Local Energy Management: Optimizing Virtual Economic Units

Von der Mercator School of Management, Fakultät für Betriebswirtschaftslehre, der

Universität Duisburg-Essen

zur Erlangung des akademischen Grades

eines Doktors der Wirtschaftswissenschaft (Dr. rer. oec.)

genehmigte Dissertation

von

Benjamin Hildebrandt
aus
Tuttlingen, Deutschland

Referent:	Prof. Dr. Michael Manitz
Koreferent:	Prof. Dr. Johann Hurink
Tag der mündlichen Prüfung:	13.10.2023

Writing a dissertation is a unique milestone in a person's life. This is also due to the fact that you focus very intensively on a topic for a long time, which requires some persistence and also means personal sacrifices. That's why, at the end, you may not only be proud of what you have achieved, but also a little relieved if it can ultimately be finalized positively. However, a positive ending cannot be taken for granted, but is usually facilitated by the fact that loved ones accompany you on this journey for a while or even beyond. I am very glad that I have many such great people as companions or that I was able to get to know them in the first place by writing this thesis. I would like to use these lines to thank you.

But let's start at the very beginning with Michael Manitz, without whose willingness to supervise this work and bring me to the chair, a thesis would never have been written. My colleagues at the chair were a very important part of this time anyway. First and foremost, of course, my friend Marc Piehl, who has been with me since I was a student and was always up for a much too long discussion. But of course he wasn't alone, because we had many great doctoral students in our year. Not only at the chair or the university, but also at the numerous workshops and conferences we were able to attend. Thank you for all the discussions, crude ideas and food for thought. However, no one was able to get me out of my comfort zone as successfully as Julian Lütkemeyer, which he should definitely take with him as a special award. I would also like to thank our secretaries Heike Küppers and Evelyn Scherer, who have always tried to give us employees the best possible support so that we can make progress with our research.

A special thanks goes to my girlfriend Teresina, who has suffered the most alongside me in the last few years, but especially in the last few months during the writing of this thesis, and in which she always had to be a certain haven of peace for me. My family is an additional important source of motivation, as they have always had my back and encouraged me when I have taken unexpected career paths. Especially my sister Franziska, who always tries to show me other perspectives on various topics. Finally, I would like to say a very special thank you to Johann Hurink, who ended up being like my second supervisor due to his thematic proximity. Without his advice, the numerous brainstorming sessions and his enthusiasm for all the scientific discussions, I would have been missing a very important mentor and person.

Contents

List of Figures

List of Tables

List of Symbols

Symbols for Sets

Symbol	Definition	IS Unit
T	periods $t \in \mathcal{T} := \{1, \ldots, T\}$	t = 15 minutes
N	participants $n \in N$	Household
K	energy storage systems $k \in K$	Device
J	demand side management (DSM) jobs $j \in J$	Job
M	DSM devices $m \in M$	Device
S_t	supplying participants $s \in S_t$ in period t	Supplier
D_t	consuming participants $d \in D_t$ in period t	Consumer
B_t	possible bipartite pairs $B_t = (S_t, D_t)$ in period t	Pairs
BCh_t	possible charge pairs $BCh_t = (K, S_t)$ in period t	Pairs
BDc_t	possible discharge pairs $BDc_t = (K, D_t)$ in period t	Pairs
$\mathcal{S}$	coalitions in cooperative games	
$\mathcal{P}$	players $p \in \mathcal{P}$ in distribution games	
$\mathcal{F}$	strategy $f_p \in \mathcal{F}_\mathcal{P}$ for player p	
H	sequence $h \in H$ in nucleolus method	

Symbols for Parameters

Symbol	Definition	IS Unit
$pl_{t,n} \in \mathbb{R}$	predicted energy load of participant n in period t	Wh
$sr_{t,n}$	supplier rate of participant n in period t	Cent per kWh
$dr_{t,n}$	consumer rate of participant n in period t	Cent per kWh
$v_{t,n}$	derived variable tariff of participant n in period t	Cent per kWh
α_k	storage process efficiency of energy storage k	Percentage
ic_k	initial charge status of energy storage k	Wh
cap_k	capacity of storage k	Wh
$pcap_{t,k}$	storage rate of storage k in period t	Wh
$stu_{t,k}$	storage deviation for energy storage k in period t	Wh
$mcap_{t,k}$	minimal charge status of energy storage k in period t	Percentage
ST_j	first possible start period of job j	Period
ET_j	last possible end period of job j	Period
dur_j	duration of job j	Periods
jl_l	periodic energy load demand of job j	Wh
$y_{n,j}$	binary, 1 if job j is associated to participant n	$[0,1]$
$z_{m,j}$	binary, 1 if job j is associated to DSM device m	$[0,1]$
$\mathbf{a}$	proposed distribution $a_p \in \mathbf{a}$ for player p	
u_p	payoff for player p	

Symbols for Variables

Symbol	Definition	IS Unit
$ol_{t,n}$	optimized load of participant n in period t	Wh
$bal_{t,s,d}$	energy exchange in period t between sup. s and con. d	Wh
$soc_{t,k}$	state of charge of storage k in period $t = 0, \ldots, T$	Wh
$ch_{t,k,s}$	charge in period t between supplier s and storage k	Wh
$dc_{t,k,d}$	discharge in period t between storage k and demander d	Wh
$x_{j,t}$	binary variable, 1 if job j starts in period t	Wh
$hc_{t,n}$	excess DSM demand of participant n in period t	$[0, 1]$
$\nu(\mathcal{S})$	characteristic function of coalition $\mathcal{S}$	
$\pi_p^{\mathcal{S}}$	Shapley value of player p in coalition $\mathcal{S}$	
$C(\mathcal{P}, \nu)$	core for the game $(\mathcal{P}, \nu)$	
$\mathcal{E}$	savings value of the of the cooperation	
$e(\mathcal{S}, \mathbf{a})$	excess function for coalition $\mathcal{S}$ and proposed distribution a	
ε_h	dissatisfaction of sequence $h \in H$	

Acronyms

BRP	balance responsible party
DELA	delayed energy load adjustment
DER	distributed energy resources
DR	demand response
DS	distributed storage
DSM	demand side management
DSO	distribution system operator
EC	energy community
ELA	energy load adjustment
ESP	energy service provider
ESS	energy storage system
EV	electric vehicle
LEM	local energy market
LFM	local flexibility market
MSFA	maximum saving flow algorithm
P2P	peer-to-peer
PV	photovoltaic
RES	renewable energy resources
TSO	transmission system operator
VEU	virtual economic unit

1. Introduction

The existing designs of energy systems used worldwide are being challenged by the necessary changes caused by climate change. The limited availability of non-renewable resources and their unavoidable carbon footprint lead to the need for more sustainable power generation. As a consequence, future systems will rely to a large extent on renewable energy resources (RES). This ongoing process can already be observed and is known as *energy transition*. One of the main challenges with this fundamental system change is that the integration of a steadily growing number of renewable resources is complex, because a majority of these energy sources are volatile and have a stochastic character (Kumar et al. (2019)). Therefore, the generation output is largely uncontrollable and less predictable as it is synchronised to some extent by the availability of sun or wind. This leads to large peaks in the generation of electricity overall. Thus more stress is put on the traditional grid infrastructure at the higher transmission grid level, but also at the distribution grid level, as a significant part of the renewable generation is already integrated there (Eur (2018)). This existing overburden of the current infrastructure already poses major problems for the existing system and therefore hinders the further integration of necessary decentralized sustainable energy generation. The International Energy Agency (2016) estimates that an additional eight trillion US dollars will need to be invested in RES by 2035 to meet climate targets and alleviate global warming. These funds will not only be financed by governments and public spending, but will require the active willingness of private investors to engage in the transformation of our energy system. This means not only large institutional investors, but also ordinary domestic citizens, so that the energy transition can be achieved through broad social acceptance and participation (Bertsch et al. (2016)). Residential households are not only responsible for a considerable share of energy consumption (approx. 30% worldwide and approx. 25% in Germany), but have now also increasingly emerged as investors in local energy production capacity and energy efficiency. This is to be further increased, but will depend on how their participation can be arranged. The conclusion is that we need a decentralized, smart and interconnected energy system, as an already existing proposal of the European Commission recommends in 2019 (Directorate General for Energy of the European Commission (2019)). In particular, the concept of local energy management through the development of approaches to local energy market (LEM) and collaborations such as energy community (EC) with the special role change of local customers are seen as two of the possible keys to solving important problems in this context.

This thesis addresses this need for a local energy management and examines how a cooperation with local participants can be set up in such an environment. The analyzed cooperation is considered from an operational planning perspective and strategic or tactical decisions (e.g. investments made) are assumed as given. Precise planning of the real-time operation of the systems is not included either, which makes detailed planning and subsequent control necessary. However, an adjustment of the operational schedules, which usually take place in a day-ahead time frame, is common in the energy sector anyway. The decision support, which is supposed to result from this thesis, is therefore located in the day-ahead planning level and focuses on the economic influence of the internal energy exchange between the participants. External opportunities for economic decisions shall only be considered to the extent that the influence of the internal planning for potential external decisions becomes apparent. The internal energy exchange is not only concerned with direct connections between the participants, but also includes the use of local flexibility in the intended planning horizon, and which economic influences these possibilities offer. The implemented and provided optimization methods use forecasted data and thus deterministic values for the economic analysis. Uncertainty has always been a significant and well-researched topic in the energy sector, which is why the data quality and known forecasting methods have a high degree of applicability. The use of deterministic data for the required analysis is thus permissible. A final investigation will then examine how a cooperation of local participants could subsequently best distribute the achieved economic added value. Before a detailed description of the contents of the thesis follows, it should be specified which problems are examined, which solutions this thesis wants to contribute to solve these problems and with which structure this will be done.

1.1. Problem Statement

This thesis considers how a cooperation of local actors can effectively and efficiently coordinate their internal energy exchanges to add economic value as the central problem.

To address this central problem, it is reasonable to decompose it into subproblems:

- How exactly should a framework for cooperation and its operational planning be structured ?
- What is the economic impact of flexibility solutions on internal energy exchange in the cooperation ?
- Are there methods for the participants to distribute the monetary benefits of the cooperation reasonably among each other afterwards ?

1.2. Contributions

The contributions of this thesis includes the following discussions, approaches and solutions:

A composable and extensible framework that offers cooperation between local and still independent participants – Chapter 2.

- Definition of locality and energy management in this context
- State of research on local market and cooperation concepts
- Conceptual design of the framework applied in this thesis

Development of a modular mathematical model that optimizes the operational decisions of the cooperations in different configurations and provides an economic analysis for all incremental configuration steps.

- A first stage with direct energy exchange between participants (Chapter 3)
- A second stage with the possibility to shift energy supply (Chapter 4.1)
- A third stage with the possibility to shift energy demand (Chapter 4.2)
- Special cases using the example of EV and outlook which possibilities can be considered (Chapter 4.3)

Establish a basis for a robust saving distribution of such a hybrid cooperation through game-theoretic evaluation – Chapter 5.

- Classification of the cooperation in existing solution concepts

- Suggestion for alternative distribution methods
- Initial analysis and assessment of the discussed distribution methods

Additional aspects to always ensured:

- Focus on internal connections between participants, but also external connection opportunities are considered
- Efficient model formulations are included that describe the essence of the problem
- Discussion of alternative solution approaches, based on the structural insights.

1.3. Outline

The structure and flow of the thesis is as follows, with the numbers corresponding to the chapter numbers:

2. 'World of Local Energy' discusses related work in local energy management with a focus on LEMs and EC to develop the framework for the proposed virtual economic unit (VEU) concept of this thesis.
3. 'Energy Exchange' presents the basic approach for the internal energy exchange of the VEU. In this set-up, participants are only allowed to exchange their energy directly between each other. In addition, an alternative solution method for the specific problem structure is provided. Finally, an effective approach is discussed to consider bidding opportunities on external auction-based energy markets, based on the optimal internal energy exchange decision.
4. 'Flexibility Options' extend the energy exchange of the participants in the VEU with realistic options to shift their energy supply and demand in time. The focus is on the utilization of storage processes with energy storage system (ESS) to make better use of the available supply and demand side management (DSM) to schedule the demand in such a way that it can be satisfied with maximum savings. Finally, the special case of electric vehicles (EVs) will be presented. Further research possibilities are then be discussed and evaluated in the context of this special case.
5. 'Cooperation Management' discusses a first analysis of possible classic game-theoretic approaches and problem-specific methods that can be applied to distribute the economic added value (savings) of the cooperation to their participants.

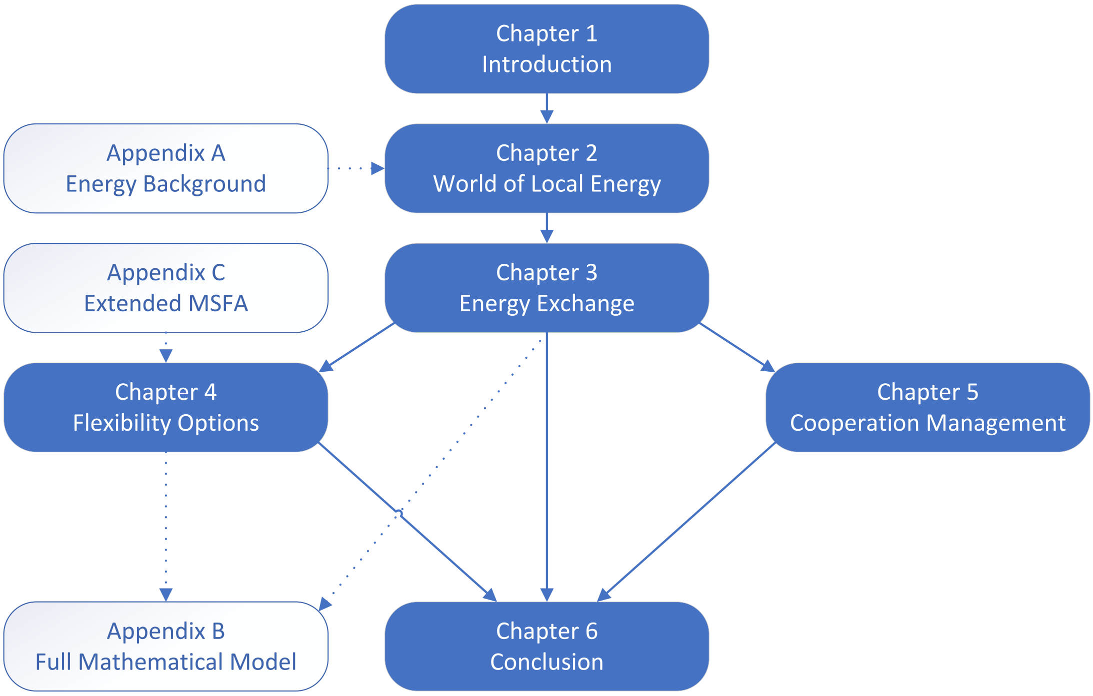


Figure **1.1**. Thesis Overview

6. 'Conclusion' addresses the research questions with view on the contributions, concludes the thesis with summary and implications, and also presents recommendations for future work.

The appendices are for further reading and for reference:

A. 'Energy Background' gives basic information on the status quo of the energy system and market designs and is recommended for readers with a limited energy background.

B. 'Full Mathematical Model' summarizes the mathematical model and notation with color-coded evolution steps.

C. 'Extended Maximum Saving Flow Algorithm' gives an overview for the extension of the maximum saving flow algorithm, without a functional charge-cycle routine.

