in the respective flow network; for other time steps they might be sources, and for other they might be neither or both. The mathematical equations of the storage processes are outlined in section B.3.4.

A.2.5 Import-export processes

Import-export processes ($N^{port} \subset N$) describe the connection of the energy system to be optimized to the superior system. From a modeling perspective, the processes bundle all information necessary for a full assessment of the energy exchange between both supply systems, e.g. distribution and transmission. Respective processes are represented by energy commodity markets. Examples are the spot market ($N^{em} \subset N^{port}$), the fuel market ($N^{fm} \subset N^{port}$) and the reserve energy market ($N^{rm} \subset N^{port}$). While the former market processes are not necessarily modeled with certain restrictions, the latter market processes intend to integrate initial ideas of the complex market design of the reserve markets including block bids. The mathematical equations of the import-export processes are outlined in section B.3.6.

A.2.6 Transmission processes

Transmission processes within IRPopt ($N^{trans} \subset N$) serve to connect energy flows of different quality and different sectors. Due to their flexible nature, transmission processes serve as interfaces between processes. Through this mechanism a multitude of processes can be connected, thus they allow the construction of energy supply systems with a high level of system integration, and therefore allowing a multitude of possibilities for system optimization. Examples of transmission processes are electrical ($N^{eg} \subset N^{trans}$), heating ($N^{hg} \subset N^{trans}$), cooling ($N^{cg} \subset N^{trans}$) and fuel grids ($N^{fg} \subset N^{trans}$). In the model, transmission processes are never sinks or sources. In the context of IRPopt the major characteristic of the electrical grid, for instance, is given by the efficiency of the network since no Alternating Current (AC) or Direct Current (DC) power flow models are incorporated in the initial implementation. The mathematical equations of the transmission processes are outlined in section B.3.5.

A.3 Component relations

The *structural composition* of the technical system demonstrates the interconnection of the spatially distributed processes within a complex societal framework. Viewed in engineering terms, in this model the real-world characteristics have been abstracted with the help of

- an *energy system graph* (section A.3.1),
- a *smart meter power connection measurement subsystem* (section A.3.2),
- and a *status component condition subsystem* (section A.3.3).

Each of the technical systems provides decisive criteria for the optimal dispatch decision based on various endogenously* determinable functions (energy flow $\mathfrak{e}$, power measurement $\mathfrak{p}$, relative status $\mathfrak{r}$ and absolute status $\mathfrak{a}$). Taken together, the model provides a coherent framework to assess the technical dynamics of various system compositions with different specifications. The integration of the three technical systems also enhances existing models.

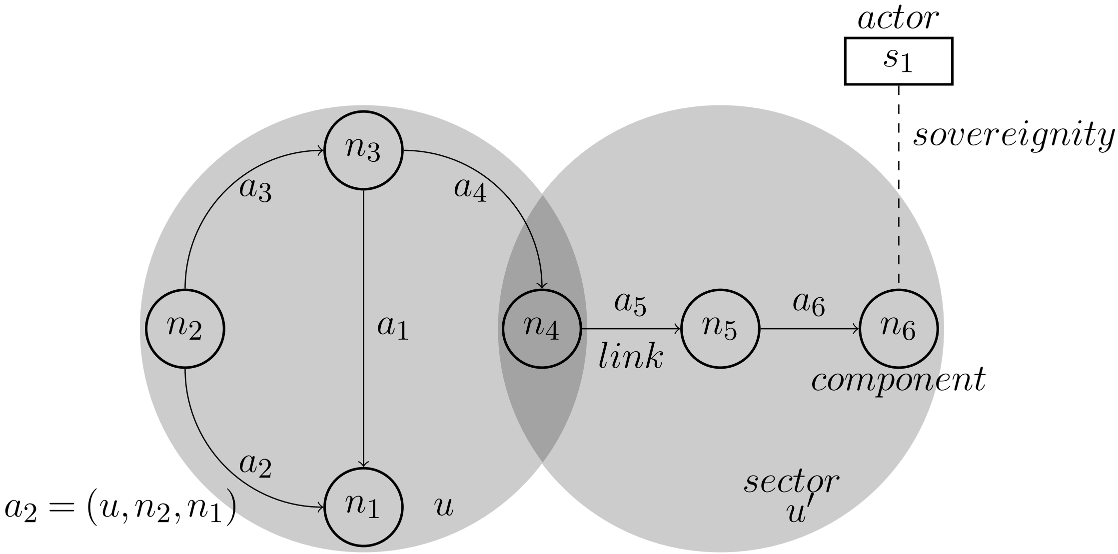
*An endogenous function describes the construct of endogenous variables or to be more precise the decision variables.

A.3.1 Energy system graph

The energy system graph constitutes the fundamental basis of the modeling approach and reflects the interconnection of the municipal system. From the modeling perspective, it resembles a *commodity flow graph* with nodes as engineering processes and arcs as flow gateways. In this context, the *energy system graph* $E = (N, A)$ needs to be seen as multiple source multiple sink flow network with the set of engineering processes N as nodes and the set of energy links A as arcs with $A \subset U \times N \times N$. Arcs as system links are represented by $a = (u, n, n')$ as ordered 3-tuple with source node $n \in N$, target node $n' \in N$, and sector index $u \in U$ denoting the type of the connecting energy carrier.

$E = (N, A); u, u' \in U$

$A = \{a_1, a_2, a_3, a_4, a_5, a_6\}; N = \{n_1, n_2, n_3, n_4, n_5, n_6\}$



$\overleftarrow{A}_{u,n_1} = \{a_1, a_2\}$

$\overrightarrow{A}_{u,n_1} = \{\}$

Figure A.1 Schematic representation of some important principles of the energy system graph $E = (N, A)$ in order to determine the energy flow function $\mathfrak{e}$

Every arc of the multi-commodity flow and store network is associated with exactly one commodity (e.g. energy carrier) flowing through it. The arcs between the same nodes can be distinguished by the sector $u \in U$ they are associated with. In this sense and by taking into account that flows are naturally directional, a directed arc $a \in A$ is defined as follows $a = (u, n, n'), a' = (u', n, n') \Rightarrow (u \neq u') \vee (a = a')$. A formal example graph is given in Figure A.1.

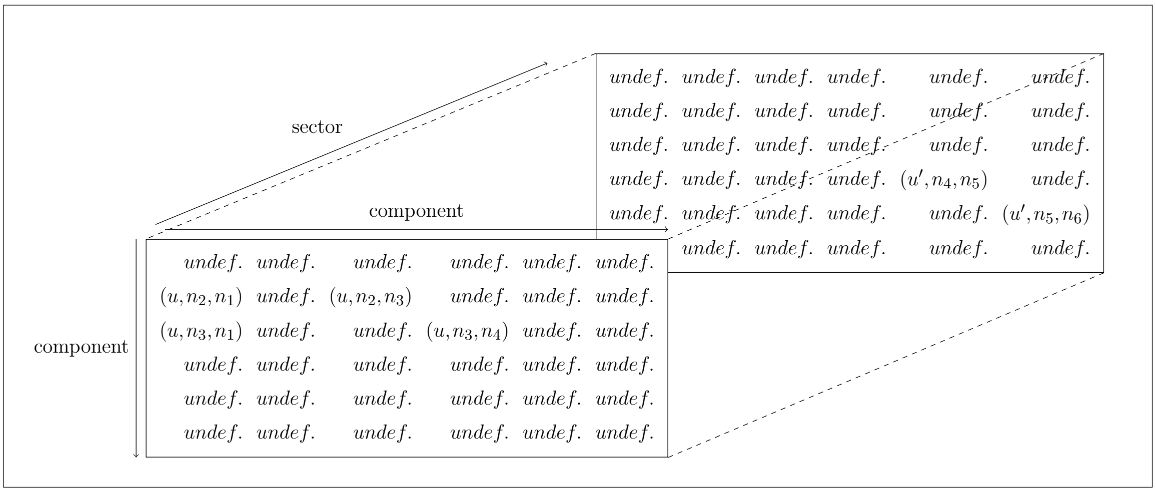


Figure A.2 Representation of the principles of the energy flow function $\mathfrak{e}$ for a given time step $t \in T$ with $u, u' \in U$ and $n_1, n_2, n_3, n_4, n_5, n_6 \in N(undef. = undefined)$

The energy flow in [MWh] through each arc $a \in A$ is described through the energy flow function $\mathfrak{e} : T \times A \to \mathbb{R}_{\geq 0}$ representing the flow of energy through arc $a \in A$ at time $t \in T$. Considerung the possession of the individual processes $n \in N$, the specific actor $s \in S$ may only operate the energy flow along arcs adjacent to a node n they have optimization sovereignty over ($n \in N^s$ with $N^s = \mathfrak{n}(s) \subset N$). The set of energy links an actor can operate during the optimization run is denoted by $A^s = \{a = (u, n, n') \in A : n \in N^s \vee n' \in N^s\}$. This optimal operation policy for a number of system links is determined on the basis of the conveyed data of the gateway of the arcs according to a certain objective. Thereby, each gateway is associated with one or more legal contracts, covering for instance connection and supply or market participation (see section A.4.1). Thereby, the technologies are treated equally and no individual option accorded a preferential dispatch status, once the system management objective has been set.

In order to express energy flows between processes in the configured energy system network based on the direction of the energy flow, the sets $\overrightarrow{A}^{u,n}$ and $\overleftarrow{A}^{u,n}$ are introduced, with $\overrightarrow{A}^{u,n}$ being the set of arcs in the energy system graph E with component $n \in N$ being the source (emitter of the energy flow) in the respective sector $u \in U$ with $\overrightarrow{A}^{u,n} = \{a = (u, n, n') \in A : n' \in N, n \neq n'\}$ and $\overleftarrow{A}^{u,n}$ being the set of arcs in the energy system graph E with component $n \in N$ being the target (receiver of the energy flow) of the respective sector $u \in U$ with $\overleftarrow{A}^{u,n} = \{a = (u, n', n) \in A : n' \in N, n \neq n'\}$.

A process $n \in N$ might receive energy in a certain sector $u \in U$ from a different process $n' \in N$ with a directed link inbetween. For a given node $n \in N$ and with respect to the energy flow of sector $u \in U$, the receiving flows or the incoming balance at a certain time step $t \in T$ can be described with the following sum of energy flows $\sum_{a \in \overleftarrow{A}^{u,n}} \mathfrak{e}_{t,u,n',n} = \sum_{a \in \overleftarrow{A}^{u,n}} \mathfrak{e}_{t,a}$. Analogous the emitting energy or the outgoing balance of n can be summarized with $\sum_{a \in \overrightarrow{A}^{u,n}} \mathfrak{e}_{t,u,n,n'} = \sum_{a \in \overrightarrow{A}^{u,n}} \mathfrak{e}_{t,a}$.

A.3.2 Power connection measurement bundles

It is expected that also residential clients might be equipped with smart meter technologies in the future. In the context of *load metering*, innovative future business might also give more weight to a capacity charge instead of energy rate.

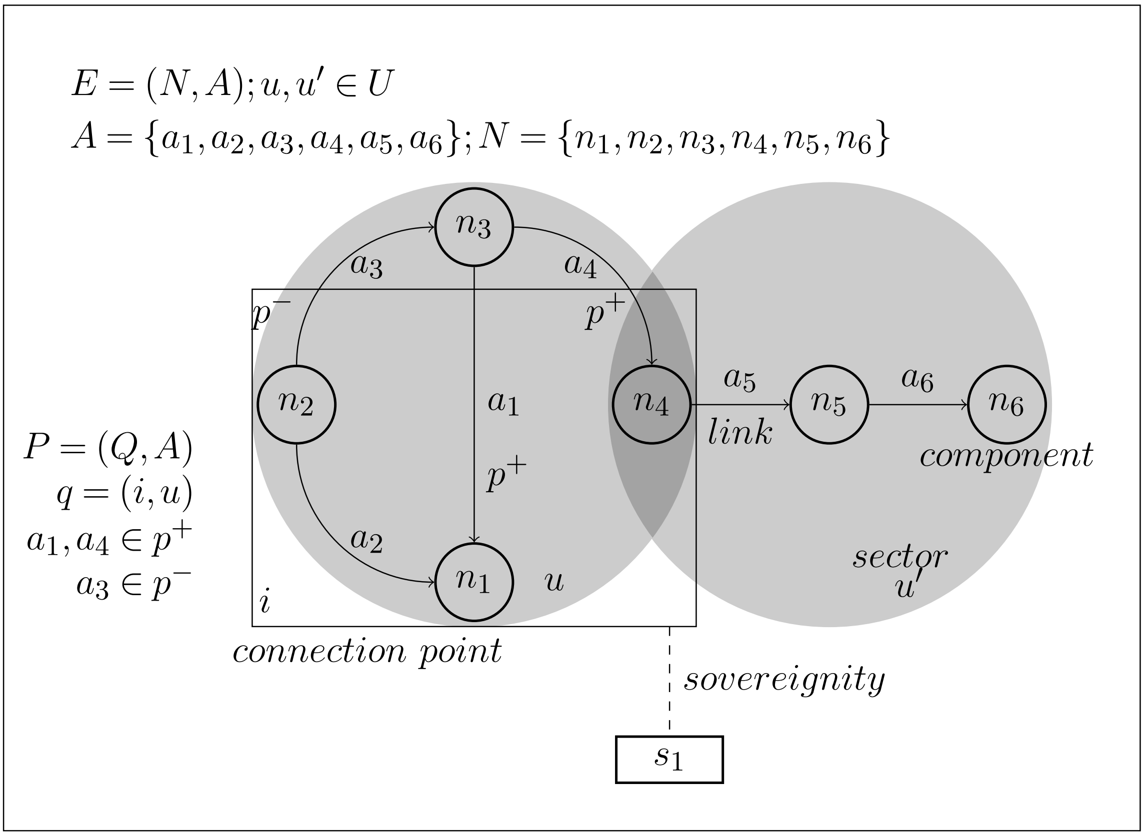


Figure A.3 Schematic representation of some important principles of the power measurement subsystem $P = (Q, A)$ in order to measure the power $\mathfrak{p}$

The *power connection measurement subsystem* $P = (Q, A)$ models the capacity measurement of a set of power connections Q and the set of system links A. A connection $q \in Q$ is formalized as 2-tuple $q = (i, u)$ with $i \in I$ as definable connection points and $u \in U$ as sector affiliation. Similar to the engineering components and the system links, the power connections are assigned to an actor in order to define operation sovereignty with the help of the following function $\mathfrak{q}: S \rightarrow Pot(Q)$. According to this, Q^s is denoted by $Q^s = \mathfrak{q}(s) \subset Q$.