Figure **1.1** shows the structure of the thesis in a graphical way

2. World of Local Energy

The public and political consensus on local energy management has already changed over the last decade, as it has been proven that current systems cannot cope with the already mentioned upcoming challenges. Due to the higher demand for flexibility in the system as a whole and the need for a better coordination between supply and demand on distribution grid level already, this area of research is becoming increasingly interesting. It is therefore important to define what 'local' actually means and which actors or stakeholders can appear in an environment for local energy management. The role of these stakeholders in the system and how they can help as local actors to increase the integration of distributed energy resources (DER) into distribution grids will be discussed, as well as the technical requirements that are necessary to enable such an environment in the first place. The upcoming role of prosumers and services needed to empower that kind of stakeholder is the focus of the related research, analyzed and summarized in Chapter 2.1.

The discussion about new players, changing roles, business models or the identification of stakeholders, however, can only be a first step. This alone will not lead to a better coordination of the commodity 'electricity' between supply and demand on distribution grid level. In order to achieve this, these players and stakeholders have to participate in some kind of electricity market or have to use a comparable mechanism for the coordination process of energy supply. The literature already offers a wide range of concepts, which are collected, summarized and classified in Chapter 2.2 in order to provide an overview of previous research. Finally, in Chapter 2.3, the cooperative approach which is relevant for the comprehensive analysis of this thesis is presented and differentiated from previous research.

2.1. Local Grid Framework

The rising focus on the local scope and distribution grids in recent years is primarily due to the increasing amount of available DER as more and more former consumers decide to run their own power generation. This increase is not surprising, due to the changing political and social consensus, but it is also naturally favoured by the decreasing investment costs due to technological progress. However, this does not necessarily lead to an immediate reorganisation of the grid structure or processes, even if this is unavoidable in the long term. This is mainly due to the unresolved issues of system security and stability (see e.g. Khorasany et al. (2018)), which are not automatically addressed with a stronger focus on the local scope. A bidirectional energy flow even increases the risk for voltage issues, which, together with the already volatile nature of renewable energy resources (RES), lead to a higher demand for flexibility. Congestion management is also a factor to be considered. First of all, it will be important to clarify what the term *local* is supposed to mean for local energy management in context of this thesis. As there is still no generally applicable legal definition or preference in the research literature, this is addressed in Chapter 2.1.1. After this concise discussion, Chapter 2.1.2 then takes a closer look at the different stakeholders and actors that have an influence on local energy management. Some of them are already involved in traditional systems and will therefore influence future systems to some extent, or their role could change. In the following, the technical intricacies and the proposals of current research to solve them are explained in Chapter 2.1.3 of this thesis. Chapter 2.1.4 then finally deals with a special fundamental concept for future grid design. Microgrids are basically designed so that they could supply and control a local area independently of this central grid. As a fundamentally applicable concept, this is difficult to implement due to the associated, very cost-intensive, overall infrastructure refitting requirements. However, it could certainly be used in new grid investments or partial retrofits and there is numerous literature that may intersect with the approach in this thesis.

2.1.1. Local Definition

The term *local* as an adjective is always a limiting factor. It delimits a certain part of a whole from its rest. This can be, for example, a geographical area, whereby it depends on the scale of what is ultimately to be considered local and what is not (a region, a city, a community). At the moment, there is no legal regulation that further defines or indicates a clear preference what *local* ultimately means in the context of local energy management. The obvious definition may be the geographical delimitation of an area, but this is not necessarily appropriate in this case. Such an area selection contains the risk of requiring several distribution grids and higher grid levels for the interaction and communication between local actors. To a certain extent, this may contradict the idea and the goal of local energy management to keep as much energy as possible local in order to relieve higher grid layers. It should also be noted that when operating with multiple distribution grids or even transmission grids, the communication and coordination required for safe operation becomes more complicated, as more potential actors and/or systems are involved. In this thesis, *local* therefore defines an interrelated part of an energy grid, with the maximum coverage of exactly one distribution grid area. The geographical area covered by this local grid area is not relevant. With this defined delimitation, only one distribution grid needs to be coordinated and hence only one grid operator needs to be communicated with. This is a realistic view but may change if the technical conditions allow larger catchment areas to be managed in a practicable way.

The defined delimitation leads to an local grid area that basically includes all connected buildings and their owners/occupants (local actors) within the distribution grid. This limits the number of local actors typically up to 200 (in Germany, see RONT (2011)) and leads to boundaries that provide a natural environment for local structures or entities (like markets, communities or cooperations) in which these local actors can participate. The concrete structure and process of such local structures or entities is not relevant at the moment, but will be defined later. As the physical affiliation to the grid infrastructure is the only reason for this allocation, there is no obligation for the local actors to participate in any way, but they have the possibility to do so. If they want to diversify their energy exchanges within the local grid area, each local actor should have the ability to conclude multiple contracts for this purpose. In this case, it is also possible that several communities or cooperations emerge in one local area. Moreover, the additional participation in neighbouring local areas cannot be ruled out either, despite the local focus. Figure **2.1** illustrates the connection of different local grid areas with the transmission systems and high/medium voltage distribution grids in regional or city domains. The local actors in each local grid area can now diversify their energy exchange by cooperating with each other, having the energy exchange managed by local energy service providers (ESPs), or by acting independently in this environment. A direct connection between two local actors does not have to exist, a virtual connection that can be executed through the distribution grid is sufficient. In the meantime, further microlevels are conceivable that are connected to the grid infrastructure or even act autonomously, which is addressed in Chapter 2.1.4.

The subdivision of the natural market environment created by an local grid area into

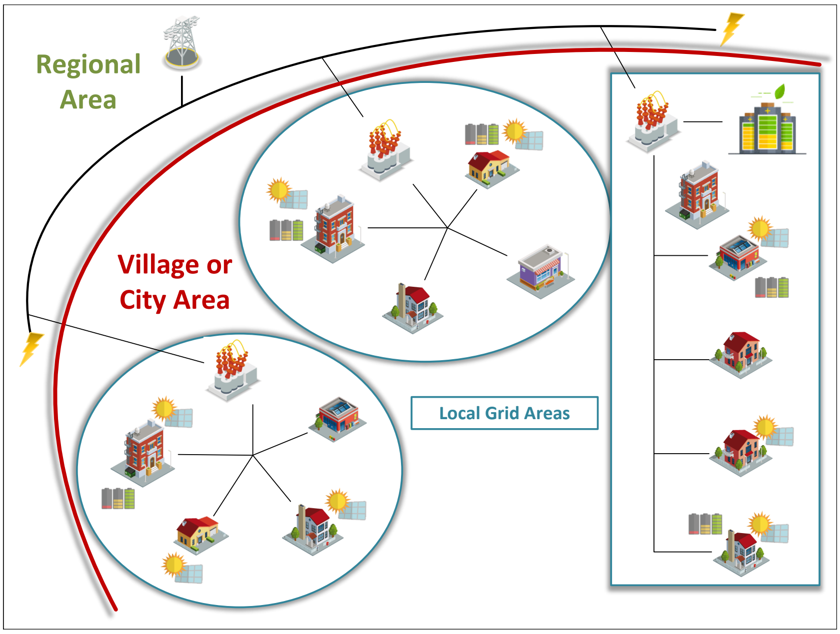


Figure **2.1**. Grid Areas

further sub-markets is theoretically possible in a liberalised energy market. Since this would mean additional coordination and communication in a comparatively small area, such a step is rather unrealistic. Therefore, this thesis assumes that, apart from the special microlevels, only one local market for energy trading is realistic for one or several local grid areas (if technically feasible). This does not mean that cooperations and communities will have a similar limitation. However, it remains also to be defined how these local players can operate in a local market environment. The commodity electricity is likely be tradable between several local grid areas, to the extent that this is practicable under the strictly necessary security aspect. Unrestricted local trading will therefore not be possible, and grid operators will be even more key as actors in this new environment than they already are in today's energy systems. Grid capacities are also limited in the local grid area and will be more heavily used in the coming years as more active end users become a reality.

2.1.2. Stakeholders and Actors

The majority of stakeholders and actors that will exist in a future framework for local grids are already part of the current grid infrastructure. Thus, they have a key influence on local energy management issues, but their role in the grid will have to change significantly in order for them to to reap the benefits of a locally oriented approach.

This section is therefore not only about describing these actors, but also to define more precisely their changing roles and to show how, at the same time, the degree of their involvement is changing.

The largest group within the current grid infrastructure with the least influence and degree of activity are **end users**. These players are usually only rate payers, pooled by retailers who offer to cover their demand at any time. If they want to feed energy into the grid, they are limited by fixed feed-in tariffs and/or that their energy cannot be processed. The possibilities of end users are therefore limited to a passive role. **Prosumers** are usually those end users who are able to generate their own energy. The term itself is also often used to refer to the *proactive* role that these end users are expected to take in the future (see e.g. Abapour et al. (2015)). In this thesis, the ability to produce energy is required to take on this proactive role. Prosumers are thus energy consumers who can cover their own or even others' energy consumption using domestic size generation modules (like i.e. PV panel, microCHP) or distributed storage (DS) solutions. Normally, a prosumer only becomes a temporary energy producer and must continue to draw part of its demand from external sources, like ordinary consumers. In the existing grid framework, though, the possibility of selling is severely limited and still imposes an already passive role on prosumers. The coming energy transition will change this and require a defined (pro)active role as suppliers of energy and the required flexibility in local grid areas. Sajn (2016), for example, differentiates four types of prosumers: private prosumers, citizen-led energy cooperatives, commercial prosumers and public institutions. A distinction is desirable in principle, but not necessary in the context of this thesis, since all mentioned types of prosumers should be integrated into local energy management. However, their fundamental influence on the system may vary due to the associated energy quantities. Instead of making a distinction among prosumers, this thesis defines **active consumers** as a separate group within end users. Unlike prosumers, they do not produce their own energy, but are able to influence the electricity flows in the grid by actively adjusting their demand. There are various approaches to this, some of which have already been researched for an extended period of time. Demand response (DR), for example, attempts to promote favourable consumption behaviour through pricing, while newer approaches focus primarily on the use of modern devices and the associated advantages of smart homes. Demand side management (DSM) aims to make parts of consumption controllable so that it takes place at preferred times without consumers suffering a loss of utility. There are also other energy efficiency programmes that consider, among other things, the storage and later delivery of electricity without own generation opportunities. However, these will not be discussed further in this thesis. The overall downside for end users is that the required active role is currently difficult to fulfil. They are not familiar with, or even able to be integrated into the current market structure, as trading volumes are far too large (see USEF Foundation (2015) and almost every other framework approach). Participation in major power exchanges and markets is therefore unrealistic. In summary, there is a need for regulatory changes, new services and market platforms to empower end users for the new role. Furthermore, the time commitment for activities in local energy management must remain moderate, as for most prosumers the potential additional income will only be a supplementary one.

The increased amount of DER and renewable energy in general has made the role of **grid operators** much more challenging. As is well known, they are ultimately responsible for the operation and stability of the transmission grid (by a transmission system operator (TSO)) or the distribution grid (by a distribution system operator (DSO)) as a system operator and must ensure a constant balance between energy production and consumption (i.e Villar et al. (2018), KUL Energy Institute (2015)). The volatile and uncertain nature of most renewable energy generation complicates this mandate and automatically increases the demand for flexibility to ensure the required stability. Ancillary service markets have so far the best way for TSOs to quickly obtain sufficient flexible capacity from large generation units. However, these services are usually non-renewable and expensive. In the future, flexibility offered by end users could help make a TSO mandate easier and cheaper. This is even more the case for DSOs, as they have a much more direct relationship with end users than a TSO. For a DSO, the coordination of local energy and the communication with new active participants naturally poses more challenges. The most crucial change in this regard is certainly the introduction of smart meters, which gives better insights for and from end users. At the same time this also implies a possible introduction of tariff differentiation for end users (i.e. USEF Foundation (2015)). By making better use of local generation and flexibility, large investments in grid capacities may in turn not be necessary or can be significantly reduced.

While grid operators have the technical responsibility for the balance in the grid, they pass on the administrative responsibility for it to the a so-called **balance responsible party (BRP)**. This important entity is an already operating actor in the energy environment. The balance responsible party (BRP) has to ensure the balance of traded energy quantities, resulting from the energy demand and the directly produced or purchased energy on associated markets (see e.g. EURELECTRIC (2014), KUL Energy Institute (2015)). Since a BRP has to pay certain penalties or finance its restoration in case of a deviation from its trading portfolio, it is their natural goal to minimise these costs caused by an imbalance. Predicting the energy load as accurately as possible is therefore essential for a BRP to ensure that the trade portfolio it is responsible for only requires few corrections. All market participants have also the option of delegating their own responsibility to a contractual partner. It is to be assumed that in a local market environment, this type of entity must also occur, since market participants will cause imbalances there as well. In this case, the local actors must now also take over these administrative responsibilities for their trade portfolio if they want to use the opportunities of the new metering points. However, considering the trading sizes of individual local actors, it can be assumed that the possibility of delegating responsibility will be increasingly used and that responsibility will initially be taken over by the market platform itself or local BRPs will be formed that are available as external service providers. With increasingly active end users and the rising level of digitalisation, on the other hand, the quality and quantity of information is also improved. This enables more accurate planning/forecasting for all stakeholders, and the potential for savings is considerably greater through the provision of appropriate energy and flexibility services.

In this thesis, the term **energy service provider (ESP)** is used to refer to a **retailer** operating in wholesale energy markets. ESPs offer to carry out the whole energy exchange for end customers at certain conditions. For this purpose, they exchange the required quantities of energy with an associated BRP or directly on wholesale energy markets, with the related responsibilities (i.e. Villar et al. (2018), KUL Energy Institute (2015)). In a local market environment, ESPs will continue to offer their services to end customers, as a basic supplier must still be present. In addition, they can counter the increased competition from local activities in various ways. It is possible that they themselves appear and act as a local actor or to simply expand their services in an attempt to directly influence or gain more information about the consumption patterns of end customers. The already mentioned DSM and DR concepts are possible approaches to such a service extension and will also be discussed in detail in this thesis. From the ESP's point of view, however, it is mainly about influencing the consumption of the end customers and thus being able to plan better. The above-mentioned concepts that make this possible include a certain incentive for the end customers if they participate, but if the ESPs have to compensate less for any uncertainties of DER or to optimise the balancing costs required as BRP, it may be more lucrative overall.

A presumably new role in a local energy environment is assigned to the **aggregator**, who is expected to act as an intermediary between individual local market participants (end users) and the energy markets in which they can participate. In literature, there are several interpretations of this role and also other names for it (see e.g., Rosen and Madlener (2013), Menniti et al. (2014) or Moret and Pinson (2019)). However, the role is seen as a key figure for future energy management and flexibility within the smart grid concept (Carreiro et al. (2017)). On closer inspection, an aggregator merely pools demand or supply to be able to trade more profitably on the market with the associated market power. In this dimension, the aggregator differs from an ESP only to a limited extent, which already bundles demand in the current market environment. This is one of the reasons why it is not unreasonable to expect that existing ESPs simply take on the additional tasks and thus additionally cover this role. Besides the bundling of the supply or demand of local end users, an aggregator is also seen as a market participant for flexibility products. The aggregator uses pooled flexibility provided by its customers also (i.e., by means of storage capacities or DR/DSM activities) in order to offer it as a service to grid operators (TSO and DSO) or (other) BRPs. However, the flexibility can of course also be used to increase their own profits, as an aggregator itself may have to take the role of a local BRP (i.e. Olivella-Rosell et al. (2018), Torbaghan et al. (2016))

Electricity markets are usually managed by **market operators** and therefore, such central figures will also appear in a local market environment. It does not matter how the trade is actually done, whether through bilateral contracts or a pool-based mechanism where offers and bids are matched until the market is cleared. Which tasks the market operator has to fulfil depends on the respective market mechanism and the time spectrum of the market type (day-ahead market, intraday market, etc.). Different terms for this are also known in literature, whereby usually only the scope of the task is narrowed down. In Chapter 2.2 this is considered in a more detailed way.