The introduced subsystem is directly build up on the energy system graph. A specific power connection q is freely bundled with relevant arcs $a, a' \in A$ to a specific power sub-system $p \in P$ (with the restriction that all arcs within a bundle belong to the same actor, i.e. $\exists s \in S : a \in A^s \; \forall a \in p$) and a positive or negative influencing parameter for each arc since a certain actor exhibit different connections with various private or foreign engineering components. Arcs which increase the capacity of the power connection are summarized under the set p^+ and arcs which decrease the capacity of the power connection are summarized under the set p^-. In terms of the optimal operation of energy flows, the power flow function $\mathfrak{p}: Q \times M \rightarrow \mathbb{R}_{\geq 0}$ determines the capacity at each defined connection for every monthly time step $m \in M$ on the basis of the following condition $\left(\sum\limits_{a \in p^+} \mathfrak{e}_{t,a} - \sum\limits_{a \in p^-} \mathfrak{e}_{t,a} \right) \leq \mathfrak{p}_{m,q} \cdot \Delta t, \forall t \in T^M$. If there is an energy flow along a specific arc (arcs demonstrate the outgoing and ingoing energy flows of certain engineering components) and this arc is assigned to a specific power connection the power flow function measures the maximum capacity over the length of T^m. T^m is derived from T and groups the respective time steps t of each individual month. Associated contracting specifications are similar to the energy flow network (see section A.4.2). A formal example of the subsystem is given in Figure A.3.

A.3.3 Component condition status system

The *component condition status subsystem* represents single physical properties of individual processes ($n \in N$). Next to the energy flows and the power measurements, the optimal operation of the system depends also on the *operating mode* of single processes. In this sense, e.g. the dynamics of start-up modeling as well as of types of wear modeling of different processes might be integrated.

To model such cases, two simple status condition functions are implemented. Previously, to ensure a sector specific $u \in U$ operation strategy of the individual processes ($n \in N$), a 2-tuple of $k = (u, n)$ is introduced with $k \in K$. Depending on the particular usage context, the function can be given by an absolute condition function $\mathfrak{a}: T \times K \rightarrow \{0, 1\}$ or by a relative condition function $\mathfrak{r}: T \times K \rightarrow [0, 1]$. As outlined, the absolute and relative status can be determined for each sector specific component

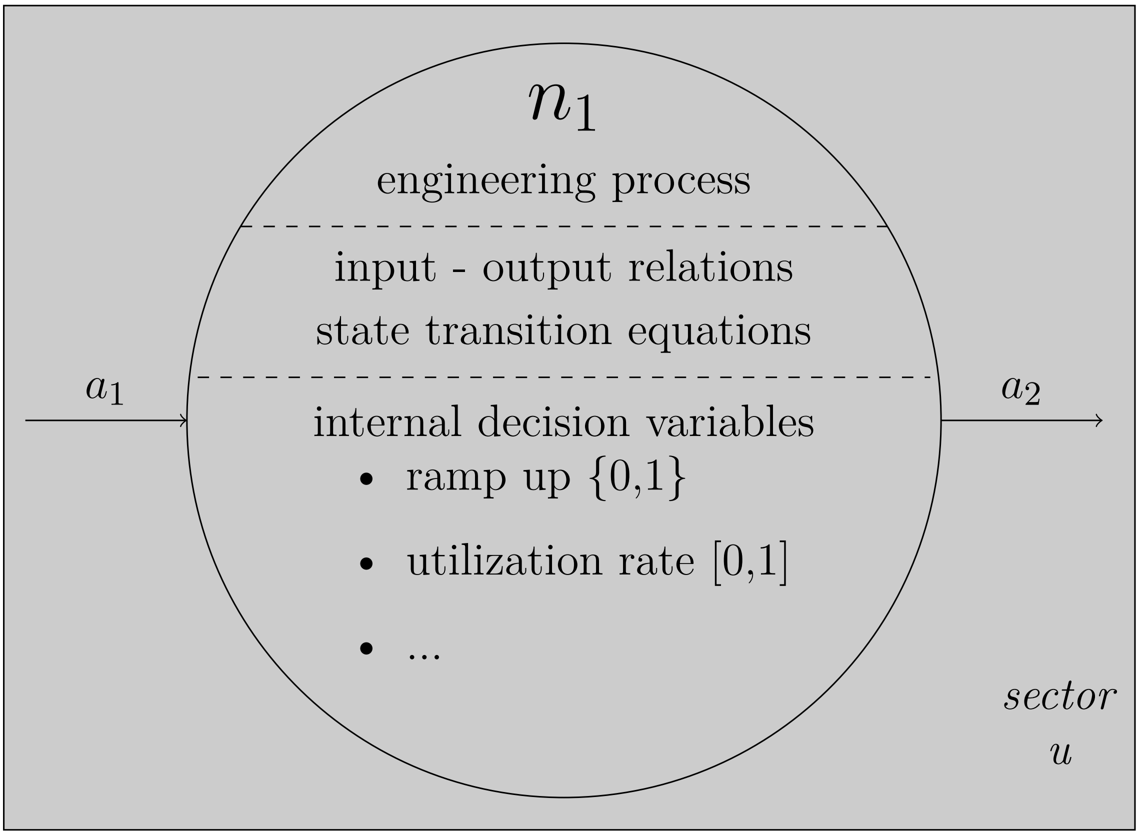


Figure A.4 Schematic representation of important principles of the component condition status system N in order to determine the absolute status $\mathfrak{a}$ or relative status $\mathfrak{r}$

$k \in K$ and time step $t \in T$ separately. The illustrative representation of the major principles is depicted in Figure A.4.

The first case allows, among others, the reheating process costs of a power plant, where the ramp-up depends on the off-time before a start-up. The second case, for example, is relevant at every start-up or shut-down of a power plant and thus signals required additional labor costs which always occur to the same extent (see section A.4.3). In this context, processes are no longer only a black-box since single physical characteristics can be taken into account in the objective function with the help of the constructs of $\mathfrak{r}$ (relative status function) and $\mathfrak{a}$ (absolute status function).

A.4 System coordination

The optimal operation of the system is conducted on the basis of the data obtained by various *technical network gateways*. Thereby, each gateway is associated with one or more legal contracts, covering for instance connection and supply or market participation. The system coordination facilitates the *commercial interactions* between market actors and thus represents the economic module of *IRPopt*. Thus, legal contracts at different gateways determine *contractual relationships* between various actors which are fundamental to operational decisions. The reason for this is that the contracts define the exchange of monetary units between actors. The perceived value of the decision depends on the objective function.

The implementation is also carried out with the assistance of several networks. Each technical graph (see section A.3.1) or subsystem (see sections A.3.2 and A.3.3) (and thus each endogenous function) is interrelated with economic graphs (and therefore various exogenous functions) as outlined in the following:

- the energy flow $\mathfrak{e}$ is mapped with the *energy system tariff network* $\mathfrak{w}$ (section A.4.1),
- the power measurement $\mathfrak{p}$ is mapped with the *power connection tariff network* $\mathfrak{x}$ (section A.4.2), ,
- the relative status $\mathfrak{r}$ and absolute status $\mathfrak{a}$ is mapped with the *status condition tariff networks* $\mathfrak{y}$ and $\mathfrak{z}$ (section A.4.3).

Taking all these together the system is able to show multi-layered interaction as observed in reality.

A.4.1 Energy flow tariff network

As actors optimize energy flows from an economic perspective, energy flows in E need to be related to financial flows between actors (see section A.3.1). This is done by associating each energy flow (through arc $a \in A$ in the energy system graph at time $t \in T$) with a set of energy tariffs.

Contractual tariff relationships between actors for these energy flows are depicted through energy tariff graphs. Since a multitude of contractual relationships can exist for a given energy flow (e.g. the consumer pays the sales department for the consumed energy, which in turn pays the network and the trading unit for the energy provision and energy supply) and these can differ in their dependence of the flow of energy and the point in time (e.g. fixed energy tariffs over time or flexible energy tariffs over time depending on the amount of energy dispatched), energy tariffs are formalized through a set of energy tariff graphs $G^E = \bigcup_{a \in A} \bigcup_{t \in T} G^E_{t,a}$. An illustrative representation is given in Figure A.5.

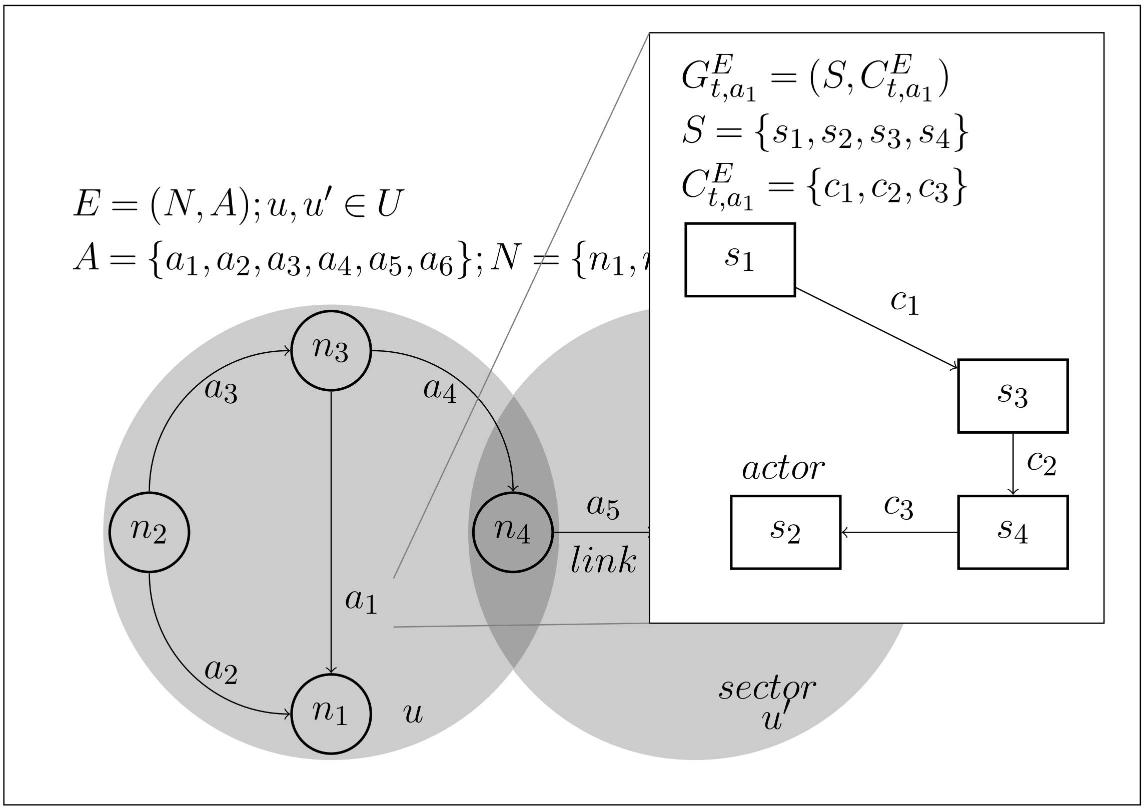


Figure A.5 Schematic representation of some important principles of the energy flow tariff network $G^E_{t,a} = (S, C^E_{t,a})$. For a determined energy flow $\mathfrak{e}$ along arc a_1 the energy tariff function $\mathfrak{w}$ defines the financial flows between the actors. According to the contractual agreement, s_1 needs to pay to s_3 while s_3 needs to pay to s_4, and s_4 needs to pay to s_2

Each *energy tariff graph* $G^E_{t,a}$ is a directed graph $G^E_{t,a} = (S, C^E_{t,a})$ describing the contractual relationships between actors $s \in S$ for the given energy flow along arc $a \in A$ in the energy system graph E at time $t \in T$ with $C^E_{t,a} \subset S \times S$. Each energy tariff graph arc $c \in C^E_{t,a}$ is associated with a corresponding tariff in [€/MWh] via the energy tariff function $\mathfrak{w} : T \times A \times S \times S \to \mathbb{R}_{\geq 0}$. The function specifies the contractual relationship between actors $s \in S$ for the flow of energy from component $n \in N$ to component $n' \in N$ at a time $t \in T$ for a given sector $u \in U$.