There will also be key changes for the **generation companies**, i.e. the producers in an energy system (Kirschen (2019)). Due to the increasing number of DER, they will be able to offer more of their capacity as security reserves for stability. As the provision of such reserves is usually more expensive, this competition is not considered a compelling disadvantage. On the other hand, it will also happen that generation companies themselves will increase their share of RES, on a much larger scale, of course.

This in turn increases the demand for flexibility and generation companies will certainly be able to consider investment opportunities here as well.

2.1.3. Technological Necessities

This section will give a general insight into the technical necessities of local energy management and does not claim to provide an in-depth technical analysis. Rather, the aim is to show what is necessary for local energy management concepts, such as local markets or local actors in general to become active. This includes the concept used in this thesis, which will be presented later. The fact that a certain transformation of the existing grid infrastructure is necessary in any case to realise bidirectional energy flows has been known for a long time and is therefore also part of the research. Here a reference is made to Farhangi (2010) and Fang et al. (2012), which offer a profound insight into the discussion on *smart grids*. This comprehensive term for the previously mentioned transformation process to a next-generation power grid not only uses bidirectional flows for energy but combines them with information exchange between participants. In this way, the power grid of the future enables broad communication that can better coordinate distributed energy generation and also integrate automatic monitoring and restoration processes through the use of numerous sensors. The adaptability of the grids is to be increased through the expanded control options, so that customers in the electricity grid have more opportunities to participate in it.

There are three central systems that are required for the realisation of smart grids and which are discussed in literature. The most important system is the *smart infrastructure system*. As before, it should coordinate the distribution of energy, but be able to do so more effectively. In addition, it should also enable a better exchange of information through better metering and monitoring in the grid infrastructure. This improved information exchange should ultimately also lead to the expansion of communication in the grid so that different systems, devices and applications can be used. Consequently, it is the precondition for the *smart management system*, where these devices, systems and applications are to be considered. This is intended to make effective use of the possibilities available through the expanded infrastructure. These include increasing energy efficiency in the grid and improving the balance in the grid so that fewer corrective interventions have to be made. However, additional goals such as better emission control, cost reductions in the operational management of the infrastructure and the maximum possible utilisation of existing and deployed resources are also to be addressed. The last layer is the *smart protection system*, which should not only enable processes and applications to detect potential errors in the system, but also to prevent them or, if this is not possible, to try to resolve these errors. Strengthening the reliability of a smart grid is therefore a major aspect of this system. On the other hand, the most important aspect is the protection of this new infrastructure, because as the possibilities expand, the risk of misuse, disturbances, or attacks on this sensitive part of modern life also increases. In this context, personal data protection is also an issue, with increased concerns raised.

Smart meters as an important component have already been gradually integrated into the system for years and are replacing the usual electricity meters at the end customer (see e.g. Kabalci (2016)). Hereby not all functions are actually used by the grid yet, and also the transformation is also far from complete. There are still too many unresolved issues and restrictions that need to be fully addressed (see e.g., Colak et al. (2016)), such as the privacy issues already mentioned.

2.1.4. Microgrids

In local energy management, there are two basic perspectives for future grid layouts. The most common variant involves using or expanding the possibilities of the existing grid infrastructure. The utilisation of the existing infrastructure is the economically easiest way to implement local energy concepts, as no major investments are to be expected, but only the right technical concepts (*smart grids*) have to be realised. In recent years, the research associated with this grid concept has been referred to as the 'transactive grid', reflecting the more active use of the existing grid infrastructure and providing a more holistic view of the energy transition process (see e.g., Abdella and Shuaib (2018), Abrishambaf et al. (2019)). Nevertheless, there is another perspective that needs to be discussed at least briefly, as it is already being used experimentally and could become increasingly popular in areas of grid infrastructure that are being built from scratch. The concept of microgrids represents autonomous grids that have emerged in the context of energy self-sufficient projects. Figure **2.2** illustrates that in this grid everything necessary to ensure self-sufficient control of the grid and also its security is available. Meanwhile, through an interface to the common distribution grid or to other microgrids, there is also the possibility of expanding the scope for energy trading and flexibility services beyond the own microgrid. On reflection, microgrids

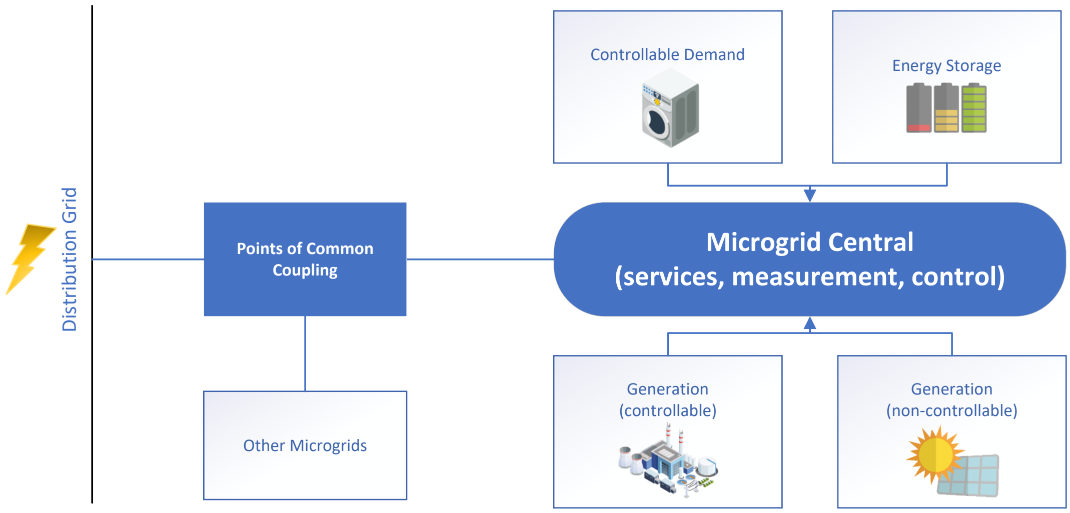


Figure **2.2**. Microgrid Environment

with a connection to the external grid are a new controllable grid level that can be located below the distribution grid.

The reason why this grid layer is also discussed in this thesis is that the existing literature addresses the so-called micro markets. These concepts can be designed to use the special and additional possibilities of microgrids, which does not necessarily exclude a general use as a local energy management concept. In Lane et al. (2013) or Faber et al. (2014), the focus is on the basic concept and how grid architecture, pricing, and consumer interaction can take place. Block et al. (2008) and Sikdar and Rudie (2013) focus their analysis on the market mechanism to be applied, while Cui et al. (2014) examine the benefits for an energy community that aims to maximise its total welfare. Densmore and Prasad (2015) on the other hand, see the investors of such a grid as a decision-relevant target group, which aim to maximize their revenues. Heidari et al. (2018), in contrast, prefer a concept of optimal management of DER within a microgrid. Menniti et al. (2014) and Shamsi et al. (2016) examine possible energy trading between microgrids, which drastically increases the scale and scope of such an aggregated market. The topic of blockchains can also be found in micro markets and is addressed by Kounelis et al. (2017), among others. The separate consideration of flexibility in micro markets is rare but possible, as shown by Nguyen et al. (2011).

The concept that is analysed in this thesis can theoretically also be used in microgrids. However, this requires a connection to the distribution grid and thus also to other higher grid levels. This is necessary because a self-sufficient 'islanded' microgrid offers little scope for the design of markets and communities. The choice and number of possible contract and business partners is severely limited in such an environment, as there is practically a natural monopoly of the grid owner. For consumers or prosumers, it therefore requires sufficient regulation or community management of the grid in an islanded variant.

2.2. Local Power Economics

At its core, local energy management is primarily about the future role of the previously rather passive private households, as they represent the majority of potential actors in the discussed local environments. Ideally, many of them are, or will, become active end users to increase the local production of energy or to provide additional flexibility within the energy system. However, in order for them to take a more active role, individual actors in local environments will need a monetary incentive to do so, like e.g., Bertsch et al. (2016) explain. Part of this monetary incentive, though, will depend primarily on how active end users are actually able or willing to be. This is a detail that is not often discussed in social studies related to the topic or marginalized by referring to information and communications technologiess and the affinity of younger generations to use such technology. This aspect will be discussed in more detail in Chapter 2.3.

The simplest solution for integrating active end users would naturally be to let this mass of potential market participants take part in the existing electricity markets. However, this simplicity is not practicable, because it has to be kept in mind that prosumers usually do not reach the trading volumes required to be active in these markets, nor are they in a position to conduct market negotiations on this scale. The first intuitive approach is therefore to form smaller sub-markets, which are now collectively referred to in literature as *local power markets*. Official sources such as the International Energy Agency (2016) and researchers such as Ilieva et al. (2016) divide local power markets into two central categories:

- Local energy markets (LEMs) trade local energy resources to achieve a proper balance between local demand and local supply, that can be realized by the given grid infrastructure.
- Local flexibility markets (LFMs) trade local energy resources to make adjustments to correct forecast errors and to ensure the stability of the local power

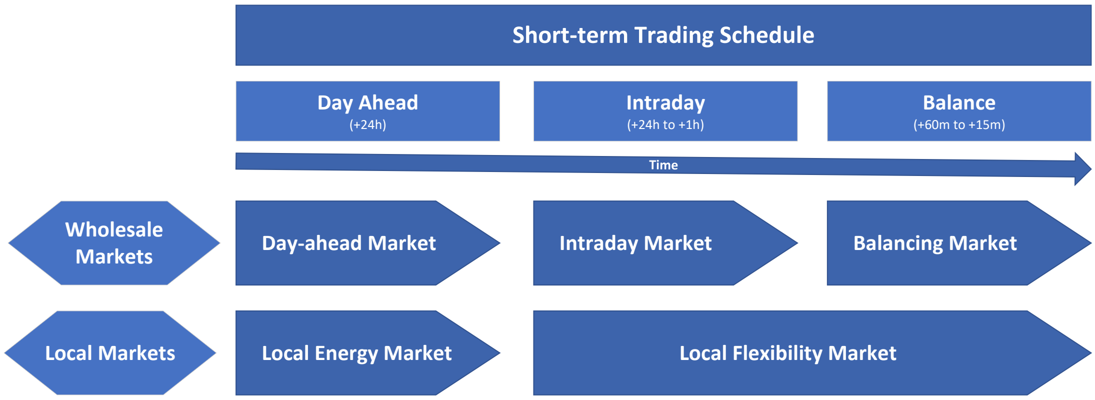


Figure **2.3**. Relation of Wholesale and Local Markets (refer to International Energy Agency (2016))

grid.

LEMs provide an effective solution for managing local resources, as e.g., Lezama et al. (2019) and Soares et al. (2014) explain. Most of the research on LEMs focuses on electricity trading. Only few publications consider heat (such as Hvelplund (2006) or Block et al. (2008)). LFMs offer a great opportunity for relieving pressure on the distribution and transmission grids by providing flexibility options for grid operators to balance generation and demand in the system (see i.e. Villar et al. (2018); Olivella-Rosell et al. (2018); Khajeh et al. (2020)). This subdivision also links the local power markets to the time structure and tasks of wholesale energy markets, as can be seen in Figure **2.3**. In the project presented by Le Cadre et al. (2019), LFMs are further subdivided and an equivalent to balancing market is defined to trade ancillary services, as in the wholesale energy market system. Local structures are thus aligned with the previous energy markets, but already due to the market participants involved they are more than just small-scale replicas. Chapter 2.2.1 is therefore dedicated to this important topic and also offers the first more extensive literature review.

Another line of research addresses energy communitys (ECs), which may have similarities with some approaches of LEM. However, the idea of ECs does not necessarily have to be based on a market concept but can also pursue other goals. In Chapter 2.2.3, this research line is examined in more detail through a literature review. A holistic definition and clear demarcation of LEMs and ECs does not yet exist, and political actors also tend to define goals and directions in which they want to develop the field. The two literature reviews are therefore intended to provide an insight into previous research, which will serve as the basis for a virtual economic unit (VEU) to be examined in this thesis. Chapter 2.3 describes in more detail the necessary assumptions and the basic concept for the environment examined in this thesis.

2.2.1. Local Energy Markets

Since the early 2000s, LEMs and their characteristics have been the subject of research. The initial focus, however, was mainly on the critical analysis of possible local market structures for energy services and their integration, as well as smaller local energy projects with wind and solar power (see Kamrat (2001) or Hvelplund (2006)). Until the 2010s, approaches were still predominantly oriented towards virtual power plants, although this concept is primarily about coordinating DERs in such a way that conventional power plants can be simulated with it. A virtual power plant pools existing supply and makes it more competitive in wholesale energy trading, as Lamparter et al. (2010) or Vytelingum et al. (2010) explain. The weakness of virtual power plant concepts is that there is no local aspect and that it only arises randomly when it occurs. When markets with an explicitly local character come more into focus, they tend to address local flexibility first, although the concepts sometimes also consider energy trading in general, as in Nguyen et al. (2011), Ding et al. (2013) or Menniti et al. (2014). Hybrid concepts for local markets trading both energy and flexibility continue to be the subject of research for the time being, as in Bayram et al. (2014) or Ampatzis et al. (2014). At the same time, the first literature is also developing for new roles within local market environments, such as the aggregator described in Chapter 2.1.2. LFMs then become an integral part of research and receive increased attention, such as in Torbaghan et al. (2016) or Pavlovic et al. (2016). Simultaneously, there is growing interest in LEMs that focus on energy trading and thus consolidate the separation of the two local power markets. The widespread attention in the last five years is mainly due to society's increased interest in the negative consequences of climate change. The extreme electricity prices in 2022 make a local perspective even more interesting for private individuals and municipalities. In Figure **2.4**, this development is illustrated by the number of sources found of the period 2001-06/2022 in different literature databases. Across all databases, on average only 23% (1507/6662) of the relevant sources have been published in the years 2001 to 2016. From 2017 onwards, an exponential increase in topic-relevant literature can be observed in all databases, with the peak in 2021 so far, thus accounting for 77% (5155/6662) of the relevant literature. The search for relevant sources is performed using the following search term: "local

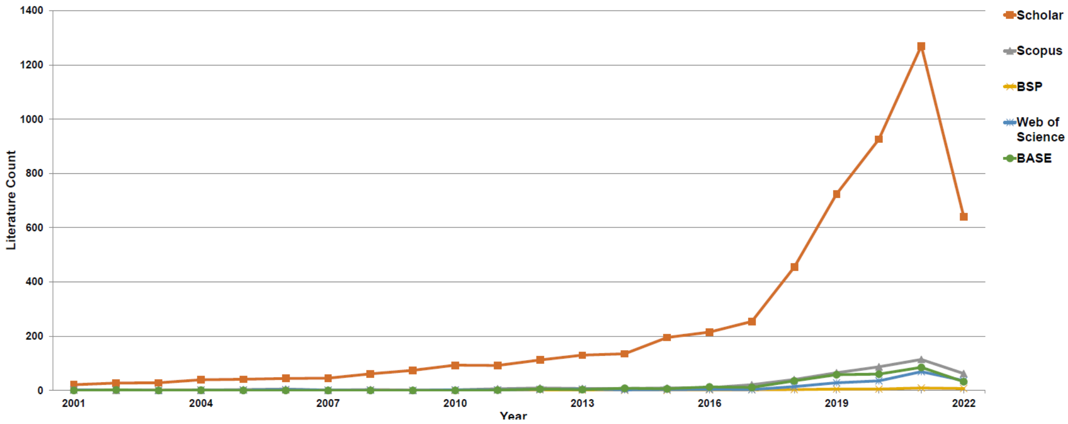


Figure **2.4**. Literature by Years

energy market*" OR "local electricity market*" OR LEM. In order to consider different types of terms (e.g. "local energy markets" or "local electricity marketplace" etc.), the terms are provided with the wildcard *. Since local electricity markets are often used synonymously in science, the search term contains the search operator OR so that at least one of the terms appears in the sources. However, sources that do not have a scientific publication focus (e.g. scripts, encyclopaedias) or that do not provide substantive content for the discussion of the search term are not used.

A more intensive analysis of the literature surveyed reveals different research priorities. Four topics stand out in particular, which are also shown in Figure **2.5**. The majority of publications, around 36% are mainly concerned with energy storage system (ESS) in local energy environments (e.g., energy storage via batteries in private households, by e-cars or via double-layer capacitors). Studies on the use of blockchains are represented with approximately 31%, although in the last years a decresing trend can be seen here. Blockchain-based LEMs ultimately do not represent a practicably implementable solution, as the computing effort required for this technology and the associated energy consumption are far too high. Load management control by DSM and DR is represented by about 26% of the publications and is discussed in the context of stability and flexibility of local power grids. The peer-to-peer (P2P) principle is also the basis of investigation in many publications, with the analysis of community-based P2P market structures, forming an alternative to purely decentralised approaches (approximately 19%), being most strongly represented. Publications focusing on cooperations within a local energy market are strongly underrepresented with less than 1%, whereas studies on game-theoretical approaches in the context of local energy markets are a bit more widespread (a total of approximately 3% for cooperative game

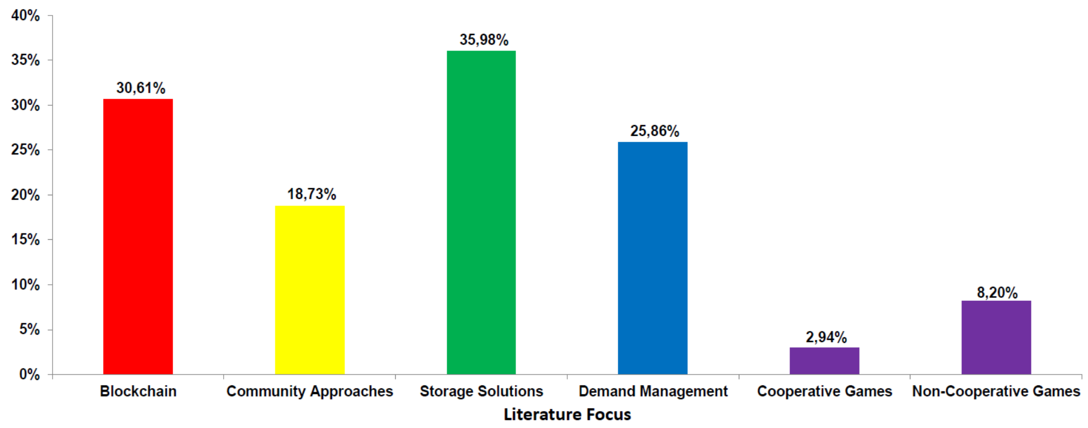


Figure **2.5**. Thematic Focus of Analyzed Literature

theory, and 8% non-cooperative game theory).

2.2.2. Local Market Frameworks

In general, a LEM is a market platform where locally generated (renewable) energy is traded to meet local demand. All potential market participants must be located in a defined local area and fulfil the technical prerequisites to participate in such a local market. The fundamental goal of this type of market is to use DER more effectively, to support grid security and to integrate local prosumers better into the energy system (see e.g., Saad et al. (2011)). There are basically two different approaches as to how the framework conditions for local energy and flexibility trading may be designed in the future. Both approaches follow the basic idea of the market mechanisms found in the wholesale energy markets. However, adapting these market mechanisms faces new challenges due to the local character of the market participants and the fact that they may not negotiate at a professional level, as Parag and Sovacool (2016) or Pinson et al. (2017), among others, show. It should be noted that depending on the market design, a different form of the bidding and clearing algorithm must be applied.

The first approach to a local market framework is based on P2P connections between two independent trading partners. Basically, this type of direct interaction is nothing more than a bilateral contract where each local market participant can trade its energy without mediation. The first work that addressed such connections in power systems is by Wu and Varaiya (1999) from the 2000s. The first concrete definition of P2P trading platforms in terms of a decentralised market follows in the work of Blouin and Serrano (2001). Due to the necessary decentralised structure for P2P trading, this area is predestined for Satoshi Nakamoto's blockchain concept, which gained worldwide attention with the cryptocurrency 'Bitcoin' in 2009.[1] After 2014, notable P2P-related publications in the energy sector are therefore mainly based on a blockchain approach. Mihaylov et al. (2014) first propose a Bitcoin-like virtual currency for trading locally produced renewable energy, while Al Kawasmi et al. (2015) suggest an adaptation of Bitcoin for trading carbon emissions. Discussions about regular trading platforms and how these approaches can be integrated follow later, as in Horta et al. (2017) or Mengelkamp et al. (2018). However, there are also highly regarded projects that have examined the topic practically, such as the Brooklyn Microgrid Project in Mengelkamp et al. (2018) or Mannaro et al. (2017) in Sardinia. These microgrid-based studies also highlight a key weakness of blockchain approaches, as they only work on a small scale due to the computational intensity and resource requirements for the associated processes. Large-scale deployment is therefore currently unrealistic, and there is also a resurgence of discussion around P2P as a non-blockchain trading platform (see e.g., Long et al. (2017); Sousa et al. (2019); Tushar et al. (2019)). Theoretically, P2P trading is a way to not only make the energy system demand-driven, but also to involve consumers more strongly and personally in managing their energy consumption in the future. Moreover, if this trade has a local character by being limited to a specific area, it can also create a sense of community in which it can be decided specifically with whom and which type of energy resource trade takes place. Jogunola et al. (2022) present a P2P-energy trading platform that, in addition to cost savings for individual participants, is also intended to maximise the economic welfare of the local energy market. The results show that dependent on the market composition[2], the economic welfare ranges between 60-85%, with a higher value increasing the overall benefit of participants in a local energy market. Furthermore, the cost savings of the participants range on average from 16% (market composition with 20% demanders) to 45% (market composition with 80% demanders). These studies thus presented underline the cost benefits for the individual market actors as well as an improvement in welfare for the entire community through participation in a local energy market. However, the studies still lack a view on the influence of seasonal changes. Another critical aspect is that all actors are assumed to cooperate although they continue to act independently on the market. This is rather unrealistic given the individual economic goals of the acting persons for the effort of energy trading.

The second group of approaches is based on the mediation of supply and demand,

[1] A more comprehensive insight into the topic is provided by Swan (2015), among others.
[2] The proportion of buyers to sellers

as in existing energy markets. All local market participants have a contract with the market to participate, but direct negotiations or bilateral contracts between traders are not allowed. A local market operator as central entity manages the market and the energy quantities traded there, usually in an auction-based system (see e.g., Vytelingum et al. (2010)). As Pinson et al. (2017) states, such a centralised approach is about pooling supply and demand, setting a market price and thus coordinating locally traded resources. Electricity thus becomes a commodity in this market that is non-differentiable. This basic principle is the same in any related publication, but the idea of how the market should function in detail and which tasks the central entity should take over varies. Rahbari-Asr et al. (2014) uses the central market operator as a regulator in a constrained market environment, while Jelenkovic and Budrovic (2015) describe the role as that of a pure facilitator, collecting offers and distributing them to demanders. Menniti et al. (2014) use a city energy provider to coordinate energy exchange between multiple micro smart grids to manage a geographical area. Khorasany et al. (2017), on the other hand, focuses on the action of the central entity as an auctioneer. In Xiao et al. (2018) the market operator is even supposed to consider social aspects and Faqiry and Das (2019) explore the idea of a DSO-based centralised approach with only aggregators as intermediate agents in the market environment. The research results on local energy markets generally illustrate that the actors involved can fundamentally benefit from a local energy exchange and that even local self-sufficiency is possible to a certain extent. Bose et al. (2021) show, for example, based on households at the same grid level, that actors within a local energy market can cover 30-41% of their required energy demand from internal resources. The internally purchased electricity quantities result in a monetary advantage for the participants, as in this use case the average electricity price across all internal energy inflows is approximately 8 cents/kWh lower. A complete renunciation of an external power supply does not seem possible at present, apart from specific microgrid studies, which have already been discussed in Chapter 2.1.4. An area-wide self-sufficient energy supply at the local level is therefore unrealistic, which is why local energy management must also expand to existing energy systems and will not replace them. In Paschalidis et al. (2012), a market-based mechanism is developed where the platform operator offers regulation service reserves for the wholesale market, meaning that there are also possible links between the local market level and the existing markets. Mengelkamp et al. (2018) analyse the development of electricity costs within a local energy market dependent on the energy production generated by PV, which can be triggered by a fluctuating number of market participants and weather conditions.

The authors show that by steadily increasing the amount of energy produced, the average total electricity price for the players decreases continuously. Consequently, there is an incentive for existing participants to acquire additional market participants. At a certain point, the average total electricity price of the local energy market undercuts the comparative price of external resources, so that participation in the local energy market becomes increasingly lucrative.

2.2.3. Energy Communities

The exact description of what constitutes an EC and how such a community can be distinguished from local markets is not yet clearly defined in the research on local energy management. The European Union also discusses ECs in the European Parliament and the Council of the EU (2019) showing that no final definition for such a community exists in this policy area, nor does it seem desirable at present. The member states are only encouraged to work out the prerequisites and framework conditions for a variety of possible communities, so that an EC can define its own purpose in more detail. Example for this are the preference for renewable energies for energy production, the scope of coordinated services between the participants (energy and flexibility) or a more flexible design of the local catchment area of the EC. Therefore, the basic direction of the EU only specifies that the community should enable local energy exchange between participants to support the EU goal of transition to cleaner and cheaper electricity. However, various repetitive key points can be found in the ideas discussed in the research and thus give at least an indication of the direction in which these communities may develop (see e.g., Koirala et al. (2016), Moroni et al. (2019) or Lode et al. (2022)). A fixed membership based on geographical affiliation or grid-related connection is usually not intended, as such a constraint on participation is unrealistic in the liberalised energy market anyway. An EC therefore consists of a collection of individually independent prosumers who join together as a group for the purpose of local energy exchange. They therefore have the technical capabilities to engage in local energy trading and are, in the best case, located in the same area. An EC differs from a LEM in that no market mechanism is required for carrying out the local energy exchange. The central entity, which is always present in these concepts, regulates how the energy exchange between the participants is carried out. This type of community manager could, of course, also make use of market mechanisms, which is why many discussed concepts cannot always be clearly categorised.

In their study, Moret and Pinson (2019) present a concept for energy communities based on a community-based energy market. They investigate the benefits derived from participants' decisions influenced by a central authority and the associated fairness in energy sharing. The authors use a decomposition-based algorithm to solve the optimisation problem. The individual needs and costs for each prosumer as well as the influence of the central entity on the benefit of the community are considered separately. If each prosumer acts alone on the market instead of joining the community and thus also acts internally, the aggregate total costs of the prosumers increase by about 328%. Moreover, the authors show that the influence of the central entity has a significant impact on improving the community's performance (additional 16% lower total costs). The community-based approach generates the best overall fairness values compared to various trading models. For example, in contrast to the individual trading approach, the investigated fairness increases by a factor of six. Capper et al. (2022) refer to these communities as community self-consumption markets. The participants in such a community, together with a central entity, conduct internal energy trading within a distribution network. The authors first state that this type of market is mainly focused on creating financial incentives for participants by trading and using locally produced energy as intensively as possible. Furthermore, according to the authors, self-consumption markets can support the formation of smaller energy communities within the energy market, as multiple operators can operate in such a market environment seeking to increase the benefits of smaller groups.

Crespo-Vazquez et al. (2019) consider the decision problem of the central entity of such communities more intensively, but include also internal and external energy flows. The authors analyse the effectiveness of the community with stochastic optimisation, since exact data on prices and the internal energy load are unknown. Additionally, scenarios with and without energy storage are considered. They show that the community enables a more effective use of locally generated energy, as the surplus can be distributed internally at lower cost (17% of local demand is met locally) with the simultaneous effect of a peak load reduction of 5%. With storage taken into account, the cost of energy supply for the actors decreases by a further 1.6%, as more energy is available for internal trade. Compared to a P2P trading model, the costs in the community-based approach decrease by 25% (with storage) and 23.7% (without storage). Further studies demonstrate the benefits of energy storage for each actor or in the local energy market. In their work, Huynh et al. (2022) show that energy storage significantly improves self-sufficiency by keeping energy locally available, thus reducing wholesale purchases and peak load. These considerations are equally transferable to mobile energy storage (e.g., e-cars), as Faia et al. (2021) show. They demonstrate that the electricity stored in e-cars both reduces the peak load and trading this electricity to other local prosumers reduces the total cost of the community by up to 3.5%.

The studies presented show overall cost advantages for such communities and how differently an EC can be structured. The central decision-maker can also be represented differently and be responsible for different tasks. The consideration of the exact costs that are taken into account is sometimes critical, as values that are not relevant for operational decision-making can also be included. This can occur when the existence of operational costs is suggested for electricity generation plants, even if these are only calculative. An example of this would be when the investment costs of PV systems are allocated to the operative costs. This leads to a distorted data-base and undermines the validity of the results. The central decision-maker can also be described in different ways and be responsible for diverse tasks. The evaluation of the study results should also be considered critically when the savings achieved by the community are analysed in more detail. If, for example, the total savings of the community only consist of the summed savings values of the individual actors, this value has no general significance for the success of the community. The total savings value only highlights that individual participants in the EC can generate an advantage, which is also possible in a LEM environment. When studies examine how the economic added value for the community as a whole can be increased, it is sometimes unclear what shares individual participants contribute to this success. This makes it more difficult to verify how an equitable distribution of these savings can be carried out. Studies addressing this distribution can be found in Chapter 2.2.4. The before mentioned studies considering participation in an EC, the individual participants no longer have any further contracts, such as individual contracts with an ESP, but that the EC manages the external energy exchanges. This creates an economic dependency of the individual participants, which is theoretically possible, but falls short in an otherwise liberal energy market. Nevertheless, the studies give a good overview of how the sector can be structured, what possibilities for diversification exist and how the community should be structured for the studies in this thesis.

Verschae et al. (2016) present an energy management model for prosumers that takes into account controlled and uncontrolled generation and consumption. Prosumers are given the opportunity to plan their consumption, but also to manage possible deviations from their plan. In addition, they should also have the possibility to help each other within a community to eliminate deviations. Chronis et al. (2021) present a review of discussed models, mechanisms and concepts related to EC in order to present their own tool. This tool is intended to investigate the economic advantages of a LEM, which is deployed in a EC. It becomes apparent, however, that the calculations are based only on the personal goals of the participants and not on the community itself. Another important point that emerges in the study is that the term EC is also used to define a boundary of the operational area rather than a concrete community.