The presented modular and flexible graph-theoretical framework enables the modeling of various kinds of contractual relationships between different actors. The division of the technical and economic systems on different layers allows a good quality mapping of the reality and the integration of changes with respect to legal and contractual requirements. This also delimits *IRPopt* from existing system models. *IRPopt* dissolves the domain and equips various tariffs for sub-domains and thus for the inner system structure. By taking into account the single actory, the socio-economic environment of the real world can be modeled in more detail. Commercial actors can also be incorporated even though they are not directly tangent in terms of a specific energy flow between two processes. In this context, various kinds of contractual agreements are depictable. Finally, on this basis, *IRPopt* might focus more on commercial aspects than the reviewed models which are more economically-oriented.

A.4.2 Power measurement tariff network

The *power connection subsystem* P describe the capacity measurement of definable power bundles $q, q' \in Q$. A power bundle $q \in Q \subset Pot(N)$ aggregates a subgraph of grouped processes and their directed edges. Aim is to measure the net capacity inflow into these component groups (see section A.3.2). Analogous to the energy subsystem, financial flows in the power subsystem are modeled through *capacity tariff graphs*. A power tariff graph $G^P_{m,q}$ ($G^P = \bigcup_{q \in Q} \bigcup_{m \in M} G^P_{m,q}$) describes the effective tariffs between actors for a power bundle $q \in Q$ net capacity measurement at month of interest $m \in M$.

The power tariff graph $G^P_{m,q} = (S, C^P_{m,q})$ is parametrized through the tariffs in [€/MW] between the set of actors S for each capacity measurement in $q \in Q$ at time $m \in M$. The (partial) power tariff function is given by $\mathfrak{x} : Q \times M \times S \times S \to \mathbb{R}_{\geq 0}$. The principles are illustrated in Figure A.6.

Since the power measurement is also mapped with a corresponding tariff network, the user can attach more weight to one of the concepts or, to the same extent, integrate both concepts.

A.4.3 Component condition status tariff network

Next to the tariffing of the energy flows and the capacity measurements, the engineering processes also demonstrate costs regarding the ramp-up and wear and tear. These costs are determined on the basis of the status condition system (see section A.3.3). Even though, the status conditions are attached to the single engineering processes, the *absolute and relative status tariff graph* share the same characteristics as in the other two cases.

The absolute and relative status cost graph, formalized by $G^A_{t,k} = (S, C^A_{t,k})$ or rather $G^R_{t,k} = (S, C^R_{t,k})$, describe the financial flows between actors regarding the status costs of a given engineering component assigned to a certain sector $u \in U$ at time $t \in T$. The union of absolute status cost graphs (also the same for the union of the relative status

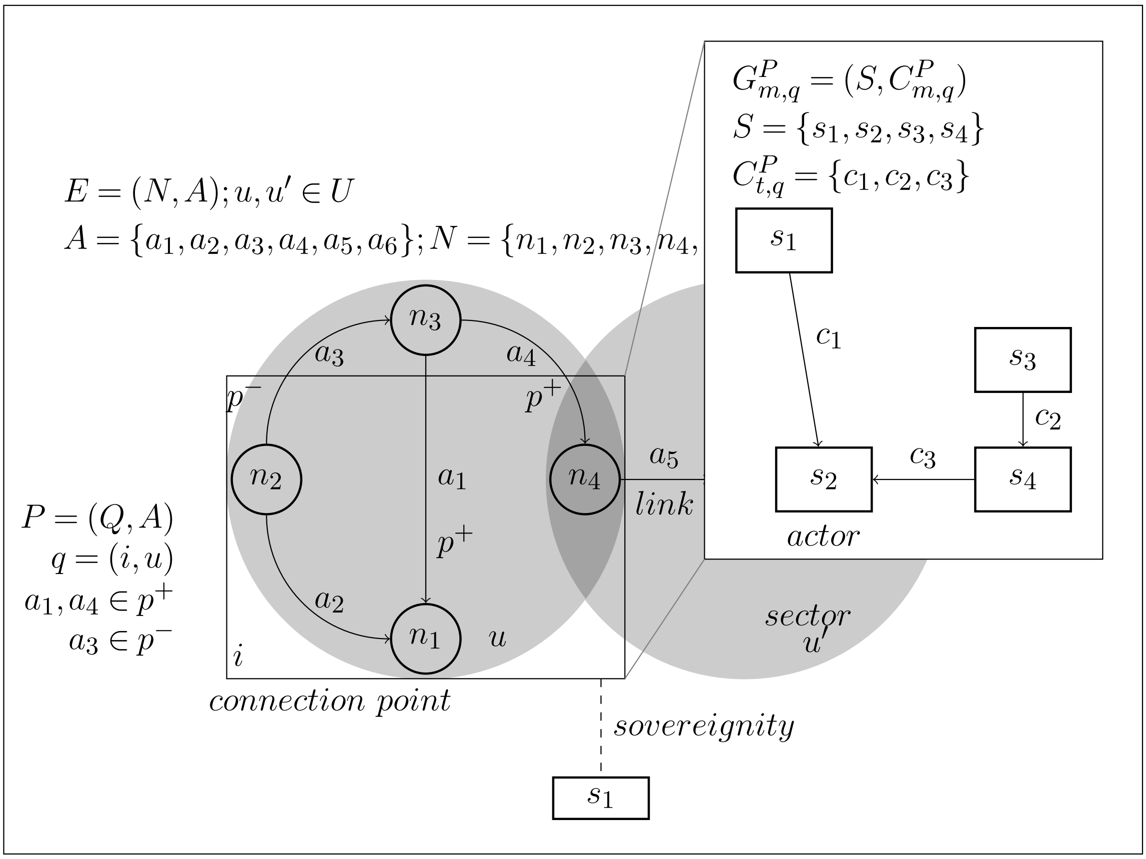


Figure A.6 Schematic representation of some important principles of the power measurement tariff network $G^P_{m,q} = (S, C^P_{m,q})$. For a determined power measurement $\mathfrak{p}$ regarding connection point i the power measurement tariff function $\mathfrak{x}$ defines the financial flows between the actors. According to the contractual agreement, s_1 needs to pay to s_2, s_3 needs to pay to s_4, and s_4 needs to pay to s_2

cost graphs) is denoted by $G^A = \bigcup_{t \in T} \bigcup_{k \in K} G^A_{t,k}$. For each actor $s \in S$, an arc $c \in C^A_{t,k}$ can be defined representing the share of the cost in [€] s has to pay to s' for the part of the cost of sector component k at time t. An arc $c \in C^A_{t,k}$ is associated with the absolute status tariff function $\mathfrak{y} : T \times K \times S \times S \to \mathbb{R}_{\geq 0}$. The same applies for the relative status tariff function $\mathfrak{z}$. The principles is are illustrated in Figure A.7.

While for example, the status condition system is able to identify a full charging cycle based on the absolute condition function, the tariff network maps respective costs accordingly. Taking the presented technical and economic systems together, the modeler can integrate costs and revenues related to energy, capacity as well as physical aspects in varying degrees.

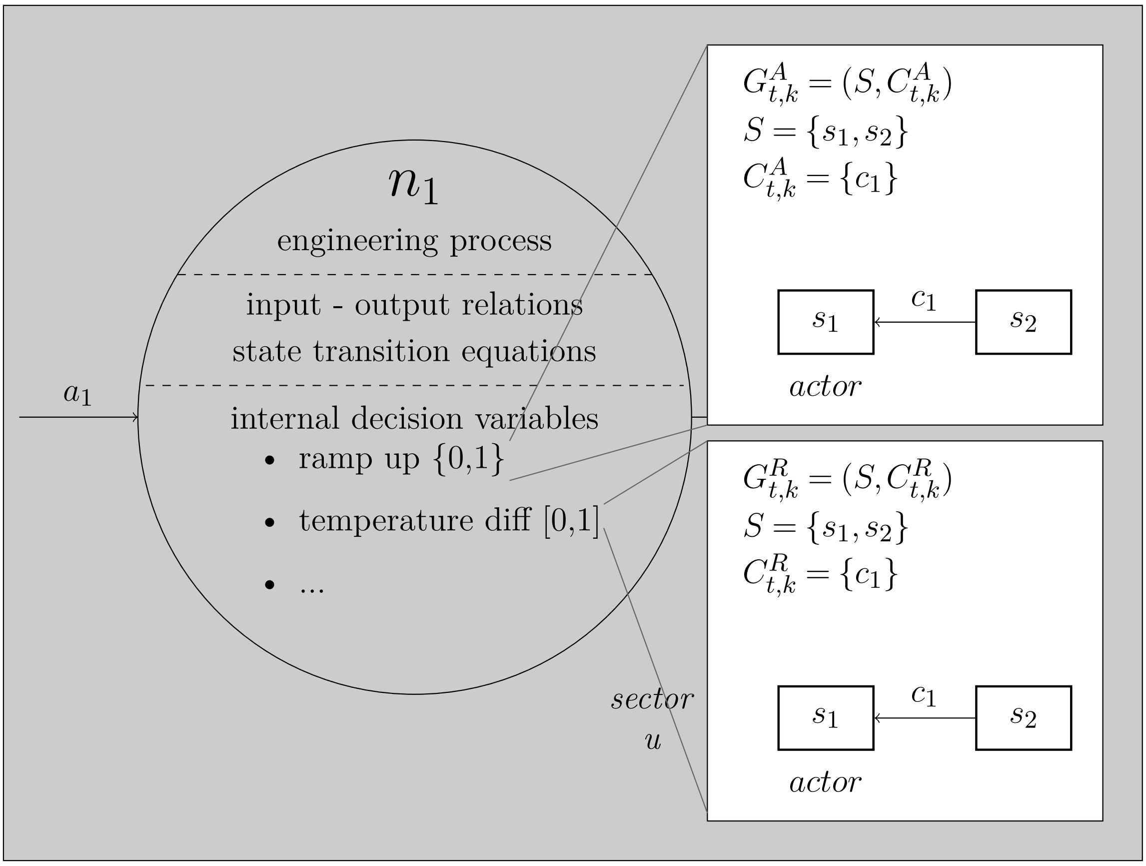


Figure A.7 Schematic representation of some important principles of the absolute and relative condition status tariff network $G^A_{t,k} = (S, C^A_{t,k})$ and $G^R_{t,k} = (S, C^R_{t,k})$. For a determined absolute or relative condition change $\mathfrak{n}$ and $\mathfrak{z}$ of node n_1 the absolute and relative status tariff function $\mathfrak{y}$ and $\mathfrak{z}$ define the financial flows between the actors. In both cases, s_2 pays to s_1

A.5 Market principles

The development of innovative business models for emerging system configurations and for the integration of renewable technologies require the implementation of *advanced market aspects*. Only by comprehensively modeling the complexity of the system's interactions and of the market processes, synergies and challenges can be determined. Nowadays, major concepts applied are

- *decentralization* (section A.5.1),
- *flexibilization* (section A.5.2),
- and *virtualization* (section A.5.3).

The modeling of *IRPopt* offers various building blocks for a more precise analysis of these smart market constructs.

A.5.1 Decentrality mechanism

Academia and practitioners agree on the disruptive quality of decentralized solutions for future energy systems. For a successful integration, explicit solutions are required with respect to community-specific cross-sectoral demand and supply structures. With an appropriate business model, municipal utilities might be capable to transform themselves successfully. For better decision-making, they need to investigate under what conditions certain business models might represent a sustainable part of future systems and their potential portfolio. Next to the presented technical and economic variability, among other aspects, *IRPopt* provides modeling blocks like energy contracting, direct consumption, direct energy marketing, and power bundling.

A.5.2 Flexibility mechanism

In line with a decentralized energy system, the construct of flexibility is related to the freely definable and easily combinable design of *IRPopt* in terms of modeling existing and emerging real-world excerpts from building level to municipal level. This includes not only the location and connection of small- and large-scale processes but also the monitoring and control by prosumer groups, organizational units and public institutions. This allows, the flexibility assessment of power to heat or gas application as well as of storage and electric vehicle solutions. As stated before, business model design can be assessed by considering changing boundary conditions as time-dependent energy and capacity customer tariffs and market prices. Additionally, the processes itself can be enhanced with the help of different building blocks. On the one hand a building block regarding demand response is available. Loads can be shifted according to a certain volume and time. On the other hand, plant operation might include maintenance periods and station outages. Thus, the robustness of future business models is also assessable in terms of unexpected events.

A.5.3 Virtuality mechanism

The idea of virtuality is of particular relevance for the aggregation of distributed energy resources that are optimally coordinated. A cluster or pool of emerging small-scale processes is capable to offer the same services in the same way as conventional large-scale processes. This is feasible for all processes of all different sectors and might also lead to multi-energy systems. In addition to the co- or tri-generation in a renewable energy dominated future, the construct of pooling becomes more important in the provision of balancing services. In this context, advanced market processes as block bids in the reserve auction are also available. Regulatory developments can be taken into account with the freely selectable period of a block length.