2.2.4. Game Theory in Local Markets

Currently only a limited amount of game-theoretical studies is available for local energy management, as primarily concepts of the possible market design and the new roles are in demand. The focus on LEM in research also prefers game-theoretical studies with non-cooperative characteristics, which is why the proportion of this literature is also much larger, as Chapter 2.2.1 states. Zhang et al. (2020) present an algorithm for a community-based local energy market. The trading behaviour of both suppliers and demanders is modelled separately in a non-cooperative game to maximise the utility of each player. The suppliers set their profit-maximising energy offers in response to the amount of energy demanded by the consumers, while the consumers set their energy demand in such a way that their cost-benefit ratio is maximised. The market operator sends the data as the basis for decision-making to the respective players, whose individual payoff function depends on the strategies of the other players. This results in a classic *Nash* procedure, which is solved with the Nash equilibrium on both sides. The developed algorithm is terminated when suppliers and consumers play their equilibrium strategy. It is shown that the algorithm increases the profit of all players, since the prices obtained through internal trade are more lucrative for both suppliers and demanders than those of an external ESP. A reduction of the net load during peak periods is possible with this approach, as the demanders determine the amount of energy according to their cost-benefit ratio, thus allowing demand to be shifted to cheaper time periods. Amin et al. (2020) are developing an algorithm for linking actors in peer-to-peer energy trading so that the best possible outcome is achieved for both sides within a community. A preference list is created for each actor, listing possible trading partners in descending order of achievable profit. The algorithm then iteratively searches for a supplier for each buyer that does not have a trading partner yet and maximises the trade for both sides. A Nash process emerges in which the algorithm searches for the best response of the remaining suppliers to the best strategy of the demander, resulting in a trading contract. The authors show that all actors make a profit compared to the initial situation without the algorithm, since the external electricity price is higher than the electricity price achieved by the algorithm. In addition, the market remains stable in terms of trading contracts, as there are no contract defaults. Cui and Xiao (2020) investigate a community of buildings that can act as actors on a P2P trading platform. The aim is to assess the efficiency of internal trading as well as cost minimisation potentials for the buildings. Since the individual owners of the buildings act selfish, the developed algorithm is considered as a non-cooperative game. The Nash equilibrium is achieved here when all buildings choose one strategy and no deviating strategy choice by any actor can improve its outcome. The results show that the community can reduce dependence and interaction intensity with external actors through internal energy trading. In the non-cooperative studies, it is noticeable that authors consistently optimise the individual goals of actors and examine what individual effects occur when entering a local energy market. However, as in the presented studies, community-based approaches are stated to be investigated, although there is no consideration of a community perspective or definition of goals for a community. Furthermore, there is a lack of information on how the peer-to-peer connections are structured and regulated so that dynamic markets can emerge that do not respect the limits of the underlying physical infrastructure.

Cooperative game theory in local energy management is comparatively less represented, as competitive market designs are much more commonly studied. Nevertheless, some insights can be gained from the studies accessible so far, mostly related to ECs. Long et al. (2019) model a cooperation in which the actors engage in internal and external energy trading and additionally have access to energy storage. This decision-making is modelled by a nonlinear program, taking into account the Shapley value to achieve a stable and fair distribution of energy costs and revenues for the coalition actors. The authors compare their method with other algorithms (e.g., 'bill sharing') and find that the Shapley-based method ensures the fairest allocation and an optimal control of the batteries. In addition, this method significantly reduces the energy bills of all actors compared to traditional sales to electricity suppliers, as the internal sales price is lower. Wanapinit and Thomsen (2020) investigate the advantages of cooperating with diverse energy sources. The designed mixed-integer program aims to minimise the total costs consisting of energy import, emission and operating costs. Then, game-theoretic approaches are used to distribute the achieved cost savings in terms of the Shapley value. The results show that total cost savings of 4-11%

are possible through cooperation, and external energy purchases can be reduced by 12% without storage, and by up to 22% with energy storage. By using the Shapley values, the authors illustrate that fair savings distributions are possible in all cooperation scenarios, so that all cooperations are stable. It should be noted that in special cases the Shapley value is not in the core and thus the cooperation is not stable. Worst-case surplus minimisation or nucleolus are then tools for determining stable Shapley values, as applied by Safdarian et al. (2021), among others. Azim et al. (2021) explore a P2P trading model in a local energy market for 'Negawatts', a unit of energy saved through conservation measures and then tradable. Prosumers form communities in this market sell the saved energy among themselves and to external trading partners. The algorithm used aims to optimise the economic benefit/electricity consumption of each actor in the community and is based on cooperative game theory approaches. The simulation results show that prosumers can reduce their electricity bills by 10-21% compared to a purely DR-optimised trading behaviour. The engagement in the coalition has a direct impact on the success of the cooperation within the local P2P market. Using the core and the Shapley value, the authors show that the coalitions are stable.

It is noteworthy that the studies only focus on optimising total costs and that a full cost approach is chosen for this. This means that operationally unnecessary costs are allocated to the energy generation plant and thus included in the optimisation process. Furthermore, it is insufficiently conveyed that cooperation with suppliers and demanders in the local energy sector does not truly allow for a classical game-theoretical view of cooperation. Since both sides of a market are bundled and added value is created from this cooperation, this game also has a non-cooperative component, which is considered in this thesis. The literature review can only refer the work of Fuentes González et al. (2020) and the thesis of Fuentes González (2019), which use biform games to assess the benefits of collaborative energy projects and explore such connections in the energy sector. The cooperative component there is based on the project that can only be carried out jointly, while the participants themselves compete for electricity.

2.2.5. Conclusion of the Literature Study

In general, the literature review shows that the field of local energy management is very diversified, but a focus on LEMs is clearly evident. Mixed forms between individual local organisational forms are also possible but are rarely identified as such. This is not surprising, as the transitions can be fluid, due to the still missing clear definitions for LEMs or ECs. However, there are occasional attempts (see Mengelkamp et al. (2019)) to change this, but accurately classifying a concept and finding whether it explicitly exists in this form remains challenging. The already increasing number of publications does not simplify the classification. If mathematical optimizations are used, they are designed quite superficially and the studies are limited to simple statements on the economic added value or the market mechanism used. If, on the other hand, more comprehensive problem structures are chosen, it can be observed that subproblems are not fully identified or analysed. Influences of the individual subproblems can thus only be examined with difficulty and an incomplete analysis of the overall problem results. Holistic approaches that put the problem together piece by piece and explicitly analyse sub-problems are rare. The focus on cost minimisation for operational optimisation is also critical, as the costs used are not based on the actual costs of energy production, but are allocated from other costs, such as investment costs. However, this mixing of strategic and operative planning levels is not purposeful.

This thesis will therefore not align itself with the weakly defined constructs, but instead presents a concept that provides the desired functions that are considered realistic. However, it is not excluded that this concept is already discussed under a different name[3]. The concept itself is only a framework for achieving the primarily intended objective to provide the holistic economic analysis of such a system that is missing in research literature. The centrally organised community presented in Chapter 2.3 has a certain similarity to an EC, especially due to its cooperative nature. However, the concept is to be based on the P2P connections of the participants, as in a P2P market. In contrast, the connections are not created through interaction of the individual participants but are based on the decision by a central entity. Therefore, a hybrid environment occurs that aims to utilise the advantages of each of the concepts discussed in the research. This environment will then be used to conduct a comprehensive operational analysis of the resulting system. In doing so, from simple internal connections in Chapter 3 to the use of flexible solutions in Chapter 4, a holistic modelling concept is to be developed, which is brought together piece by piece, iteratively providing new structural insights into the system. The resulting comprehensive decision support for such a community is based on the values that are especially relevant for

[3]See Hildebrandt et al. (2024), currently under review for the Journal Energy Economics

decision-making. Finally, a first approach is integrated in Chapter 5 to discuss stability and distribution of the achieved revenues for such a cooperation. A full analysis of game-theoretic approaches is beyond the scope of this thesis, but is left for future research.

2.3. Virtual Economic Units

In this thesis, it is considered that a general VEU environment consists of a limited number of associated participants that are allowed and able to cooperate as an economically linked entity. The individual participants are located in the same local grid area, whereby a direct physical connection between every participant is not mandatory. The usage of existing grid infrastructure is therefore inevitable and makes communication and coordination with DSOs necessary. The DSO itself will have to be refunded for the use of its resources. However, consideration such a fee for the optimization of a VEU only is needed if the fee is impacted by the decision. This would be the case if the fee rate is scaled and the allocated level is settled according to the degree of usage. In practice, fee rates are usually non-negotiable, regulated or restricted by supervisors, and fixed rates are common. They therefore offer often no added value for the optimization of a VEU and thus this thesis will not consider these costs. It should also be noted that the grid infrastructure has to handle the same power flows of the participants in any case (without the VEU via the ESP). Thereby, which contractual partner of a participant ultimately exchanges which energy quantities is not relevant for the fee calculation by the DSO.

In the current energy exchange environment, it is not possible for consumers or prosumers (end users) to have multiple contract partners. As long as they are connected to the electricity grid, their energy exchange is therefore only carried out by one ESP, but this ESP can be freely selected. If no ESP is actively chosen, a basic energy exchange usually exists automatically (for example, as in Germany). This type of basic contract is usually provided by the local grid operator, who act as an ESP in this case. However, it is possible to leave the basic energy exchange and switch to another ESP at any time. In the future, it will be possible for end users to have several contractual partners in parallel and to diversify their energy exchange in this way. However, the policy proposals and objectives so far are only aim at empowering local end users to become more active and to enable more local (direct) energy exchange. These two objectives, though, do not impose any obligation on local end users. This thesis there-

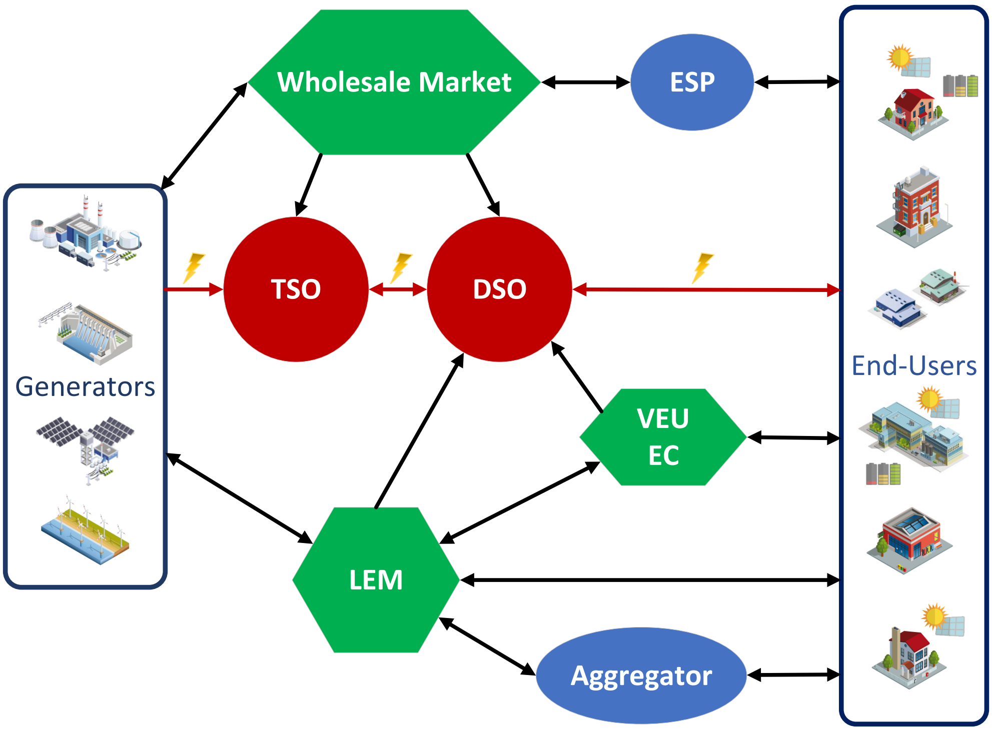


Figure 2.6. Energy Trading Scheme with Local Layer

fore assumes that, regardless of these new possibilities, there still will be some kind of basic energy exchange or basic contract partner with an ESP that ensures energy exchange for the end users. The basic contract with the ESP and the tariff conditions at hand will therefore be used as central comparison values in the further course of this thesis in order to evaluate the optimization potential. The economic connection of the participants with the cooperation and with each other is therefore of a virtual nature in two ways, which is why a virtual economic unit is created. A direct physical connection between the participants is not required and, in addition to the contractual obligations to exchange energy with the cooperation, parallel or alternative contractual partners are also permitted and necessary. There is no exclusive connection to the VEU.

Figure **2.6** illustrates the potential monetary and energy flows in a future extended energy exchange environment. As before, the energy flows (red arrows) are limited to the middle vertical axis from the generators via the grid operators (red circles) to potential end users. What is important here is the enabled bidirectional energy flow between end users and DSOs, which makes local trading possible in the first place. Theoretically, bidirectional energy flows up to the TSO are also possible with new control options. Such a supra-regional component could be used to export local surpluses to other areas. However, a trading like this requires interaction with a wholesale market, which is usually not available for local actors. In this thesis, due to the focus on local energy management, this approach is not further analyzed. The actors in the figure that are not involved in the physical energy flow only trade the commodity electricity (black arrows for monetary flows). Traditional energy trading is depicted in the upper vertical axis and shows how large generators and ESPs trade their energy quantities on wholesale markets in order to meet the demand of end users. The wholesale market participants are naturally also BRPs and have to pay penalties to the respective grid operators for deviations from their planned and submitted energy portfolio but are able to delegate their responsibilities to external services.

The local trading opportunities are shown in the lower segment of Figure **2.6**, with the LEMs as the central market platform on which end users can become active, either personally or aggregated via *aggregators* or community-based cooperations. For the locally traded energy quantities, this thesis assumes that there has to be a localized BRPs, who are responsible for the portfolio. This can be the LEM (operator) or local communities like ECs and VEUs. Although such communities also aggregate end users and thus should be able to trade their energy quantities at a LEM, they are also able to manage the energy quantities of the participants themselves. Therefore, this thesis assumes that a community will be responsible to the grid operators for these self-organized energy quantities. It also follows that more active end users or a VEU will have to take more risk for the opportunities gained in the future. This is not necessary in traditional energy trading for end users, as the ESP bears the full risk of the contracting parties. For a usual, long-term guaranteed tariff, the ESP offers end users to fully exchange their electricity at any time. However, the ESP does not have access to the exact data and plans of an end user, so the ESP estimates consumption and production in case of uncertainty. Price differences in wholesale energy markets therefore have a direct impact on the ESP's profit margin, and in case of deviations from the forecast energy quantities, the ESP pays the corresponding penalties. Now, the more active end users become, the more of this risk they must take on themselves for the potential savings or returns. They will then bear the price risk and will also be penalized for deviations in the traded energy quantities. A community such as a VEU will even have to act as a local BRP for energy quantities it manages directly. How the community passes on or distributes any costs of this responsibility is relevant for participants of such a community.

Summarized, active end user will either have to bear more risk or at least share information and data with central operators like *aggregators* or their community platform like a VEU so that they can reduce their risk. The inevitable acceptance of these risks is another reason why this thesis assumes that there still must be risk-free basic services provided by ESPs. Moreover, it is highly questionable to assume that this central and lucrative business segment of ESPs will simply be abolished in the future. The political will to enable local competitors and thus increase competition in general seems realistic, but not the closure of an entire business sector.

2.3.1. Cooperation Characteristics and Objectives

As an economic entity, the goal of a cooperation such as the VEU is to maximize the possible overall revenue for the whole community, and thus all participants. In a traditional cooperation, this would mean that a group of suppliers or consumers in a market environment join forces in order to maximize their profits or minimize their costs, respectively. A VEU, in contrast, is a hybrid cooperation that aims to pool supply and demand at the same time. In this case, participants are able to use their internal resources to meet their needs before using external sources when this is more profitable. The VEU concept allows such a revenue-orientated hybrid cooperation between these heterogenous participants by considering P2P connections. Unlike a P2P market, individual negotiations between participants in a VEU are prohibited and a central decision on preferred P2P connections between two individuals is enforced.

The central decision maker in a VEU is defined as central unit operator in the further course of this thesis. It has to be ensured that such central decisions are both optimal for participants and achieve the highest possible total revenue for the entire community. This form of energy exchange mechanism cannot actually be classified as a classic energy market, as the participants do not place individual bids. The clearing of trading volumes, on the other hand, can work in exactly the same way as in a classic two-sided auction mechanism in the clearing phase. Instead of the determination of a market clearing volume and market clearing price (as described in A.3) a VEU relies only on the P2P connections to clear the internal energy trade volumes. The decision which P2P connections should be established on is based on the potential savings of a connection which is determined by the difference of the individual tariff values in the contracts of the participants with their ESP. Due to the focus on the operational management of a VEU, this is the only appropriate basis for decision-making, as long as the energy generation has no variable production costs to consider (which is the case for photovoltaic (PV) or wind sources).

This deviates from the widespread use of full cost accounting for decision-making in this research area. Allocating strategic costs and using such values in operational optimization leads to misleading decisions. The goal of operational planning must be to use the best possible resources for operations in such a way that the best possible result can be achieved. Strategic costs (such as investment costs) have been weighed in strategic planning and are no longer relevant. This thesis therefore only considers production or generation costs if they are relevant for decision-making. Valid operational insights are also important for strategic decisions in the future, because their operational values serve as the basis for a meaningful decision there.

For the energy exchange mechanism of the P2P connection, each participant will be classified in one of two groups at any given time, either as an energy consumer or an energy supplier, depending on their current individual energy load. It should be noted that this implies that an allocation change of a participant is possible over time, but not within the same point in time. Thus, a supplier cannot decide to be a demander instead. It is further assumed that a customer's personal energy demand must be served first if local energy generation is present, implying that no participant can be in both groups at the same time. In case no supplier is present at a specific point of time, no energy exchange mechanism is needed in that time period. This system aims to predict the likely individual profit and information use to convince potential participants to join. However, as the participants remain independent at the same time, it is essential to know their exact impact on the VEU. This impact consists of their isolated performance and/or additional contributions to the achievement of the overall revenue objective. Knowledge of detailed information for each participant is an important input for economic decisions in this cooperation entity, as it is crucial for negotiations among themselves or with external parties. The VEU concept developed can be applied to various economic cooperation problems where aggregation of resources is an essential part of cooperation, but individual influences also play a role. It therefore also combines the cooperation aspects of an EC and the allocation advantages of a P2P market.

2.3.2. Options of Bundled Presence

In general, the aim of a community or cooperation is to increase the market position or negotiation power through the bundled presence. The concept of a VEU as an economic entity with a bundled presence is no exception to this possibility, as in principle it is an option for such a cooperation to actively participate in local markets or to act as the sole contractual partner to an ESP. Due to the partial independence of the participants, the latter option is not very likely to be considered. As a result, participants would have to bind themselves more strongly to the community and would still be obliged to only one contracting party, which counteracts the desired diversification of energy exchange. A function of the VEU as a single contracting party is also not beneficial for the ESP involved which would still have to bear the price risk of the markets, but could be forced to make concessions due to the greater negotiating power of the community. Above a certain size of the community or the amount of energy negotiated there, contracts with more flexible tariffs are an option, but then the ESP could be completely omitted and the community itself is directly responsible for the entire energy exchange of the participants. The potential influence of such a function of the VEU is thus not a purposeful examination object for this thesis and will be neglected.

The concept of actively participating in local markets with the VEU, on the other hand, can be much more expedient. The reason for this is that in addition to managing the internal energy flows, a likewise local option can be used to further increase the savings of a VEU. However, for a detailed and meaningful analysis of this external option, a definition of how local markets will ultimately function and available price data as comparative variables are missing. Derivation from wholesale prices is not expedient here, nor is the knowledge that the day-ahead concept of the common energy markets is very likely to be adopted. The focus of this thesis is on the internal energy flows and the implications for the local energy management of the VEU itself anyway, so a larger investigation of external possibilities is therefore beyond the scope. Nevertheless, it is a useful reference point to examine what impact the optimization of internal energy flows will also have on possible external connections. This is therefore discussed in Chapter 3.2.

In the end, a VEU must ensure an equitable distribution of savings between participants according to their contribution to the result achieved. This is less of a problem in markets where it is more the trade prices that need to be addressed and how they emerge. For potential participants there is no incentive to join a VEU if there is no improvement in their own monetary situation after entry. This will be discussed in the case studies in each step of the thesis, but will be analyzed in more detail in Chapter 5.

2.3.3. Consideration of Uncertainties

In the course of the thesis and in future practice, a number of uncertainties cannot be avoided since energy quantities can only be predicted to a certain extent by active end users. In market-based scenarios, occasional strongly fluctuating energy prices have to be considered, which entail additional risks, but also opportunities. ESPs are basically active aggregators of demand so far and rely on economies of scale because they can only forecast the demand of the individual household with difficulty. This can change with a longer affiliation of a customer to the individual supplier, as the supplier then has more data available compared to a new customer. Apart from this, it is possible for the ESPs to use the average energy quantities of an area in such a way that, with adjustments from the data of their own customers, a robust planning for their interactions on the energy markets can be set up. If an ESP has many customers in the same area, individual deviations of the customers are less decisive for the total forecast energy quantity and thus the risk of having to accept an overall deviation that needs to be corrected also decreases. A VEU, on the other hand, will have to use rather small-scale planning and has to analyze the local energy quantities very precisely. The background to this is that the number of participants will be smaller and balancing effects in the forecasts cannot be used to the same extent. In return, though, theoretically more data is available to the VEU if the participants accept this for their own additional purpose. The more detailed planning of a VEU thus has concrete advantages, because energy flows can be allocated more precisely and it is possible to act or react better. Nevertheless, for good planning it remains inevitable to define concrete steps on how to react to the uncertainties present in the system.

The fluctuations in energy quantities, which are also relevant for this thesis, are amongst others also addressed in literature with stochastic models (see e.g., Tsaousoglou et al. (2022)).

and are thus also an option for a VEU. It is quite practicable to run through different scenarios and on this basis make a weighted decision or a decision weighed according to risk affinity. In the energy sector, however, the possibility of forecasting methods is often used in order to be able to subsequently use deterministic values. Deterministic values offer various advantages in the possible design of problem-oriented decision support and optimization models, both in terms of time-criticality and methodological possibilities. The problem structure that is the objective of the analysis, however, also sets limits here or demands formulations and methods that can be disadvantageous in turn. This is also the reason why this thesis first limits the entire problem structure that can be considered in a VEU to essential components in order to then iteratively expand them. The formulations are intended to represent the core of the extensions and offer further insights for an ultimately comprehensive overall view. For this purpose, the thesis also applies forecast-based deterministic values for its case studies and the decision support models provided are also designed to benefit from this type of data provision.

The quality of forecasting methods obviously has a significant impact on the planning in a system as it ultimately depends on it. However, the focus of this thesis is not on developing a method for providing the best possible forecasts as this is already an integral part of other research and therefore the forecasts in this thesis are based on this research. Nevertheless, an overview of alternative possibilities will be given before the applied method is briefly described.

In some literature, a distinction may be made as to whether the techniques applied are more for short-term and long-term forecasting. However, basically the methods can be used in both cases. The two dominant methods here are approaches based on regression models as in Bacher et al. (2009) or Ghelardoni et al. (2013). The latter use a new procedure for a long-term forecast in which they use the empirical mode decomposition method to split the time series into two sets. This serves for the use of trends and local oscillations of the energy consumption values separately. These two sets are then used to train a support vector regression model. In recent years, the use of neural networks as a method for short-term forecasts has been increasingly investigated. Bakker et al. (2008) use neural networks techniques to predict the heat demand of individual households needed to determine the energy production of microCHP plants. Ravichandran et al. (2016) also rely on an artificial neural network based energy forecasting model to model the plants of a virtual power plant. Jogunola et al. (2022) show the current state of research in this area and present a hybrid deep learning framework to forecast the energy consumption of different building types. Commercial and domestic buildings are considered and even different countries are investigated.

For this thesis, the profile generator, based on the studies from Hoogsteen et al. (2016) is chosen to generate the energy load profiles of the VEU. With this tool it is possible to select different input data directly. These include the number of days to be simulated and a randomization seed. The penetration of the PV systems among the participants can also be selected and, for some special devices their concrete consumption values[4] can be specified. Which participant has a PV system is randomly assigned based on the penetration selected, the orientation on the roof is randomly chosen using a truncated Gaussian distribution within predefined bounds. The geographical location of the neighborhood can also be specified, as well as the composition of the neighborhood, whereby households can be categorized into seven different household types. For each household or each resident simulated there, an occupancy profile is defined by a simple behavioral model. The exact schedules of the occupants are generated by a truncated Gaussian distribution, which is also used to determine the power consumption of non-controllable appliances. The PV equipment is randomly distributed over the households and the orientation on the roof is randomly chosen using a truncated gaussian distribution within predefined bounds. The settings for a possible data generation of electric vehicle (EV) and ESS are not used in the thesis, but generated separately. The large selection of possible settings and good forecast values leads to a well-differentiated database with realistic values for the case studies.

[4]This is due to the actual purpose of the generator for DSM studies.

3. Energy Exchange

The virtual economic unit (VEU) as a community should be able to control and distribute the internal energy quantities of its participants in such a way that, primarily, an economic added value can be generated and this energy is used more efficiently locally. As long as the participants give the necessary permissions and the technical conditions are given, the direct internal energy exchange through peer-to-peer (P2P) connections between these participants provide the basic opportunity to influence energy flows within VEU. In Chapter 3.1, therefore, the key part of the approach developed for this thesis is designed and investigated with reliance on these P2P connections and without any other impacts. The focused consideration on the core property shall allow further conclusions on possible extensions and eventually external connections that a VEU could also enter. External energy exchange, away from basic contracts with an energy service provider (ESP) means active trading of internally available resources through probably bilateral contracts or auction mechanisms, as they are common in the energy sector. However, due to the unavailability of local power markets, and since a VEU will not operate in wholesale markets, an intensive investigation of operational possibilities in this area is only speculative. Chapter 3.2 therefore investigates whether the insights of internal energy exchanges can be used for a generalized strategy in external markets.

3.1. Internal Energy Exchange

The internal energy exchange, and thus the possibility to manage the energy of the participants locally, is a basic scenario type for this thesis. This basic setting breaks down the overall system to the simplest core task and initially allows only one deviation from the previous energy exchange with the individual ESP of the participants. Here, internal means that only participants of the VEU are considered and the bundling of the internal supply is used only to satisfy the internal demand. Demand or supply that is not internally used is then handled by the ESP of the respective participant. The formulation developed for this purpose is intended to serve as a basis for the further modular design of the system, when the VEU and the participants are given more options to make the energy exchange more efficient. For this, the optimization problem is first presented using the mathematical formulation in Chapter 3.1.1, before the structure is analyzed in more detail in Chapter 3.1.2. The goal of the analysis is to learn more about the structure of the problem and provide a more efficient algorithm that can exploit this structure, and by that making it applicable to more complex extensions. Subsequently, the model and algorithm will be used for a case study in Chapter 3.1.3 to investigate the economic implications of the system with realistic data. The findings of the studied internal energy exchange are then summarized and discussed in Chapter 3.1.4.

Chapter 3.1 is based on joint work conducted by
Benjamin Hildebrandt, Johann Hurink and Michael Manitz,
accepted and published in Journal *Energy Economics*,
cited here as: Hildebrandt et al. (2024).

3.1.1. Basic Optimization Problem and Mathematical Formulation

In this section, we present the basic model for the optimization of a basic VEU environment. Given is a set, N, of associated participants of the VEU, which are all in the same local grid area. The core objective of the VEU is to support the local consumption of energy generated within the VEU, which supports a better integration of locally generated energy and avoids grid congestion. The model assumes a planning horizon which is discretized into T periods, where every period $t \in \mathcal{T} := \{1, \ldots, T\}$ represents a time interval of $time$ minutes. In each period, participants have a given individual demand or supply of energy. Note that these values are the essential parameters of our problem. They are in general not exactly known during the planning phase, and therefore predictions have to be used for these values. Note, that there are many possible approaches to obtain such predictions (see e.g., Hahn et al. (2009); Keles et al. (2016); Ghelardoni et al. (2013)), however, these predictions are beyond the scope of this research. We denote the predicted load of participant $n \in N$ for time period $t \in \mathcal{T}$ by $pl_{t,n} \in \mathbb{R}$, where negative values represent energy demand, and positive values energy supply.[1]

[1]Note, that the personal energy demand of a participant is always served first when local energy generation is present, implying that no participant can have supply and demand at the same time.

In the initial situation, each participant n trades its energy load $pl_{t,n}$ with an external ESP based on the conditions of its individual service contract. This contract specifies the individual tariff conditions for the purchase or sale of energy. We assume different prices for purchase and sale (common practice in most countries), and we also consider prices per unit which may depend on the amount of energy (which is assumed to be common practice in the future). Finally, the individual contracts of the participants may differ from each other and may also depend on the time period. Formally, for participant $n \in N$ and time interval $t \in \mathcal{T}$ these tariffs are defined as follows:

$$v_{t,n}(pl_{t,n}) = \begin{cases} sr_{t,n}(pl_{t,n}) \cdot pl_{t,n}, & \text{if } pl_{t,n} \geq 0 \\ dr_{t,n}(pl_{t,n}) \cdot pl_{t,n}, & \text{if } pl_{t,n} < 0 \end{cases} . \tag{3.1}$$

Hereby a distinction is made between the individual supply rate $sr_{t,n}(pl_{t,n})$ and demand rate $dr_{t,n}(pl_{t,n})$. These rates depend on the amount of supplied or demanded energy $pl_{t,n}$ and, in general, the supply rate is smaller than the corresponding demand rate, i.e. $sr_{t,n}(x) < dr_{t,n}(y)$ for all $x > 0$ and $y \leq 0$. Based on the given loads of the participants, the initial balance of the VEU for the whole planning horizon can be calculated by summing up all values of $v_{t,n}(pl_{t,n})$ over all time periods and participants.

The aim of the cooperation now is to improve this initial balance by coordinating P2P trades between the supplier subset $s \in S_t \subset N$ and consumer subset $d \in D_t \subset N$ in a period t. To achieve the best possible balance value in this constellation and to reach the optimal system state (i.e. a maximum cost reduction or increased earnings for the overall VEU), a coordination of trades is necessary. We call this the *energy load adjustment* (*ELA*) mechanism, which decides how much energy is exchanged between the participants. We denote these amounts by $bal_{t,s,d}$ and they form the decision variables of the ELA. As mentioned, we only allow energy flows between the supplying and the demanding side, but not within the same group. As a result, we get a set $B_t = (S_t, D_t)$ of all possible pairs where energy may flow in a period t. At the end, if we sum up all inflows or outflows of a participant $n \in N$ in period t and offset them with the predicted load value $pl_{t,n}$, we get the optimized load $ol_{t,n}$ of participant n in period t. More formally, we have:

$$ol_{t,n} = pl_{t,n} - \sum_{(n,d) \in B_t} bal_{t,n,d} + \sum_{(s,n) \in B_t} bal_{t,s,n} \quad \forall\, n \in N, t \in \mathcal{T}. \tag{3.2}$$

Note, that dependent on whether n is a supplier or consumer in period t, one of the two sums will be zero. As these optimized loads $ol_{t,n}$ are the loads which get purchased from / and sold to the external provider, the objective function for the ELA mechanism results by replacing the predicted energy load values with the optimized ones. If we then maximize the sum of these computed values, we get the optimized balance value of the VEU for the given planning horizon:

$$\max Z = \sum_{n \in N} \sum_{t \in \mathcal{T}} v_{t,n}(ol_{t,n}). \tag{3.3}$$

As mentioned, we do not allow arbitrary ELAs between supplier and consumer but restrict these flows in such a way that during a given period no participant changes its role (i.e. you can only sell your surplus of energy or buy your deficit of energy from other participants of the VEU). This can be considered as a reasonable restriction as otherwise the participant with the best conditions could purchase the whole energy demand of the VEU by its external ESP and distribute it via the ELA mechanism. We can integrate this constraint by adding inequalities, which are modifications of an open transportation problem Bazaraa (2013):

$$\sum_{d \in D_t} bal_{t,s,d} \leq pl_{t,s} \qquad \forall\, s \in S_t, t \in \mathcal{T} \tag{3.4}$$

$$\sum_{s \in S_t} bal_{t,s,d} \leq -pl_{t,d} \qquad \forall\, d \in D_t, t \in \mathcal{T}. \tag{3.5}$$

The resulting model allows every participant to have various connections to other participants to satisfy or to provide demanded energy load in the VEU, depending on their associated role in a given period. Note, that dependent on the given situation, the presented model can easily be extended to incorporate other technical or economical constraints.