A.6 Municipal contexts

Last but not least, each strategy assessment is associated with *context-dependent specifications* of spatial, environmental and temporal scenarios which can influence the performance of processes or the formulation of cost. In this research paper, these prevailing physical, commercial, legal, institutional and regional conditions are comprised with *municipal contexts*. Thereby, the layer might serve for specifications of public policy interventions (such as supposed schemes for renewable energies), optimization scenario assumptions, time-frame specifications as well as environmental circumstances.

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Appendix B

Optimization Approach

Based on the *model design* presented in Appendix A and chapter 5, different integrated optimization problems can be formulated and solved. At its core, *IRPopt* is a bottom-up techno-economic numerical optimization model, implemented in GAMS/CPLEX, for solving mixed-integer problems (MIP) in different time resolutions for perennial periods. The optimization approach mainly embraces

- the *objective function* in section B.1,
- the *optimization procedure* in section B.2,
- the *process restrictions* in section B.3,
- the *evaluation approach* in section B.4,
- and the *model architecture* in section B.5.

In this context, the following paragraphs provide additional information to chapter 5 and the presented optimization approach. The additional extract aims to contribute to a better understanding of the optimization framework and to emphasize the range of modeling possibilities.

B.1 Objective function

The mathematical *objective function* of *IRPopt* $\mathfrak{f}$ is based on the determination of the optimal operation policy of the designed technical systems (unit commitment problem) taking into account the financial flows of chosen market actors, time points and energy sectors.

The major objective of *IRPopt* is to maximize revenues over the whole optimization horizon (*max* $\mathfrak{f}$) as expressed in equation (B.1). This corresponds to the sum of the optimized revenues of the energy model $\mathfrak{f}^{energy}$ in equation (B.2), the power model $\mathfrak{f}^{power}$ in equation (B.3), and the status model $\mathfrak{f}^{status}$ in equation (B.4). In this context the developed objective function enhances existing system models in two ways. First, the system model includes costs and revenues not only at the system boundaries (e.g. costs for primary energy consumption and feed-in proceeds) but also within the system (e.g. capacity charges and wear costs). Second, the objective function includes different actor perspectives and thus allows a broader focus on the commercial aspects of individuals and not only the economic aspects of the area.

$$\begin{aligned} \text{maximize} \quad & \mathfrak{f} = \mathfrak{f}^{\text{energy}} + \mathfrak{f}^{\text{power}} + \mathfrak{f}^{\text{status}} \\ \text{subject to} \quad & \mathfrak{g} = 0 \\ & \mathfrak{h} \geq 0 \end{aligned} \tag{B.1}$$

$$\mathfrak{f}^{\text{energy}} = \sum_{t \in T'} \sum_{s \in S'} \sum_{a \in A^s} \left(\sum_{s' \in S} \mathfrak{e}_{t,a} \cdot \mathfrak{w}_{t,a,s',s} - \sum_{s' \in S} \mathfrak{e}_{t,a} \cdot \mathfrak{w}_{t,a,s,s'} \right) \tag{B.2}$$

$$\mathfrak{f}^{\text{power}} = \sum_{m \in M'} \sum_{s \in S'} \sum_{q \in Q^s} \left(\sum_{s' \in S} \mathfrak{p}_{m,q} \cdot \mathfrak{x}_{m,q,s',s} - \sum_{s' \in S} \mathfrak{p}_{m,q} \cdot \mathfrak{x}_{m,q,s,s'} \right) \tag{B.3}$$

$$\mathfrak{f}^{\text{status}} = \sum_{t \in T'} \sum_{s \in S'} \sum_{k \in K^s} \left(- \sum_{s' \in S} \mathfrak{a}_{t,k} \cdot \mathfrak{y}_{t,k,s,s'} - \sum_{s' \in S} \mathfrak{r}_{t,k} \cdot \mathfrak{z}_{t,k,s,s'} \right) \tag{B.4}$$

For completion, $\mathfrak{f}$ is restricted by different equality constraints $\mathfrak{g} \in \{\mathbb{R}_{\geq 0}, \mathbb{Z}_{\geq 0}\}$ and inequality constraints $\mathfrak{h} \in \{\mathbb{R}_{\geq 0}, \mathbb{Z}_{\geq 0}\}$. These are given by technical processes derived from the nature of engineering components as introduced in section A.2. Associated MIP process formulations of the constraints are outlined in section B.3. Thereby, the existing system can be simply expanded by adding additional process restrictions without adapting the elementary mathematical foundation.

Doing this, a set of time points of interest $T^{'} \subset T$ and its derived set $M^{'} \subset M$ as well as a set of actors of interest $S^{'} \subset S$ need to be specified in order to define the optimization period as well as optimization perspective. According to the design decision taken, associated energy links ($\bigcup_{s \in S'} A^s \subset A$ of the actor $s \in S^{'}$), power connections ($\bigcup_{s \in S'} Q^s \subset Q$ of the actor $s \in S^{'}$) and engineering processes ($\bigcup_{k \in K'} K^s \subset K$ of the actor $s \in S^{'}$) are determined. The optimal operation strategy, thus, is determined by maximizing the profits from the chosen actor perspective by taking into account the incoming and outgoing financial flows. For the energy profit model (B.2), the energy flows $\mathfrak{e}$ associated with the actor(s) of interest are dispatched on the basis of the energy tariffs $\mathfrak{w}$ associated with. The profit is determined by multiplying the energy flows through certain arcs with the respective tariff. For the power profit model (B.3), financial flows are determined through the product of the measured capacity $\mathfrak{p}$ within a power connection associated with an actor of interest and any relevant financial demands as specified in the respective power tariff graph $\mathfrak{x}$. Additional cost modeling in terms of absolute $\mathfrak{a}$ and relative status $\mathfrak{r}$ changes of engineering processes, contribute through the status cost model $\mathfrak{n}$ and $\mathfrak{z}$ (B.4).

B.2 Optimization procedure

In line with the management objectives, the optimization model aims to be an actor-based multi-carrier and multi-period economic optimization model in order to reflect engineering component utilization schedule at various market conditions. By default, *IRPopt* initially optimizes from an aggregated prosumer' perspective ($S^{'} = S^{pros}$), determining the residual energy demand and excess energy supply with all processes the customers have regulative access to. With respect to the first optimization step (prosumer optimization), the tariff scheme as well as the variable costs of decentralized energy systems are of primary importance. Subsequently, the model optimizes all other energy and financial flows from the utilities' perspective ($S^{'} = S^{orga}$). A municipal energy deficit might be balanced by storage systems, generation plant activities and spot market trading. Excess energy is sold or stored. Additionally, operating reserve can be pooled and offered at the operating reserve market. With respect to the second optimization step (utility optimization), the market prices as well as the variable costs of the energy systems are most decisive.

Considering the exemplary configuration of Figure B.1, the described entity-oriented, two-step optimization procedure is conceivable. Initially, the perspective or rather set of actors of interest might be defined with $S' = \{s_1\}$. This allows to determine all processes and links the defined set of actor has regulative access to on the basis of the functions N^{s_1} and A^{s_1} as well as to calculate the optimal energy and financially

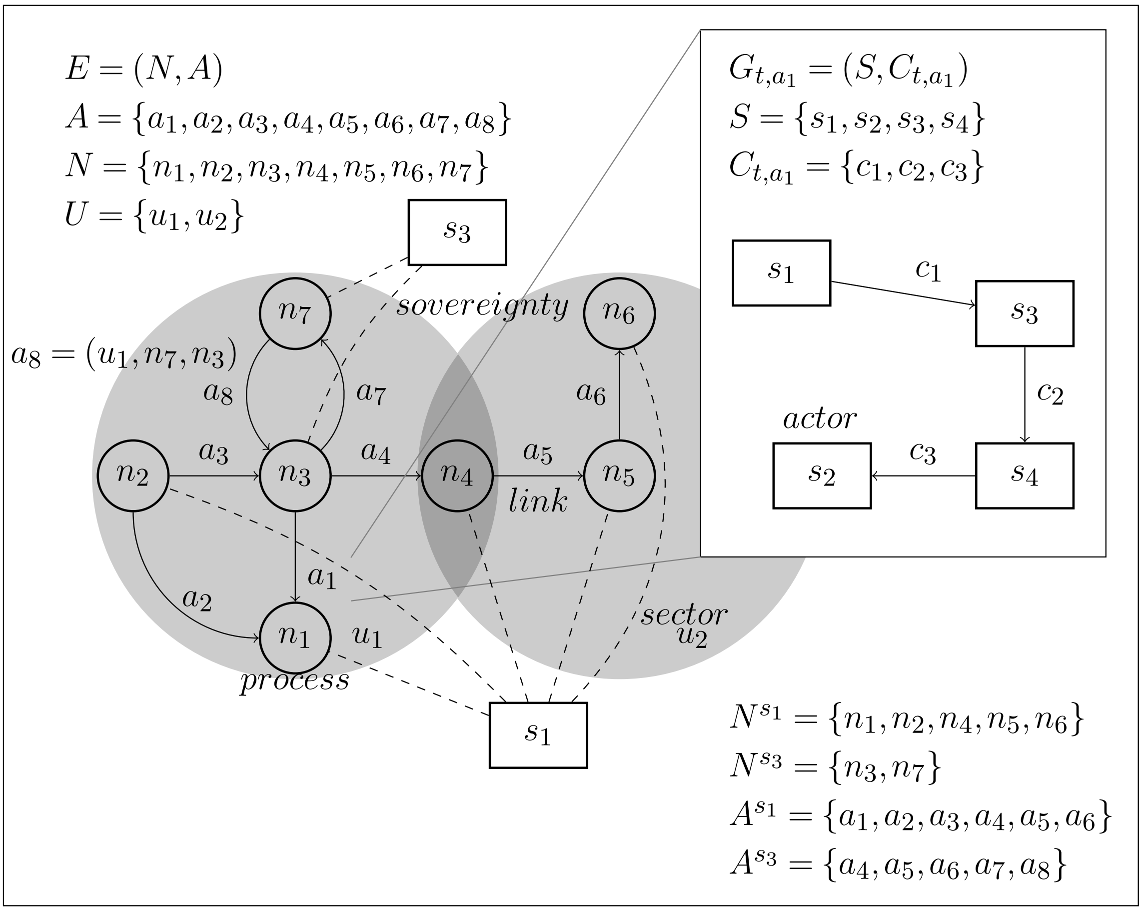

Figure B.1 Schematic representation of an exemplary configuration of the energy process graph $E = (N, A)$ and a commercial entity coordination graph $G_{t,a} = (S, C_{t,a})$.

related dispatch. Subsequently, the energy and financial flows of the exemplary model configuration might be optimized from the second perspective with $S' = \{s_3\}$. Thereby, the residual energy demand and supply of the previous dispatch is considered.

Due to the complexity, the entire optimization year $T = \{1, ..., 35040\} \subset \mathbb{N}$ for Δt of quarter-hourly time steps $t \in T$, and $M = \{1, ..., 12\} \subset \mathbb{N}$ for monthly time steps $m \in M$ is not optimized in one piece, but rather in a recursive dynamical way. In course of this, various time-local problems of the whole scheduling horizon are optimized. The length of the optimization horizon is basically freely selectable like the time steps Δt. To reduce computational complexity, in each optimization step, the optimal operation strategy is determined over an horizon comprising 48 hours while only the results of 24 hours are saved. This marks the control horizon (CH). Subsequently, the new optimization step over 48 hours starts with the final values of the saved results which simultaneously represent the initial values (IV) of the new OH. On this basis, inter-

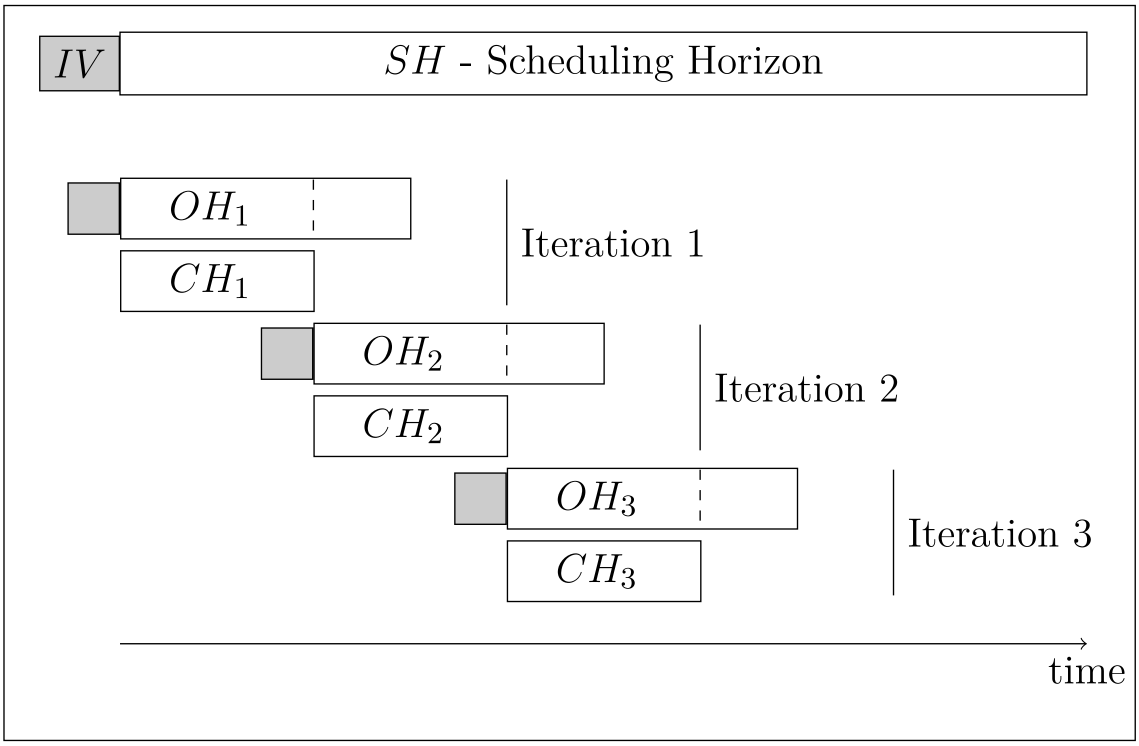

Figure B.2 Schematic representation of the applied rolling optimization approach (IV - initial values, SH - scheduling horizon, OH - optimization horizon, CH - control horizon)

temporal optimization concern issues such as use-of-storage, use-of-entitlements, and conversion plant ramp-rates are considered. For the first OH, the IV need to be stated additionally to the SH. A schematic overview of the rolling optimization approach is illustrated in Figure B.2.