In addition, the achieved coordination of energy trades will not affect the overall amount of energy load of the VEU in each time period but reduces the amount of energy load the individual participants exchange with their external ESP. As such, implementing the solution of this problem for a given time period does not directly support keeping energy local. However, having an integrated look at the optimization problems of different time periods may give a participant insight how cost savings may be achieved by moving loads or demands between time periods. To allow this, it is crucial to have good structural insights into the solutions for the basic ELA mechanism.

Since the introduced model introduces no correlation between the different periods, it is possible to solve each period individually. Furthermore, due to the resulting bipartite structure in each period t, there are interesting properties in this structure that we consider in more detail in the next section.

3.1.2. Maximum Saving Flow Algorithm

In the model for a basic VEU introduced in the previous section, we can solve each of the periods separately. The resulting problem for each period can be categorized as a modified minimum cost flow problem (see e.g., Bazaraa (2013)), with restrictions as given for transportation problems but with a specific objective function. In the case that the objective function is linear, this structure allows us to develop a very efficient algorithm, which also gives a solution fulfilling some other important properties. Therefore (from now on) we consider $dr_{t,n} \mid n \in D_t$ and $sr_{t,n} \mid n \in S_t$ to be independent of the energy amount $pl_{t,n}$, i.e. they are constant for time period t.

Note that now the problem under consideration is, at its core, a simple two-sided market for which basic mechanisms such as auctions can be used to determine the market clearing price and the corresponding market volume for the given period. However, this does not specify settled direct trades between suppliers and consumers, but only trades between the participants and the market, which means that no concrete peer-to-peer trades are determined. Although this may not be seen directly as a problem, it is the core of several disadvantages. On the one hand, due to the smaller number of players involved in such local settings, the market clearing price can react quite sensitively to minor changes in the given load values, as these changes can mean a swap of the market clearing price from the cost parameter of one participant to that of another participant. This is considered a drawback and gives individual participants or small group of participants some possibilities to influence the market clearing prize. On the other hand, since the difference between purchase and sales prices is generally quite large, market-clearing prices are much higher in the case of demand overshoot than in the case of supply overshoot, which can be seen as an undesirable discontinuity in the market setup of a local VEU.

To overcome the disadvantages of a direct two-sided market approach but still reach the same maximum cost reduction or increased earnings of the VEU, we propose a market mechanism which also specifies exact allocation of trades between suppliers and demanders (which in the mentioned auctions, is not needed). Thereby, this allocation is chosen in a way that allows for a wider range of internal price mechanisms within the VEU, including mechanisms that are less sensitive to changes in individual supply and demand values and individual prices. In particular, if a VEU decides not to allocate revenue via the market clearing price but via a fixed allocation of shares in the settled trades (possibly even including a share for the VEU), the exact allocation is mandatory. In summary, the advantage of the proposed allocation over a distribution by a market clearing price is that it determines a specific allocation of trades from the set of all possible allocations leading to the maximum savings of the VEU. This effect allows a broader spectrum of internal mechanisms of settling the payments and earnings, which are more robust against distribution-related manipulations.

In the following we first consider the optimization problem of a VEU for a single period and formulate it as a modified minimum cost flow. For a given period t let $G_t = (N_t, E_t)$ be a bipartite network with node set N_t representing the participants of the VEU. As mentioned in Chapter 3.1.1, the participants can be divided depending on their role as supplier or consumer in period t; i.e., we have $N_t = (S_t, D_t)$. Furthermore, for each node the corresponding supply or demand is specified which limits the total possible energy flow on edges out or into a node. The edge set E_t in turn represents potential energy trades between possible pairs of suppliers and consumers implying that $E_t = \{(s,d)|s \in S_t, d \in D_t\}$. With every edge $(s,d) \in E_t$ an individual saving rate $w_{s,d,t}$ is associated, which reflects the advantage of an energy flow of one unit between s and d in t; i.e. how advantageous it is to trade energy via this connection for the given time period t. This rate depends on the difference between the demand and supply rates of the associated participants (nodes) and is given by $w_{s,d,t} = dr_{t,d} - sr_{t,s}$. As we look at each period individually, the resulting structure for every saving rate matrix $w_{t,s,d}$ is that of a transportation problem for which a maximal overall saving has to be determined.

The specific bipartite structure of the above problem incorporates a useful property. More precisely, a saving rate matrix $w \in \mathbb{R}^{a \times b}$ is a Monge matrix, if it fulfills the following Monge property (see e.g. Burkard (2007)):

$$w_{sd} + w_{s'd'} \leq w_{sd'} + w_{s'd}, \; 1 \leq s < s' \leq a \; ; \; 1 \leq d < d' \leq b \tag{3.6}$$

If we sort the supplier nodes $s \in S_t$ in ascending and the consumer nodes $d \in D_t$ in descending order of their associated tariff parameter $sr_{s,t}$ or $dr_{d,t}$, it is easy to verify that this sorting procedure leads to a saving rate matrix w that fulfills the Monge property. It is known, that some problems become particularly easy for Monge matrices, like the already mentioned transportation (network flow) problems, as they can now be solved by a simple greedy procedure. For our specific problem the optimal solution can be computed in $O(n + m)$ time, similar to the *north-west corner rule* in a transportation problem (see e.g. Burkard (2007)). Before we discuss the resulting algorithm in detail, we show the sorting procedure with a small example. For this, the following associated and sorted tariffs $dr_{t,d} = \{(30, 29, 28, 27, 26)\}$ for the demanding side and $sr_{t,s} = \{(10, 11, 12)\}$ for the supplying side are given. The corresponding saving matrix $w_{s,d,t}$ is presented in Table **3.1**. Note, that the resulting matrix is sorted lexicographically.

$w_{s,d}$	d1	d2	d3	d4	d5
s1	20	19	18	17	16
s2	19	18	17	16	15
s3	18	17	16	15	14

Table **3.1**. Example of a Sorted Weight Matrix

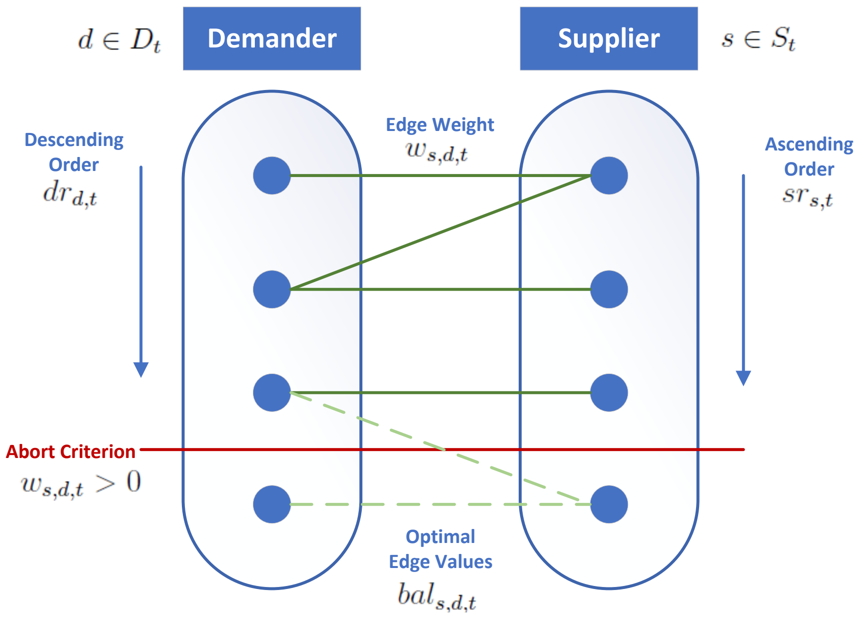


Figure **3.1**. Maximum Saving Flow Algorithm

To solve our problem, we can now take advantage of the Monge properties and the structure of the pre-sorted saving rate matrix $w_{s,d,t}$. In an iterative approach we select the most profitable edge $(s, d) \in E_t$ which is always the node pair in the north-west corner of the saving rate matrix $w_{s,d,t}$. As long as the saving value of this possible connection is positive $(w_{s,d,t} > 0)$, we establish this edge. Otherwise, we can terminate the algorithm since also all other node combinations cannot yield a positive saving hereinafter. For the established edge, we determine the maximum possible energy flow value $bal_{t,s,d}$ of this edge, which is given by $min(pl_{t,s}, pl_{t,d})$ and assign this flow to the edge. Additionally, we update the remaining available energy supply/demand of the two involved nodes s and d. Note, that this implies that at least one of the nodes will get saturated, meaning that its pl-value gets 0 and that the corresponding row or column in the saving rate matrix $w_{s,d,t}$ can be deleted. Therefore, in the next iteration again, the edge $(s,d) \in E_t$ in the north-west corner of the saving rate matrix w is the most profitable to establish. The Monge property ensures that in this way we get the optimal solution for the considered period, i.e. the optimal values for the decision variables $bal_{t,s,d}$. It is worth mentioning that this procedure does not lead to crossed edges between the two sets (see Figure **3.1** for a visualization of the algorithm based on the underlying graph structure). Furthermore, it is not necessary to compute the whole saving rate matrix for the algorithm, because the sorting procedure ensures we need to consider only the value of the current north-west corner.

The Monge property and the possibility to use the North-West Corner Rule lead to another positive side effect, besides the fact that in each step the trade with the remaining maximum saving is settled. Moreover, market participants have no incentive to choose other, still possible trading opportunities as long as the market rules for determining the distribution of savings among the participants involved in a trade are monotonically increasing in the total savings for both participants. Note, that this is the case when both participants get a specified percentage of the savings, but also the case when a market clearing prize is used. Furthermore, note that in case the participants get a specified percentage of the savings, the resulting solution is a stable solution in two aspects: on the one hand, no pair of participants exists which by a bilateral agreement have an incentive to change their trading scheme (not both can get of better at the same time), and on the other hand, a small change in the supply or demand values of individual participants can not lead to larger changes in the payment schemes. This robustness is an important property for such local market schemes or particularly for cooperations, and is not given when an auction-based scheme is used.

3.1.3. Case Studies

In the previous sections we presented a basic model for a VEU and an efficient corresponding algorithm to determine the optimal energy flows within the VEU. In this section the aim is to evaluate this VEU concept for realistic scenarios, so that we can analyze how much local energy trading is possible, how and which parameters influence the market volumes and to what extent the VEU can benefit from the local trade. To achieve this goal, we determine the operational outcome of a VEU in different seasonal scenarios (one scenario for each of the four seasons) and in scenarios which differ in the composition of the local market. For our case studies we generate a heterogeneous composed VEU that consists of 100 participants. All of them are connected to the same local part of the distribution grid and have a contract to purchase their energy consumption or to sell their energy production via an external ESP.

In order to work with realistic scenarios, we create energy load profiles for the participants by a profile generator, based on studies from Hoogsteen et al. (2016). To get a good diversification of the household structure, we use all provided profile types which the generator offers (they differ in household size and the work status of the residents). For each scenario we create energy profiles for 3 days subdivided in intervals of $time = 15$ minutes resulting in 288 time periods. For the local generation of energy we only consider photovoltaic (PV) panels. In our basic setup, only 50% of the participants are equipped with this supply option. To examine the influence of the market composition, in a second step, we vary this fraction of suppliers within the VEU to 25% and 75% for two of the seasonal scenarios. In the base scenario storage options are not included at all. Finally, the climate data used is based on the Berlin area[2].

For the economic part we use individual linear tariff structures for each participant, which are based on a triangular distribution. We want to achieve not only similar price levels for all participants in the planning horizon, but also a realistic price diversity between the individual participants. The mean value for this distributions is based on the average purchase tariff, respectively the average sale tariff in Germany[3] with a deviation of 20% from these mean values for upper and lower limits. A consequence of this parameterization of the distributions is that the two price intervals are disjoint. This effects the problem instances, in the sense that the tradeable amount of energy is not affected and is therefore equal in all cases. As a result, the abort criterion within the algorithm always states that there is no more supply or demand available in the market.

The used algorithms (*model.py and maxflow.py*) and the data generation (*profiles.py*

[2]Source Astral 1.4 https://astral.readthedocs.io/en/latest/

[3]Data from the Federal Ministry for Economic Affairs and Energy or the Federal Statistical Office of Germany

and prices.py) are implemented in Python 3.7[4] and CPLEX 12.10 is used to solve the optimization problem.

	Spring	Summer	Autumn	Winter
Origin Balance	-1.320,70 €	-354,93 €	-1.519,96 €	-2.216,73 €
Optimized Balance	-1.044,68 €	-0,95 €	-1.346,80 €	-2.134,40 €
Savings	276,02 €	353,97 €	173,16 €	82,33 €
Demand Quantity	8442 kWh	8364 kWh	8420 kWh	8434 kWh
Supply Quantity	7514 kWh	14617 kWh	6464 kWh	1480 kWh
ELA Energy	1442 kWh	1836 kWh	895 kWh	431 kWh
Energy Sale	4378 kWh	10610 kWh	4325 kWh	288 kWh
Energy Purchase	5307 kWh	4357 kWh	6281 kWh	7242 kWh

Table **3.2**. Seasonal Results

Table **3.2** shows the results achieved for the comparison of the four seasons. The table contains the origin balance values of the VEU (without trade) for each seasonal scenario in the first row and the optimized balance values in the second row. The resulting improvements for the VEU balance are given in the third row. At first glance, the balance value of the VEU is significantly better in the summer scenario and the savings of the VEU balance in this season is quite high. This depends mainly on the generated amount of energy (row ´Supply Quantity´ in Table **3.2**), due to the increasing number of hours of sunshine and the associated trading periods, which effects the amount of energy we can use for local energy load adjustments (row ´ELA energy´) and the amount that we sell to the ESP (row ´Energy Sale´). The results in the table indicate that we can use four times more energy for the ELA in the summer compared to the winter. Furthermore, it is interesting that the energy supply in summer is ten times as large as in winter. On the other hand, the consumption of the VEU is at a similar level in each season (row ´Demand Quantity´). This implies that we can use only a fraction of the surplus of solar energy for ELA. The reason for this is that there is not enough demand available during the sunny periods. So, the VEU still has to purchase a large amount of energy from the ESP (see row ´Energy Purchase´) in other periods. This indicates that for the energy transition it is of importance that next to the amount of energy supply, the distribution of the energy demand of the VEU should also be changed over time. To illustrate this, Figure **3.2** shows the external energy flows over the planning horizon for the four seasons, with negative values representing energy demand, and positive values showing energy supply. The graphs indicate that in our model, the market will clear demand or supply and has to handle the residual amount

[4] http://www.python.org

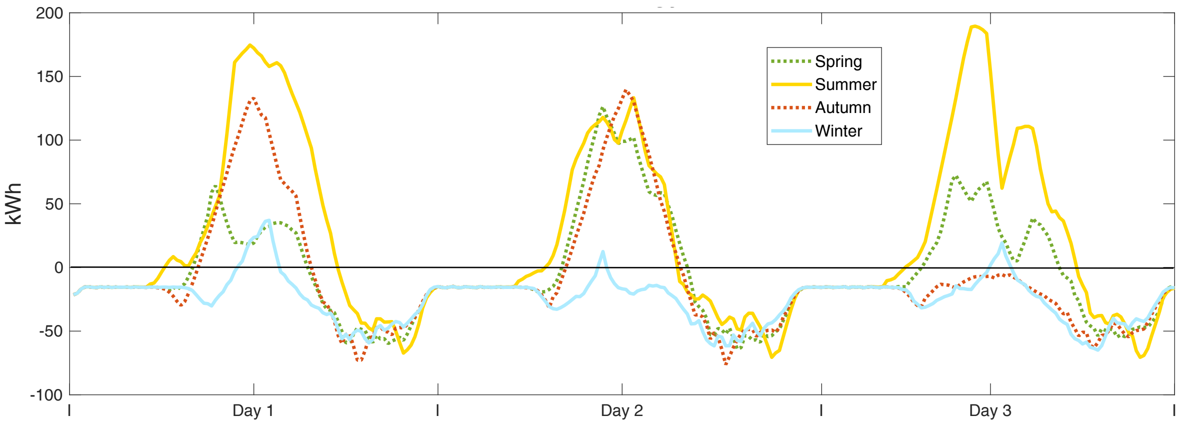


Figure **3.2**. External Energy Flows

of energy via the ESPs. This also indicates that a focus on only one type of renewable generation (in our case, solar) is not supporting local energy trades.