Additionally, considering not only a single year but multiple years $T \in T^{opt}$ results in multi-year optimization. This allows the inclusion of the system transformation dynamics. In this context, *IRPopt* determines the optimal operation of every time step of selected target years. According to the classification of [1], *IRPopt* demonstrates a quite precise optimization tool. If not every year is optimized, the values between the target years are interpolated.

B.3 Model restrictions

Constraint functions $\mathfrak{g}$ and $\mathfrak{h}$ of equation B.1 generally enter the mathematical optimization through the technical nature of the engineering processes. A qualitative characterization of the processes has been given in section A.2. In the following, a selection of most decisive engineering processes and corresponding mathematical restrictions is outlined. The extract aims to contribute to a better understanding of the optimization framework of IRPopt (see section B.1). Relevant mathematical concept foundations are outlined in section A.3. The processes are presented in the following order:

- *demand processes* in section B.3.1,
- *conversion processes* in section B.3.2,
- *collector processes* in section B.3.3,
- *storage processes* in section B.3.4,
- *transmission processes* in section B.3.5,
- *import-export processes* in section B.3.6.

In accordance with the introduced mathematical concepts, the receiving flows can be described with the following sum of energy flows $\sum_{a \in \overleftarrow{A}^{u,n}} \mathfrak{e}_{t,a}$ [MWh] with $\mathfrak{e}_{t,a} = \mathfrak{e}_{t,u,n',n}$. As outlined in section A.3.1, only existing energy links from $n \in N$ to the respective demand process $n' \in N$ of the energy system graph E are taken into account with $a \in \overleftarrow{A}^{u,n} = \{a = (u,n',n) \in A : n' \in N, n \neq n'\}$. Analogous the emitting energy of n can be summarized with $\sum_{a \in \overrightarrow{A}^{u,n}} \mathfrak{e}_{t,a}$ [MWh] with $\mathfrak{e}_{t,u,n,n'} = \mathfrak{e}_{t,a}$.

In terms of quarter-hourly values and by taking into account an optimization horizon of 48 hours the index comprises 192 time steps $t = \{1,...,T'\} \subset T$. The particular index $t^0 = 0$ is necessary for the rolling determination and transfer of initial values (see section B.2).

B.3.1 Demand processes

Demand processes ($n \in N^{dem} \subset N$) as electrical demand ($n \in N^{el} \subset N^{dem}$) or heating demand ($n \in N^{hl} \subset N^{dem}$) only absorb energy and are thus energy sinks. The energy demand is specified by a exogenous load curve $L_{t,u,n} \in \mathbb{R}_{\geq 0}$ [MWh] (a time series specifying the energy demand for an engineering component $n \in N^{dem}$ in energy sector $u \in U$ and the time steps of interest $t \in T$), which has to be satisfied by the sum of branch energy flows to the respective load of the respective energy sector ($\sum_{a \in \overrightarrow{A}^{u,n}} \mathfrak{e}_{t,a}$). A formalization of the electrical ($u_{el} \in U$) demand coverage including a generic load shifting representation on the basis of [2] is given by equations (B.5a-B.5d). The equations are also applicable for further sectors as the heating sector ($u_{th} \in U$) or the fuel sector ($u_{fu} \in U$).

$$\sum_{a \in \overrightarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} = L_{t,u_{el},n} + DR^{up}_{t,n} - \sum_{t_t=t-M}^{t+M} DR^{dn}_{t,t_t,n} \quad ,\forall t \in T^{'}, \forall n \in N^{el} \tag{B.5a}$$

$$DR^{up}_{t,n} = \sum_{t_t=t-M}^{t+M} DR^{dn}_{t,t_t,n} \quad ,\forall t \in T^{'}, \forall n \in N^{el} \tag{B.5b}$$

$$DR^{up}_{t,n} \leq C^{up} \quad ,\forall t \in T^{'}, \forall n \in N^{el} \tag{B.5c}$$

$$\sum_{t=t_t-M}^{t_t+M} DR^{dn}_{t,t_t,n} \leq C^{dn} \quad ,\forall t_t \in T^{'}, \forall n \in N^{el} \tag{B.5d}$$

$$DR^{up}_{t_t,n} + \sum_{t=t_t-M}^{t_t+M} DR^{dn}_{t,t_t,n} \leq max\left\{C^{up}, C^{dn}\right\} \quad ,\forall t_t \in T^{'}, \forall n \in N^{el} \tag{B.5e}$$

For load shifting in accordance with the explanations of [2], the positive variables $DR^{up}_t \in \mathbb{R}_{\geq 0}$ [MWh] and $DR^{dn}_{t,t_t} \in \mathbb{R}_{\geq 0}$ [MWh] are introduced. They represent hourly load shifts in upward or downward direction. DR^{dn}_{t,t_t} represents downward load shifts effective in hour t_t to compensate for upward shifts in hour t. This formulation directly tags downward load shifts to the respective upward shifts. From equation (B.5b) it follows that every upward load shift is compensated by according downward shifts in due time, taking place either before or after the upward load shift, or both. $M \in \mathbb{R}_{\geq 0}$ represents the load shift horizon. It defines in which interval around hour t downward (upward) load shifts must be compensated by upward (downward) load shifts. The equations (B.5c and B.5d) restrict maximum hourly upward and downward shifts to the predefined levels $C^{up} \in \mathbb{R}_{\geq 0}$ [MWh] and $C^{dn} \in \mathbb{R}_{\geq 0}$ [MWh]. Depending on which of the restrictions given in these two equations is tighter, only one of the equations is relevant due to equal constraint in equation (B.5b). The other constraint then simply results from equation (4). E.g, in case $C^{dn} \leq C^{up}$, equation (B.5c) contains redundant information and can be ignored. On the basis of equation (B.5e) the DR capacity is not fully utilized in both directions at the same time.

B.3.2 Conversion processes

Models for energy converters ($n \in N^{conv}$) are depending on their in- and output relation by considering important technical characteristics of the engineering component. The nodes represent sinks and sources at the same time. In the following, the equations of *electrical hot water boilers*, *heat pumps* and *combined heat and power plants* are stated.

The formulation of *electrical hot water boilers* is outlined in equations (B.6a and B.6b). In this context, the dispatch of electric boilers ($\forall n \in N^{eb} \subset N^{conv}$) is first bounded by specified maximum installed capacity $P^{max}_{u,n} \in \mathbb{R}_{\geq 0}$ [MW] - in case of the maximum heating output $u_{th} \in U$ by $P^{max}_{u_{th},n}$. Second, the sum of all electrical inflows ($u_{el} \in U$) is converted by the engineering component into the sum of all heating outflows ($u_{th} \in U$) with simultaneous consideration of the specified electrical efficiency ($0 \leq \eta_{u_{el},n} \leq 1$). With the exception of the input carrier (u_{fu} instead of u_{el}), the fuel boilers ($\forall n \in N^{fb} \subset N^{conv}$) work the same way.

$$\sum_{a \in \overrightarrow{A}^{u_{th},n}} \mathfrak{e}_{t,a} \leq P^{max}_{u_{th},n} \cdot \Delta t \quad ,\forall t \in T^{'}, \forall n \in N^{eb} \tag{B.6a}$$

$$\sum_{a \in \overrightarrow{A}^{u_{th},n}} \mathfrak{e}_{t,a} = \sum_{a \in \overleftarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} \cdot \eta_{u_{el},n} \quad ,\forall t \in T^{'}, \forall n \in N^{eb} \tag{B.6b}$$

Additional to that, electric boilers ($n \in N^{eb} \subset N^{conv}$) are able to provide positive ($u_{pr} \in U$) and negative ($u_{nr} \in U$) load-frequency control up to their maximum capacity or up to their minimum operation level at a certain time step, respectively [3]. As shown in equation (B.6c) the negative reserve is limited by the installed capacity less the actually required electrical energy for generation of heating energy. In contrast, the positive reserve is limited by the required electrical energy as outlined in equation (B.6d).

This is, however, further restricted by the maximal heat-absorbing (equation B.6e) or maximal heat-withdrawal capacity of the system (equation B.6f). In the first case, the provision of positive load-frequency control is only possible if the system can absorb further heating energy (e.g. by unused available heating storage capacities as explained in section B.3.4), since it requires an increase of electrical energy input which causes an increased heating energy output. In the second case the provision of negative load-frequency control, it need to be checked if the system is still able to cover all restrictions if heating energy is withdrawn from the system (e.g. by unused disposable heating storage capacities), since it requires a reduction of electrical energy input which causes a reduced heating energy output.

While the presented equations determine the maximum possible provision of positive and negative load-frequency control and thus the maximum flexibility potential of the system components, the actual market reserve offering and component reserve pooling depends on the modeling of the reserve market restrictions as depicted in section B.3.6.

$$\sum_{a \in \overrightarrow{A}^{u_{nr},n}} \mathfrak{e}_{t,a} \leq \frac{P^{max}_{u_{th},n} \cdot \Delta t}{\eta_{u_{el},n}} - \sum_{a \in \overrightarrow{A}^{u_{th},n}} \mathfrak{e}_{t,a} / \eta_{u_{el},n} \quad ,\forall t \in T^{'}, \forall n \in N^{eb} \tag{B.6c}$$

$$\sum_{a \in \overrightarrow{A}^{u_{pr},n}} \mathfrak{e}_{t,a} \leq \sum_{a \in \overleftarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} \quad ,\forall t \in T^{'}, \forall n \in N^{eb} \tag{B.6d}$$

$$\sum_{a \in \overrightarrow{A}^{u_{nr},n}} \mathfrak{e}_{t,a} \cdot \eta_{u_{el},n} \leq \sum_{a \in \overleftarrow{A}^{u_{nr},n}} \mathfrak{e}_{t,a} \quad ,\forall t \in T^{'}, \forall n \in N^{eb} \tag{B.6e}$$

$$\sum_{a \in \overrightarrow{A}^{u_{pr},n}} \mathfrak{e}_{t,a} \leq \sum_{a \in \overleftarrow{A}^{u_{pr},n}} \mathfrak{e}_{t,a} \quad ,\forall t \in T^{'}, \forall n \in N^{eb} \tag{B.6f}$$

The main function of a *heat pump* is to provide heat from low temperature heat sources to high temperature heat sinks. An overview of the mathematical formulation of heat pumps ($\forall n \in N^{hp} \subset N^{conv}$) is outlined in equations (B.7a) and (B.7i). It is assumed that the performance or in other words the thermal coefficient of performance $COP_{t,u_{th},n} \in \mathbb{R}_{\geq 0}$ is gradually dependent on the temperature. Furthermore, the heat pump is operated by electricity including a heat rod as a backup. The equation (B.7a) demonstrates the combined heating outflows ($u_{th} \in U$) as the endogenously determinable sum of the generated heat of the temperature dependent heating pump $P^{hp}_{t,u_{th},n} \in \mathbb{R}_{\geq 0}$ [MW] and the heating rod backup $P^{hr}_{t,u_{th},n} \in \mathbb{R}_{\geq 0}$ [MW]. While the maximal power boundary of the overall system is limited by the specified maximum thermal capacity $P^{max}_{u_{th},n} \in \mathbb{R}_{\geq 0}$ [MW] in equation (B.7b), the maximum output of the temperature dependent part is bounded by the temperature dependent capacity

$P^{max,temp}_{u_{th},n} \in \mathbb{R}_{\geq 0}$ [MW] in equation (B.7c). A complete representation also requires the inclusion of the endogenously determinable variables of the negative reserve offerings of the heat pump $P^{hp,nr}_{u_{th},n} \in \mathbb{R}_{\geq 0}$ [MW] and the heat rod $P^{hr,nr}_{u_{th},n} \in \mathbb{R}_{\geq 0}$ [MW]. The corresponding electrical inflow ($u_{el} \in U$) is the sum of the electrical demand of the heat pump and the electrical demand of the heat rod as outlined in equation (B.7d). In dependence of the value of the COP, the heat generated of the heat pump can be a few times larger than the electrical power ($u_{el} \in U$) consumed. In terms of the heating rod the specified electrical efficiency need to be taken into account ($0 \leq \eta_{u_{el},n} \leq 1$).

$$\sum_{a \in \overrightarrow{A}^{u_{th},n}} \mathfrak{e}_{t,a} = (P^{hp}_{t,u_{th},n} + P^{hr}_{t,u_{th},n}) \cdot \Delta t \quad ,\forall t \in T^{'}, \forall n \in N^{hp} \tag{B.7a}$$

$$P^{hp}_{t,u_{th},n} + P^{hr}_{t,u_{th},n} + P^{hp,nr}_{t,u_{th},n} \cdot COP_{t,u_{th},n} + P^{hr,nr}_{t,u_{th},n} \cdot \eta_{u_{el},n} \leq P^{max}_{u_{th},n} \quad ,\forall t \in T^{'}, \forall n \in N^{hp} \tag{B.7b}$$

$$P^{hp}_{t,u_{th},n} + P^{hp,nr}_{t,u_{th},n} \cdot COP_{t,u_{th},n} \leq P^{max,temp}_{u_{th},n} \quad ,\forall t \in T^{'}, \forall n \in N^{hp} \tag{B.7c}$$

$$\frac{P^{hp}_{t,u_{th},n} \cdot \Delta t}{COP_{t,u_{th},n}} + \frac{P^{hr}_{t,u_{th},n} \cdot \Delta t}{\eta_{u_{el},n}} \leq \sum_{a \in \overleftarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} \quad ,\forall t \in T^{'}, \forall n \in N^{hp} \tag{B.7d}$$

Similar to electric boilers ($n \in N^{eb} \subset N^{conv}$) heating pumps ($n \in N^{hp} \subset N^{conv}$) are able to provide positive ($u_{pr} \in U$) and negative ($u_{nr} \in U$) load-frequency control. As shown in equations (B.7e) the negative reserve is equal to the sum of the reserve offerings of the heat pump and the heat rod. The boundary of the negative reserve by the installed capacity has been already taken into account in equation (B.7b) and equation (B.7c). In contrast, the positive reserve as shown in equation (B.7g) is bounded by the required electrical energy as outlined in equation (B.6f). Both, the negative and positive reserve offering, are again further restricted by the maximal heat-absorbing equation (B.7c) or maximal heat-withdrawal capacity of the system equation (B.7i).

$$(P^{hp,nr}_{t,u_{th},n} + P^{hr,nr}_{t,u_{th},n}) \cdot \Delta t = \sum_{a \in \overrightarrow{A}^{u_{nr},n}} \mathfrak{e}_{t,a} \quad ,\forall t \in T^{'}, \forall n \in N^{hp} \tag{B.7e}$$

$$(P^{hp,pr}_{t,u_{th},n} + P^{hr,pr}_{t,u_{th},n}) \leq \frac{P^{hp}_{t,u_{th},n}}{COP_{t,u_{th},n}} + \frac{P^{hr}_{t,u_{th},n}}{\eta_{u_{el},n}} \quad ,\forall t \in T^{'}, \forall n \in N^{hp} \tag{B.7f}$$

$$(P^{hp,pr}_{t,u_{th},n} + P^{hr,pr}_{t,u_{th},n}) \cdot \Delta t = \sum_{a \in \overrightarrow{A}^{u_{pr},n}} \mathfrak{e}_{t,a} \quad ,\forall t \in T^{'}, \forall n \in N^{hp} \tag{B.7g}$$

$$(P^{hp,nr}_{t,u_{th},n} \cdot COP_{t,u_{th},n} + P^{hr,nr}_{t,u_{th},n} \cdot \eta_{u_{el},n}) \cdot \Delta t \leq \sum_{a \in \overleftarrow{A}^{u_{nr},n}} \mathfrak{e}_{t,a} \quad ,\forall t \in T^{'}, \forall n \in N^{hp} \tag{B.7h}$$

$$(P^{hp,pr}_{t,u_{th},n} \cdot COP_{t,u_{th},n} + P^{hr,pr}_{t,u_{th},n} \cdot \eta_{u_{el},n}) \cdot \Delta t \leq \sum_{a \in \overleftarrow{A}^{u_{pr},n}} \mathfrak{e}_{t,a} \quad ,\forall t \in T^{'}, \forall n \in N^{hp} \tag{B.7i}$$

The dispatch of *combined heat and power plants* ($n \in N^{chp} \subset N^{conv}$) is inspired by the implementations of [3] which in turn base on the formulations of [4]. In this context, [4] presents a mixed-integer model to describe the steady state characteristics of a combined heat and power plant. These equations are complemented with temperature-sensitive start-up behavior according to [5], maximum and minimum ramp-rates also according to [5], minimum operation and down time intervals according to [6] as well as own formulations regarding the provision of load frequency control.

Equation (B.8a) determines the required fuel load by taking into account a load dependent electric efficiency and a heat power loss coefficient. In this context, the coefficients α^{I} and α^{II} are used to describe the electrical efficiency as a function of the boiler load as outlined in equations (B.8b and B.8c). The power loss coefficient β is calculated by equation (B.8d) for every timestep t for predefined ambient $K^{cw} \in \mathbb{R}$ [K], feed $K^{ff} \in \mathbb{R}$ [K] and return flow $K^{rf} \in \mathbb{R}$ [K] temperatures. Further explanations regarding the extracted equations are given in [4].

Additionally, the equation (B.8e) and (B.8f) restrict the maximum and minimum boiler load, respectively. If thermal plants are online, they need to stay above a certain threshold and are thus not able to vary their generation in the full range. In this context, a binary variable $S_{t,n} \in \{0,1\}$ is introduced, which states that the plant n is online ($S_{t,n} = 1$) or offline ($S_{t,n} = 0$) at the time step of interest t. The electricity $u_{el} \in U$ energy output is bounded above by the maximum net boiler output $P_{u,n}^{max} \in \mathbb{R}_{\geq 0}$ [MW] and by the minimum net boiler load $P_{u,n}^{min} \in \mathbb{R}_{\geq 0}$ [MW]. At the same time, the maximum heat energy output is restricted by equation (B.8g) [4].

While the presented equations are applicable for combined heat and power plants with extraction condensing turbine, the equations might be also applicable for plants with back pressure turbines. The less or equal sign in equation (B.8g) needs to be replaced by an equal sign. Furthermore, the cooling losses need to be equal to zero [4].

$$\sum_{a \in \overleftarrow{A}^{u_{fu},n}} \mathfrak{e}_{t,a} = \alpha_n^I \cdot \Delta t \cdot S_{t,n} + \alpha_n^{II} \cdot \Big(\sum_{a \in \overrightarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} + \beta_{t,n} \cdot \sum_{a \in \overrightarrow{A}^{u_{th},n}} \mathfrak{e}_{t,a} \Big) \quad , \forall t \in T^{'}, \forall n \in N^{chp} \tag{B.8a}$$

$$\alpha_n^I = \frac{P_{u_{el},n}^{min}}{\eta_{u_{el},n}^{min}} - \alpha_n^{II} \cdot P_{u_{el},n}^{min} \quad , \forall n \in N^{chp} \tag{B.8b}$$

$$\alpha_n^{II} = \frac{P_{u_{el},n}^{max} / \eta_{u_{el},n}^{max} - P_{u_{el},n}^{min} / \eta_{u_{el},n}^{min}}{P_{u_{el},n}^{max} - P_{u_{el},n}^{min}} \quad , \forall n \in N^{chp} \tag{B.8c}$$

$$\beta_{t,n} = 1 - \frac{K_{t,n}^{cw} \cdot \ln(K_{t,n}^{ff} / K_{t,n}^{rf})}{K_{t,n}^{ff} - K_{t,n}^{rf}} \quad , \forall t \in T^{'}, \forall n \in N^{chp} \tag{B.8d}$$

$$\frac{P_{u_{el},n}^{min} \cdot \Delta t}{\eta_{u_{el},n}^{min}} \cdot S_{t,n} \leq \sum_{a \in \overleftarrow{A}^{u_{fu},n}} \mathfrak{e}_{t,a} \quad , \forall t \in T^{'}, \forall n \in N^{chp} \tag{B.8e}$$

$$\sum_{a \in \overleftarrow{A}^{u_{fu},n}} \mathfrak{e}_{t,a} \leq \frac{P_{u_{el},n}^{max} \cdot \Delta t}{\eta_{u_{el},n}^{max}} \cdot S_{t,n} \quad , \forall t \in T^{'}, \forall n \in N^{chp} \tag{B.8f}$$

$$\begin{aligned}\sum_{a\in \overrightarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} \leq & \sum_{a\in \overleftarrow{A}^{u_{fu},n}} \mathfrak{e}_{t,a} - \sum_{a\in \overrightarrow{A}^{u_{th},n}} \mathfrak{e}_{t,a} \\ & -0.1 \cdot \sum_{a\in \overleftarrow{A}^{u_{fu},n}} \mathfrak{e}_{t,a} - 0.1 \cdot S_{t,n} \cdot \left(\frac{P^{max}_{u_{el},n}}{\eta^{max}_{u_{el},n}} - P^{max}_{u_{el},n}\right) \cdot \Delta t \\ & +0.1 \cdot 0.1 \cdot \sum_{a\in \overleftarrow{A}^{u_{fu},n}} \mathfrak{e}_{t,a} \quad ,\forall t \in T^{'}, \forall n \in N^{chp}\end{aligned} \tag{B.8g}$$

Since larger thermal units are not entirely able to change output in any speed, ramp-constraints need to be considered. These limit the maximum increase or decrease of generated power from one time period to the next Δt, reflecting thermal and mechanical inertia. The problem formulation of equations (B.8h) and (B.8i) is extracted from [5]. The parameters $RU_n \in \mathbb{R}_{\geq 0}$ [MW] and $RD_n \in \mathbb{R}_{\geq 0}$ [MW] are representing the maximum ramp-up and ramp-down requirements of a plant $n \in N^{chp}$ at every time step the plant is already running. Besides, the maximum ramp-up at start-up for the unit is specified with $SU_n \in \mathbb{R}_{\geq 0}$ [MW] and the maximum ramp-down at shut-down is specified with $SD_n \in \mathbb{R}_{\geq 0}$ [MW].

$$\begin{aligned}\sum_{a\in \overrightarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} \leq & \sum_{a\in \overrightarrow{A}^{u_{el},n}} \mathfrak{e}_{t-1,a} + RU_n \cdot S_{t-1,n} \cdot \Delta t + SU_n \cdot (1 - S_{t-1,n}) \cdot \Delta t \\ & - min\{SU_n, (P^{min}_{u_{el},n} + RU_n)\} \cdot (1 - S_{t,n}) \cdot \Delta t \quad ,\forall t \in T^{'}, \forall n \in N^{chp}\end{aligned} \tag{B.8h}$$

$$\begin{aligned}\sum_{a\in \overrightarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} \geq & \sum_{a\in \overrightarrow{A}^{u_{el},n}} \mathfrak{e}_{t-1,a} - RD_n \cdot S_{t,n} \cdot \Delta t - SD_n \cdot (1 - S_{t,n}) \cdot \Delta t \\ & + min\{SD_n, (P^{min}_{u_{el},n} + RD_n)\} \cdot (1 - S_{t-1,n}) \cdot \Delta t \quad ,\forall t \in T^{'}, \forall n \in N^{chp}\end{aligned} \tag{B.8i}$$

Besides, minimum up and down time constraints are directly extracted from [6]. The integration is motivated among others by the fact that the start-up procedure of a unit is associated with not inconsiderable costs so as a unit should be only started up if it can run at least a few hours [3]. In this context, $B^{on}_n = min\left\{T^{'}, (T^{on}_n - T^{on,ini}_n) \cdot S_{t^0,n}\right\}$ and $B^{off}_n = min\left\{T^{'}, (T^{off}_n - T^{off,ini}_n) \cdot (1 - S_{t^0,n})\right\}$ states the number of periods during which unit $n \in N^{chp}$ must be online and offline due to its minimum up time or down time constraint, respectively. In order to cover all the different time periods of the optimization horizon $T^{'}$, equations (B.8j-B.8l) are necessary of ensuring minimum up time. Analogously, equations (B.8m-B.8o) are important of ensuring minimum down time. The $T_n^{on} \in \mathbb{R}_{\geq 0}$ specifies the required operation periods of a unit after the start-up and $T_n^{off} \in \mathbb{R}_{\geq 0}$ specifies the required idle periods after a shut-down. Additional to that, $T_n^{on,ini} \in \mathbb{R}_{\geq 0}$ indicates the number of periods unit n has been online prior to current optimization horizon and $T_n^{off,ini} \in \mathbb{R}_{\geq 0}$ states the number of periods unit n has been offline prior to the current optimization horizon.

$$\sum_{t=1}^{B_n^{on}} (1 - S_{t,n}) = 0 \quad ,\forall n \in N^{chp} \tag{B.8j}$$

$$\sum_{t_t=t}^{t+T_n^{on}-1} S_{t_t,n} \geq T_n^{on} \cdot (S_{t,n} - S_{t-1,n}) \quad ,\forall t \in B_n^{on}+1,...,T^{'} - T_n^{on}+1, \forall n \in N^{chp} \tag{B.8k}$$

$$\sum_{t_t=t}^{T^{'}} (S_{t_t,n} - (S_{t,n} - S_{t-1,n})) \geq 0 \quad ,\forall t \in T^{'} - T_n^{on}+2,...,T^{'}, \forall n \in N^{chp} \tag{B.8l}$$

$$\sum_{t=1}^{B_n^{off}} S_{t,n} = 0 \quad ,\forall n \in N^{chp} \tag{B.8m}$$

$$\sum_{t_t=t}^{t+T_n^{off}-1} (1 - S_{t_t,n}) \geq T_n^{off} \cdot (S_{t-1,n} - S_{t,n}) \quad ,\forall t \in B_n^{off}+1,...,T^{'} - T_n^{off}+1, \forall n \in N^{chp} \tag{B.8n}$$

$$\sum_{t_t=t}^{T^{'}} (1 - S_{t_t,n} - (S_{t-1,n} - S_{t,n})) \geq 0 \quad ,\forall t \in T^{'} - T_n^{off}+2,...,T^{'}, \forall n \in N^{chp} \tag{B.8o}$$

Start-up processes in accordance with the equations outlined in [5] explicitly models the cooling behavior of units during the offline time. By introducing an operational temperature variable $K_{t,n}^{op} \in \mathbb{R}_{\geq 0}$ with $S_{t,n} \leq K_{t,n}^{op} \leq 1$, the temperature decay after the shut-down of a unit can be taken into account. Thus, the compensation of the lost thermal energy by burning additional fuel with the help of a heating variable $H_{t,n} \in \mathbb{R}_{\geq 0}$ can be internalized. Combined with the start-up procedure, a comprehensive start-up cost function is applied in *IRPopt*.

The start-up and shut-down procedure is generally given by equation (B.8p). In addition to the already introduced variable $S_{t,n} \in \{0,1\}$ for the representation of the online ($S_{t,n} = 1$) and the offline status ($S_{t,n} = 0$) of a unit n at time step t, two further binary variables are defined. While $Z^{up}_{t,n} \in \{0,1\}$ determines the start-up procedure, $Z^{dn}_{t,n} \in \{0,1\}$ determines the shut-down procedure. Thus, if the unit is switching from offline to online $Z^{up}_{t,n} = 1$ and if the unit is switching from online to offline $Z^{dn}_{t,n} = 1$. Both variables must not be 1 at the same time.

The temperature related start-up modeling extracted from [5] is formulated in equations (B.8q and B.8r). If the unit n is online the equations enforces a value of $K^{op}_{t,n} = 1$. $H_{t,n}$ can be described as the required amount of heating for the start-up procedure which affects the temperature through the recursive equations. As a result the heating variable is normalized to the range of $0 \leq H_{t,n} \leq 1$. $T^{off,ini}_n$ states the number of periods unit n has been offline prior to the current optimization calculations. $\lambda_n \in (0,1)$ [1/period] defines the heat-loss coefficient for Δt.

Finally, in consideration of the relative and absolute status function of IRPopt $\mathfrak{f}^{\text{status}}$ as explained in section A.3.3 and applied in equation (B.4) the start-up costs can be determined for every time period Δt. Therefore, the start-up procedure needs to be equal to the absolute status condition function $Z^{up}_{t,n} = \mathfrak{a}_{t,u,n}$ while the heating variable needs to comply with the relative status condition function $h_{t-1,n} = \mathfrak{r}_{t,u,n}$.

$$Z^{up}_{t,u,n} - Z^{dn}_{t,u,n} = S_{t,n} - S_{t-1,n} \quad ,\forall t \in T^{'}, \forall n \in N^{chp} \tag{B.8p}$$

$$K^{op}_{t,n} = \exp^{-\lambda_n \cdot T^{off,ini}_n} + H_{t^0,n} \quad ,\forall t = 1, \forall n \in N^{chp} \tag{B.8q}$$

$$K^{op}_{t,n} = \exp^{-\lambda_n \cdot \Delta t} \cdot K^{op}_{t-1,n} + (1 - \exp^{-\lambda_n \cdot \Delta t}) \cdot S_{t-1,n} + H_{t,n} \quad ,\forall t \geq 2, \forall n \in N^{chp} \tag{B.8r}$$

Similar to the electric boilers, the provision of positive and negative load-frequency control of combined heat and power plants is first possible in terms of the maximal heat-absorbing or maximal heat-withdrawal capacity of the system whilst taking the maximum and minimal operation level of the plant into consideration. Thereby, also the ramp-up and down constraints have to be respected (see equations (B.8j-B.8l) and equations (B.8m-B.8o)). Moreover, since extraction condensing steam turbines are able to expand the steam in the steam turbine down to condenser pressure or to use it for heating of the district heating system (see equation (B.8g) the provision of positive and negative load-frequency control of combined heat and power plants is also possible in this context.

B.3.3 Collector processes

Collector processes ($n \in N^{coll}$) as *themal solar panels* ($n \in N^{sp} \subset N^{coll}$) and *electrical phtovoltaic panels* ($n \in N^{pv} \subset N^{coll}$) as well as wind turbines ($n \in N^{wt} \subset N^{coll}$) and river hydro plants ($n \in N^{rh} \subset N^{coll}$) depend on environmental circumstances. In case of photovoltaic technologies ($n \in N^{pv}$) the decisive input parameter is represented by the exogenous insulation time series $I_{t,n} \in \mathbb{R}_{\geq 0}$ [W/m^2]. The dependence of the time series t on the engineering component n can be explained with the fact that the systems might be spatially distributed and thus experience a different environmental influence. Furthermore, the energy output of the processes is equal or lower than the product of the electrical efficiency $0 \leq \eta_{u_{el},n} \leq 1$, the surface area $A_n \in \mathbb{R}_{\geq 0}$, the length of the time step Δt and the [W] to [MW] conversion factor, as given by equation (B.9). Further technical intricacies including temperature influences are described in [7, 8].

$$\sum_{a \in \overrightarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} \leq I^0_{t,n} \cdot \eta_{u_{el},n} \cdot A_n \cdot \Delta t \quad ,\forall t \in T^{'}, \forall n \in N^{pv} \tag{B.9}$$

While $n \in N^{sp}$ show nearly the same characteristic in u_{th} as $n \in N^{pv}$ in u_{el} the presented equation can be adopted. Crucial equations of $n \in N^{wt}$ and $n \in N^{rh}$ are extracted from [8] and [9], respectively. In this context, provision of negative load frequency control is possible by curtailing the maximum energy output in a certain time period for $n \in N^{pv} \cup N^{wt} \cup N^{rh}$.

B.3.4 Storage processes

An energy system might contain multiple storage elements ($n \in N^{store}$) as electrical storage systems ($n \in N^{es} \subset N^{store}$) and heating storage systems ($n \in N^{hs} \subset N^{store}$). The positive defined state of charge variable $SOC_{t,n} \in \mathbb{R}_{\geq 0}$ [MWh] of the electrical storage system at the end of period Δt is calculated according to equation (B.10a) based on the constraints of equations (B.10b-B.10e). Thereby, the state of charge at a given time point $t \in T$ of component $n \in N^{es}$ for sector $u_{el} \in U$ is defined recursively as the sum of the $SOC_{t-1,n}$ at the previous time point, the added charge, the withdrawn energy and the self-discharge of the component in dependency of the self-discharging rate. While the charging and discharging efficiency is equal and given by $0 \leq \eta_{u_{el},n} \leq 1$, the self-discharging rate in Δt is given by $0 \leq \eta^{self}_{u_{el},n} \leq 1$. The endogenously determined $SOC_{t,n}$ is bounded below by $SOC^{min}_{n} \in \mathbb{R}_{\geq 0}$ [MWh] as shown in equation (B.10b) and bounded above by $SOC^{max}_{n} \in \mathbb{R}_{\geq 0}$ [MWh] as shown in equation (B.10c). Additional to that, the discharging (sum of all branch energy flows out of a energy storage of a certain sector) and charging (sum of all branch energy flows into an energy storage of a certain sector) is restricted by the maximum charging and discharging capacity $P^{max}_{u_{el},n} \in \mathbb{R}_{\geq 0}$ [MW] as outlined in equation (B.10d) and (B.10e). Previously, the initial state of charge $SOC_{t^0,n}$ need to be specified.

$$\begin{aligned} SOC_{t,n} =& SOC_{t-1,n} + \sum_{a \in \overleftarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} \cdot \eta_{u_{el},n} \\ & - \sum_{a \in \overrightarrow{A}^{u,n}} \mathfrak{e}_{t,a} / \eta_{u_{el},n} - SOC_{t-1,n} \cdot \eta^{self}_{u_{el},n} \quad , \forall t \in T^{'}, \forall n \in N^{es} \end{aligned} \tag{B.10a}$$

$$SOC^{min}_{n} \leq SOC_{t,n} \quad , \forall t \in T^{'}, \forall n \in N^{es} \tag{B.10b}$$

$$SOC_{t,n} \leq SOC^{max}_{n} \quad , \forall t \in T^{'}, \forall n \in N^{es} \tag{B.10c}$$

$$\sum_{a \in \overleftarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} \cdot \eta_{u_{el},n} \leq P^{max}_{u_{el},n} \cdot \Delta t \quad , \forall t \in T^{'}, \forall n \in N^{es} \tag{B.10d}$$

$$\sum_{a \in \overrightarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} / \eta_{u_{el},n} \leq P^{max}_{u_{el},n} \cdot \Delta t \quad , \forall t \in T^{'}, \forall n \in N^{es} \tag{B.10e}$$

Electricity storage systems are also able to provide load-frequency control. On the one hand, the provision is restricted by the maximum charging or discharging capacity. This is stated in equation (B.10f) for the positive reserve and in equation (B.10g) for the negative reserve. On the other hand, the provision is restricted by the current state of charge. While an empty storage is not able provide positive reserve, a completely filled storage is not able to provide negative reserve. This is shown in equation (B.10h) and (B.10i), respectively.

$$\sum_{a \in \overrightarrow{A}^{u_{pr},n}} \mathfrak{e}_{t,a} \leq P^{max}_{u_{el},n} \cdot \Delta t - \sum_{a \in \overrightarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} \quad ,\forall t \in T^{'}, \forall n \in N^{es} \tag{B.10f}$$

$$\sum_{a \in \overrightarrow{A}^{u_{nr},n}} \leq P^{max}_{u_{el},n} \cdot \Delta t - \sum_{a \in \overleftarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} \quad ,\forall t \in T^{'}, \forall n \in N^{es} \tag{B.10g}$$

$$\begin{aligned} SOC^{min}_{n} \leq & SOC_{t-1,n} + \sum_{a \in \overleftarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} \cdot \eta_{u_{el},n} \\ & - \sum_{a \in \overrightarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a}/\eta_{u_{el},n} - \sum_{a \in \overrightarrow{A}^{u_{pr},n}} \mathfrak{e}_{t,a}/\eta_{u_{el},n} \quad ,\forall t \in T^{'}, \forall n \in N^{es} \end{aligned} \tag{B.10h}$$

$$\begin{aligned} SOC^{max}_{n} \geq & SOC_{t-1,n} + \sum_{a \in \overleftarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} \cdot \eta_{u_{el},n} \\ & - \sum_{a \in \overrightarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a}/\eta_{u_{el},n} - \sum_{a \in \overrightarrow{A}^{u_{nr},n}} \mathfrak{e}_{t,a}/\eta_{u_{el},n} \cdot \eta_{u_{el},n} \quad ,\forall t \in T^{'}, \forall n \in N^{es} \end{aligned} \tag{B.10i}$$

Besides, heating storage systems ($n \in N^{hs} \subset N^{store}$) are defined with similar equations in sector $u_{th} \in U$ even though they are not really able to provide load frequency control energy. However, as shown e.g. in equation (B.6e) and equation (B.6f) of the electric boiler, the equations might indicate flexibility potential of the system and thus heat-absorbing or heat-withdrawal capacity of the storage system. This enables to provide load-frequency control of conversion processes with heating energy output in the first place.

Additional to that, the operation and maintenance costs and thus the wear of the battery can be integrated in terms of *IRPopt* in a similar way as the start-up cost of the conversion plants. Doing this, the normalized charge and discharge cycle ($0 \leq cs^{O\&M}_{t,n} \leq 1$) needs to equated to the relative status condition function ($cs^{O\&M}_{t,n} = \mathfrak{r}_{t,u,n}$).

B.3.5 Transmission processes

Transmission processes ($n \in N^{grid}$) of the *electrical grid*, the *heating grid* and the *fuel grid* ($n \in N^{fg} \subset N^{grid}$) are kept deliberately simple and do not yet incorporate constitutional physical laws as done in [10, 11]. Thus, all different grids can be described with the same mathematical equations. As formulated in equation (B.11a), the sum of all branch energy flows out of a certain electrical grid u_{el} must be equal to the sum of all branch electrical energy flows into this grid at every time period t. Losses can be taken into account on the basis of the efficiency matrix ($0 \leq \eta_{u_{el},n} \leq 1$). Additional to that, the flow capacity of different grid elements of a certain sector can be also maximally limited by $P_{u_{el},n}^{max}$ as formulated in equation (B.11b). This allows among others initial technical restrictions regarding different grid levels in the electrical sector.

$$\sum_{a \in \overrightarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} = \sum_{a \in \overleftarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} \cdot \eta_{u_{el},n} \quad ,\forall t \in T^{'}, \forall n \in N^{eg} \tag{B.11a}$$

$$\sum_{a \in \overrightarrow{A}^{u_{el},n}} \mathfrak{e}_{t,a} \leq P_{u_{el},n}^{max} \cdot \Delta t \quad ,\forall t \in T^{'}, \forall n \in N^{eg} \tag{B.11b}$$

B.3.6 Import-export processes

The modeling of the import-export processes describes the energetic connection to the super-ordinated system. In this context, different energy markets ($n \in N^{market} \subset N$) as the spot market ($n \in N^{em} \subset N^{market}$), the fuel market ($n \in N^{fm} \subset N^{market}$) or the reserve market ($n \in N^{rm} \subset N^{market}$) are implied. While the former market processes are not necessarily modeled with certain restrictions (e.g. excess or required energy of engineering components connected to an energy market can be imported and exported in any units at any time steps), the latter market processes try to integrate initial ideas of the complex market design of the reserve markets. In this context, both a solution for reserve pooling as well as a solution for block bids are receiving particular attention in *IRPopt*. However, a retrieval of load-frequency reserve is not implemented yet. For modeling reason, next to the positive and negative reserve sectors ($u_{pr} \in U, u_{nr} \in U$), engineering components like primary, secondary and tertiary reserve markets ($n \in N^{rm} = prm, srm, ptrm$) as well as primary, secondary and tertiary reserve pools ($n \in N^{rp} = prp, srp, trp$) are available. Thereby, engineering components like the electric boilers $n \in N^{eb}$ which are able to provide positive or negative load frequency control $\sum\limits_{a\in\overrightarrow{A}^{u_{pr},n}} \mathfrak{e}_{t,a}$, $\sum\limits_{a\in\overrightarrow{A}^{u_{nr},n}} \mathfrak{e}_{t,a}$ are not directly connected to the reserve market but rather to specific reserve pool elements which are again connected with the associated reserve market elements. One the one had, this allows the definition whether an engineering component is able to provide all of the different forms of load-frequency control or only a selection of positive and negative primary, secondary and tertiary. On the other hand, the auxiliary construction allows the virtual pooling of the provision of different plants. The mathematical formulation for negative reserve sector $u_{nr} \in U$ is given in equation (B.12a-B.12d). The presented equations are also valid for the positive load frequency reserve sector u_{pr}.

In this context, $\forall x \in \mathbb{N}$ with $\forall t_x \in t_{x\cdot T^{on}(x)+1}, ..., t_{(x+1)\cdot T^{on}}$ equation (B.12a) formulates the n-th block bid. For every block bid x, the ingoing flows to the reserve pools ($n \in N^{rp}$) need to be greater or equal at every timestep t than the outgoing flows of the reserve pools to the reserve market at the intial timestep of the block bid t_x. T_n^{on} specifies the corresponding block length of the tender period of the reserve market offering. In addition to that, minimal and maximal restrictions for the biddings are introduced in equation (B.12b) and equation (B.12c), respectively. Finally, symmetric bids for the negative and positive load frequency reserve are also realizable with the help of equation (B.12d).

$$\sum_{a\in\overleftarrow{A}^{u_{nr},n}} \mathfrak{e}_{t,a} \geq \sum_{a\in\overrightarrow{A}^{u_{nr},n}} \mathfrak{e}_{t_x,a} \quad ,\forall t \in \{x\cdot T^{on}(x)+1, ..., (x+1)\cdot T^{on}(x)\} \quad ,\forall n \in N^{rp} \tag{B.12a}$$

$$\sum_{a\in\overrightarrow{A}^{u_{nr},n}} \mathfrak{e}_{t,a} \geq P^{min}_{u_{nr},n} \cdot S_{t,n} \cdot \Delta t \quad ,\forall t \in T^{'}, \forall n \in N^{rp}, \forall n' \in N^{rm} \tag{B.12b}$$

$$\sum_{a\in\overrightarrow{A}^{u_{nr},n}} \mathfrak{e}_{t,a} \leq P^{max}_{u_{nr},n} \cdot S_{t,n} \cdot \Delta t \quad ,\forall t \in T^{'}, \forall n \in N^{rp}, \forall n' \in N^{rm} \tag{B.12c}$$

$$\sum_{a\in\overrightarrow{A}^{u_{nr},n_{prp}}} \mathfrak{e}_{t,a} = \sum_{a\in\overrightarrow{A}^{u_{pr},n_{prp}}} \mathfrak{e}_{t,a} \quad ,\forall t \in T^{'} \tag{B.12d}$$

B.4 Evaluation approach

While the objective function at present only integrates the variable cost of the processes, *IRPopt* also determines the net present value (NPV) of payment series of individual customer groups as well as business divisions by the sum of variable payments and fixed cash flows over the optimization iterations. Fixed cash flows are given by levelized investment costs of decentralized systems as well as monthly and yearly levies. This requires further input data concerning technology costs, economic lifetime, discount rate. In addition to the profitability level business cases can be also evaluated in terms of emission volume and autarky level.

B.5 Model architecture

The computational programming of the optimization approach has been conducted in a GAMS (General Algebraic Modeling System) 24.7.4 environment. In order to solve different scenarios of a certain optimization problem, GAMS calls the IBM ILOG CPLEX Optimizer. The environment allows the formulation of the optimization problem in a notation similar to their algebraic notation which enables a comprehensible representation also for non-programmers. The available GDX (GAMS Data eXchange) functionalities are utilized for exchanging and thus reading and writing GAMS data. GDX files represent binary files that are portable between diverse platforms. Moreover, put commands are used to produce comma delimited output files.

The bulk of programming effort has been concentrated on three major parts of the framework: the network system and subsystem development, the engineering component library, as well as the associated unit commitment procedure. Although GAMS does not really support object-oriented design concepts, the programming of the numerical model environment followed some object-oriented ideas. Emphasis has been placed on code reusability as well as well as flexible expandability.

In terms of the system network development, an increased use of logical conditions has been necessary in order to keep problem complexity as small as possible. The structure decides on the integration of commercial actors as well as engineering components but also provides necessary information about the contractual agreement for the unit commitment problem. The less unnecessary elements, items and dynamics and thus sets, parameters, variables and constraints are configured, the better the performance of the optimization procedure.

The library of the engineering components consists of several modules from which individual processes are instantiated to populate a specific model. In this context, commonalities can be leveraged on the basis of set hierarchies. Due to the abstract and general problem formulation regarding the unit commitment programming, new components can be easily integrated and connected with the existing constructs and are also considered by the objective function. Thus, future expansion especially in terms of engineering components do not require any changes of the existing code. Parallelization of optimization runs has been realized by optimizing each optimization year on its own. Additional to that, the implemented model constructs have been tested in terms of the program correctness.

Each optimization job of *IRPopt* consists of the general steps 1-9 as outlined in the following. In this context, the dynamic optimization procedure leads to the repeated execution of recursive steps 5-8. The CPLEX (IBM ILOG CPLEX Optimization Studio software package) is applied to solve the optimization problem.

1. Program start: load data of the scenario specification files (optimization year, number of time steps, length of the optimization horizon and storage horizon, etc.);

2. Database import: declare and define input sets (actors, components, etc.) and parameters (system links, process specifications, etc.);

3. System configuration: develop and parametrize (calculation of unknown coefficients) relevant systems (energy flow graph, energy tariff network, etc.) and subsystems (power measurement bundles, etc.);

4. Variable declaration: declare relevant variables (energy flow function, etc.) for the formulated optimization problem;

5. Problem initialization: determine sub sets (optimization horizon, etc.) and initial process values (state of charge, etc.);

6. Optimization run: calculate optimal performance on the basis of the CPLEX solver;

7. Evaluation procedure, assessment of specific indicators (net present value, energy flow shares, etc.);

8. Results output: write output files (comma delimited files, gdx files, etc.);

9. Program end: new start of the procedure for further optimization years.

The GAMS/CPLEX-based MIP implementation is embedded in an extensive software infrastructure. Taken together they form a decision system for municipal energy utilities. The software infrastructure encapsulates the dry formalism of the optimization model behind a generic process and user-friendly web interface. Required model expansions may be realized independently from the software engineering due to a specifically developed deployment process. Decision makers are able to perform sensitivity analyses based on what-if analysis with assistance provided by an energy system visualization tool, a sensitivity management tool, and a schematic representation of the comparison of results. The distributed architecture allows several business units to take part in the problem solving. In this context, master data management including time series analysis to support the scenario generation can be maintained independent from the actual model application. Through the interdisciplinary framework IRPopt aids in understanding the system implications and economic potential of innovative business models to support management decision-making of municipal energy utilities.

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Statement of Contribution

The author of the doctoral thesis has made significant contributions to all manuscripts from conceptual design, to model development, numerical implementation, structuring and drafting the text, and correspondence with journals and referees. The following paragraphs detail the contribution of the author to the core chapters of this thesis and acknowledge major contributions of others.

Chapter 1

The author of the doctoral thesis was sole responsible for drafting this chapter.

Chapter 2

The author of the doctoral thesis devised the conceptual ideas and drafted the review manuscript on his own. Prof. Dr. Thomas Bruckner supervised the research project and commented on the final manuscript.

Chapter 3

The author of the thesis conceived the presented idea and encouraged Simon Johanning, Stephan Seim, Kerstin Schuchardt, Jonas Krone, and Rosa Haberland to investigate the legal framework of a selected business model and aided in interpreting the results. The author of the doctoral thesis also took the lead in structuring and writing the manuscript. All authors provided critical feedback and contributed to the writing. Prof. Dr. Thomas Bruckner supervised the research project and commented on the final manuscript.

Chapter 4

The author of the doctoral thesis conceived the original idea and designed and implemented the optimization model. Jonas Krone investigated the research field, performed the optimization calculations, and analyzed the model results. The author of the doctoral thesis and Jonas Krone discussed the research process and research results. Dr. Stefan Kühne provided the software and hardware environment. The author of the doctoral thesis took the lead in structuring and writing the manuscript. Jonas Krone contributed to the writing of the manuscript. Prof. Dr. Thomas Bruckner supervised the research project and commented on the final manuscript.

Chapter 5

The author of the doctoral thesis and Balthasar Burgenmeister designed the theoretical framework and implemented the optimization model. David Georg Reichelt implemented the software workflow. The author of the doctoral thesis investigated the theoretical background, planned and carried out the optimization calculations and analyzed the model results. Dr. Hendrik Kondziella and Dr. Stefan Kühne supervised the research project. The author of the doctoral thesis wrote the manuscript. Balthasar Burgenmeister and Prof. Dr. Thomas Bruckner provided critical comments on the final manuscript.

Chapter 6

The author of the doctoral thesis conceived the presented idea and wrote the manuscript. Simon Johanning contributed to the final version of the manuscript. Prof. Dr. Thomas Bruckner supervised the research project and commented on the final manuscript.

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Declaration of Authorship

Hiermit erkläre ich, die vorliegende Dissertation selbstständig und ohne unzulässige fremde Hilfe, insbesondere ohne die Hilfe eines Promotionsberaters, angefertigt zu haben. Ich habe keine anderen als die angeführten Quellen und Hilfsmittel benutzt und sämtliche Textstellen, die wörtlich oder sinngemäß aus veröffentlichten oder unveröffentlichten Schriften entnommen wurden, und alle Angaben, die auf mündlichen Auskünften beruhen, als solche kenntlich gemacht. Ebenfalls sind alle von anderen Personen bereitgestellten Materialien oder erbrachten Dienstleistungen als solche gekennzeichnet.

Bibliographic Description

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Modeling and Optimizing of Integrated Multi-Modal Energy Systems for Municipal Energy Utilities
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The development of sustainable business models is a challenging task since various factors might influence the results of an assessment. Given the complexity at the municipal level, system interdependencies between different alternatives need to be considered. One possibility to support decision makers is to apply energy system optimization models. Existing optimization models, however, ignore the roles different actors play and the resulting impact they have.

To address this research issue, this thesis presents an integrated techno-economic optimization framework called IRPopt (Integrated Resource Planning and Optimization). A proven graph-based energy system approach allows the accurate modeling of deployment systems by considering different energy carriers and technical processes. In addition, a graph-based commercial association approach enables the integration of actor-oriented coordination. This is achieved by the explicit modeling of market actors on one layer and technology processes on another layer as well as resource flow interrelations and commercial agreements mechanism among and between the different layers. Using the optimization framework, various optimization problems are solvable on the basis of a generic objective function.

For demonstration purposes, this thesis assesses the business models demand response and community storage. The applied examples demonstrate the modeling capabilities of the developed optimization framework. Further, the dispatch results show the usefulness of the described optimization approach.

Finally, this thesis presents a conceptual techno-socio-economic model vision. The coupling of system optimization with an actor simulation allows a combined analysis of sociological and technological dynamics in terms of business model assessment.