In Figure **3.3**, more detailed information on the market composition throughout the day is given. The graphs indicate that the fraction of producers on a specific point in time depends on the weather conditions, PV alignment, the time of day and also the time of year, (i.e. the possible time window for power generation starts earlier and lasts longer in summer, even if weather-related influences cause interruptions, such as on Day 2). The chart also indicates that we only have a few hours with production in winter, with a peak around noon. These findings give more detailed insight how large the focus on one generation source (solar) effects the market volume of internal trades (see also Figure **3.4** where these values are given). On sunny days the volume is limited by the quantity of demand, as we can see on Day 1 and 3 in summer. The fraction of producers is comparable in these days and based on the weather the amount of energy supply is quite high. However, the trade peak is at evening times, when the residents are back home and the demand consequently rises. However, in winter, the market volume is limited by the amount of supply because the time window for power generation and therefore market activity is significantly shorter. From this, we can conclude that it is important to identify at which time trade is possible throughout a day and if the market is heavy on demand or supply at a specific time period or season. This analysis can be used to decide on choices for the type and compilation of renewable generation in a VEU but also for choices of appliances used for certain demands (e.g., heating). The latter may lead to more beneficial times or market compositions, especially if we prefer PV as the only renewable energy generation source for a VEU.

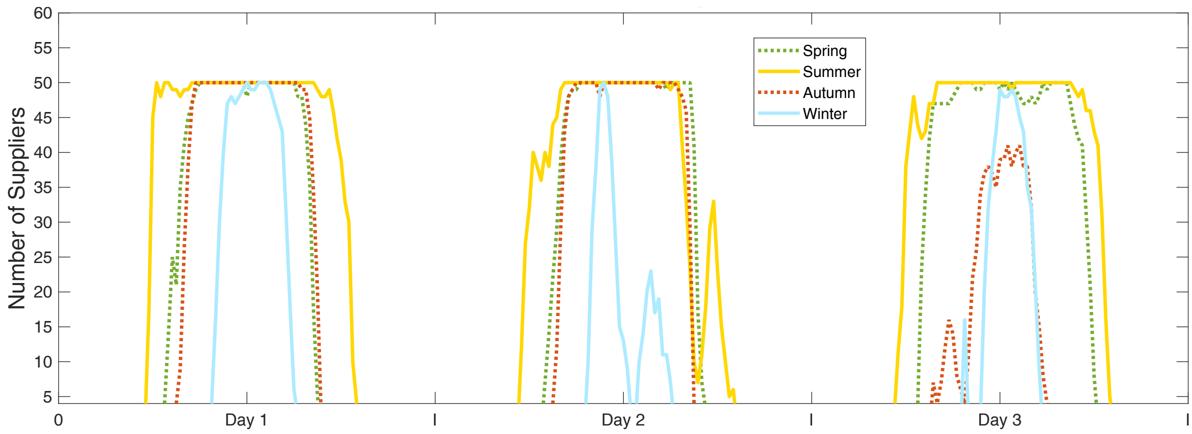


Figure **3.3**. Virtual Market Composition

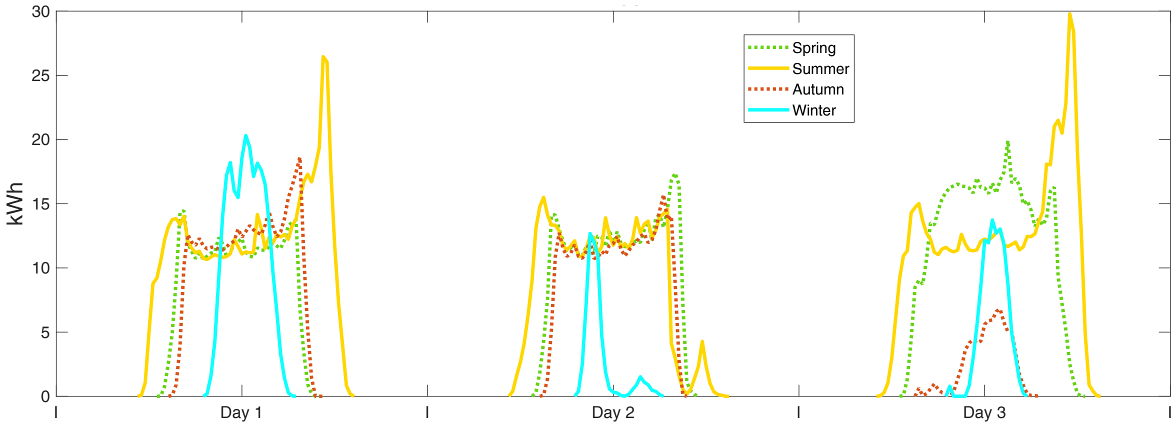


Figure **3.4**. ELA Energy Flows

Therefore in the following we analyze different scenarios where we vary the fraction of producers. The corresponding results are presented in Table **3.3**. In the first (and fourth) column we see the initial results in summer (and winter, respectively) where a 50% fraction of the households has PV-generation. The following columns then show the results for scenarios with a 25% and a 75% penetration in the specific season. When we decrease the fraction of households with PV panels to 25% in summer (Column 2), the total amount of energy supply is lower (row ´Supply Quantity´ in Table **3.3**), but at the same time the amount of internal trading grows by 27% (row ´ELA energy´) which leads to an increase of the savings value by 23% (row ´Savings´) in this season. This also explains the achieved results, when we increase the fraction of households with PV panels to 75% (see Column 3). Now, for the very high amount of energy supply only a few customers are present, resulting in a decrease in the amount of ELA energy flows (45%) and reduced savings (44%).

In contrast, in the winter period we can notice a somehow opposite result. When we decrease the proportion of suppliers to 25% (Column 5) we limit the already small supply and consequently cannot see any increase in savings (row ´Savings´) or the amount traded (row ´ELA energy´). We therefore may expect that an increase of the fraction to 75% should result in an increase of savings and the amount traded. However here another aspect becomes more dominant – the own consumption of a resident. In winter, the PV output of a participant is smaller compared to the summer and so the overall generation surplus (row ´Supply Quantity´) is already used to a large extent in own consumption.

	Summer 50%	Summer 25%	Summer 75%	Winter 50%	Winter 25%	Winter 75%
Origin Balance	-354,93 €	-1.446,16 €	795,60 €	-2.216,73 €	-2.386,62 €	-2128,99 €
Optimized Balance	-0,95 €	-1.007,34 €	994,87 €	-2.134,40 €	-2.334,59 €	-2.082,69 €
Savings	353,97 €	438,82 €	199,27 €	82,33 €	52,03 €	46,30
Demand Quantity	8364 kWh	8357 kWh	8404 kWh	8434 kWh	8375 kWh	8422 kWh
Supply Quantity	14617 kWh	7243 kWh	22628 kWh	1480 kWh	586 kWh	1837 kWh
ELA Energy	1836 kWh	2275 kWh	1009 kWh	431 kWh	261 kWh	236 kWh
Energy Sale	10610 kWh	3860 kWh	18284 kWh	288 kWh	0 kWh	606 kWh
Energy Purchase	4357 kWh	4974 kWh	4060 kWh	7242 kWh	7789 kWh	7191 kWh

Table **3.3**. Variation Results

These presented results have shown that the season, time, and the time-depen-dent composition of a local market have a quite diverse influence on its overall performance and it is not possible to make a general statement about how the market should be structured throughout a year. However, with our tool and the knowledge of the energy flows in the system, we are able to determine a beneficial static or more dynamic structure with flexible participants, who are able to join a VEU temporarily, but stay unattached in the long term.[5] The tool can be the base to support the participants in investment decisions, i.e., to decide if it is beneficial to invest in a PV (or other appliances) and to step into the market as an additional supplier and to determine if this decision is of value to the VEU.

3.1.4. Discussion

The case studies show that for the considered setting we are able to improve the balance for a basic, but realistic VEU, simply by coordinating local energy supply and demand with the ELA mechanism. Furthermore, we provide the targeted structural

[5]This may turn into other billing or fee concepts with participation levels, but is not a topic of this thesis. See also in Chapter 3.1.4

insights and additional information for more complex settings, i.e. the influence of the market composition in general and the amount of supply or demand at a certain point in time. The conclusion is that we have to extend the flexibility of a VEU to react better to the market parameters if we want to exploit more of the still huge potential in this setting. In the following we point out possible expansion strategies.

A simple solution to extend the flexibility is to allow participants to join and leave a VEU cooperation dynamically. In this case, the VEU can regulate the market composition by temporarily accepting additional participants who provide the missing supply or demand for additional trading, if the market is heavily one-sided. With our tools, a VEU is able to forecast and prepare for such scenarios. The downside of such dynamic participant affiliation is that it is both technically and legally complex to control. When we focus on a static cooperation instead, the most promising solution to boost the flexibility of the VEU is to consider energy load shifting options to exploit more beneficial time periods. This is an already discussed aspect of decentralized energy management, and the energy load shifting options would allow the VEU to shift parts of their energy demand (via demand side management) or energy supply (via storage integration) to get the required flexibility. The downside is that this may results in a conflict of aims between the use of the ELA mechanism (a periodic decision) or to locally shift the load (leading to a multi-period decision). Our tool and its basic setting can be used to address this realistic extension. Note, that the load shifting application will also benefit the system, if the two price intervals of supply and demand are not disjointed. In that case, we can shift the non-tradeable energy load in a certain period to another period, instead of using the, most likely, less beneficial conditions of the ESP.

Another conclusion of our studies for a VEU management is to diversify the sources of power generation within a cooperation and also consider more controllable elements in their energy environment, like micro combined heat and power devices or heat pumps. In that way, the VEU would gain more control over the times of local energy production and consumption and the way additional energy demands (e.q. heating) can be included in this setting to also benefits a more comprehensive view on energy management. An integrated approach can furthermore benefit the relationship with the net operator – by supporting local net stability. The VEU is already able to create more predictable local energy flows and therefore can be of value for the net operator. Another advantage is the use of rolling planning concepts, especially with controllable energy generators. Using a long-term planning horizon for optimization, but updating it at fixed intervals and renewing it with changed data helps to quickly identify deviations and refine the plan.

To summarize, the developed model and the maximum saving flow algorithm find optimal values for the considered setups and give us valuable insights what is achievable in this simple setup and also possible in more complex setups. These insights could be achieved since we built our base approach from scratch and as simple as possible. Additionally, with our tools we also gain information about the virtual energy flows in this local energy community and the composition of the achieved savings. We may use these insights to develop better strategies for internal pricing (profit-distribution) in later stages with e.g. game theory approaches, that follow efficient contract theory. The question in this context is, how to design the contracts for the participants to get a stable cooperation. Finally, external stakeholder, such as net operators, may also use these insights to develop pricing strategies for their network charges.

If the integration of decentralized energy management solutions will be intensified and the overall benefits of these solutions will have an effect on the political decisions, it is also possible to address other questions concerning the VEU setting or local energy markets in general. The allowance of such economic cooperation leads to now technical and economical issues, and to further detailed questions on issues of law and tax regulation.

3.2. External Trading

The focus of this thesis is the evaluation of the potential economic influence on the internal energy exchange that a VEU can handle. The local setting of the participants ensures that generated energy is used as far as possible within the community and thus locally. However, due to the still existing access to the distribution grid, there is an alternative external connection for energy services. This external connection is also the base for the participants' basic contracts to their ESP for the energy quantities that cannot be exchanged internally. A centrally organized energy exchange with individuals outside the community via regional or local market platforms can therefore further increase the efficient use of locally available energy. This additionally market level, on which a VEU may act, may also be settled in the same distribution network and can exist in parallel. It is also not unrealistic for an active VEU to also participate in neighboring local markets, which in turn cover other distribution grids. This would require further control options and more extensive communication with several distribution system operators (DSOs) but shows that an external perspective may also exist in a more regional area. The integration of external trading possibilities is thus an interesting extension and is therefore discussed in this section. However, we keep the perspective of how the internal planning level can provide further information and data for external optimization.

The VEU has the opportunity to participate on both sides of a local market, as both supply and demand of the participants are aggregated. Although the low trading volumes still make integration in wholesale energy markets unrealistic, local energy markets (LEMs) will be accessible. How such a LEM may be structured concretely, which market types and which market mechanisms can be used, is discussed in Chapter 2.2. For a first analysis the details of a local market structure are negligible, because for the cooperation the only question is which energy quantities should be traded internally or externally (due to the achievable prices at the local market in order to generate optimal savings). Assuming that an orientation towards the systematics of the wholesale energy markets is reasonable, an auction-based local day-ahead market could be a likely option in the local area. This implies a focus of the required optimization on the bidding process. Therefore, a simultaneous solution to determine internal and external trading quantities faces various problems. On the one hand, the market prices are not available and are thus themselves part of the optimization process. Additionally, it is not certain that bids with the determined bidding prices will be accepted in the end. The use of stochastic optimization could cover these influences and open up a potential solution. In the following section, a simpler and faster sequential approach is presented that can be used as long as the market design involves a bidding process. In this case, the external bids are based entirely on the available optimal solution for the internal energy exchange and the decisions made there. The information that can be derived from this optimal solution then provides the basis for the decision-making process to design the external bids or serves to support the bidding strategy used. The advantage is that even if the external bids do not get into the market closing, the optimal internal use is already planned and available.

3.2.1. Derived Bidding Decision

The derived values relevant for an external optimization are the optimized energy quantities $ol_{t,n}$ of the participants $n \in N$ in the periods $t \in \mathcal{T}$, the associated tariff values $v_{t,n}$ and the optimal internal ELA $bal_{t,s,d}$ between the suppliers $s \in S_t$ and

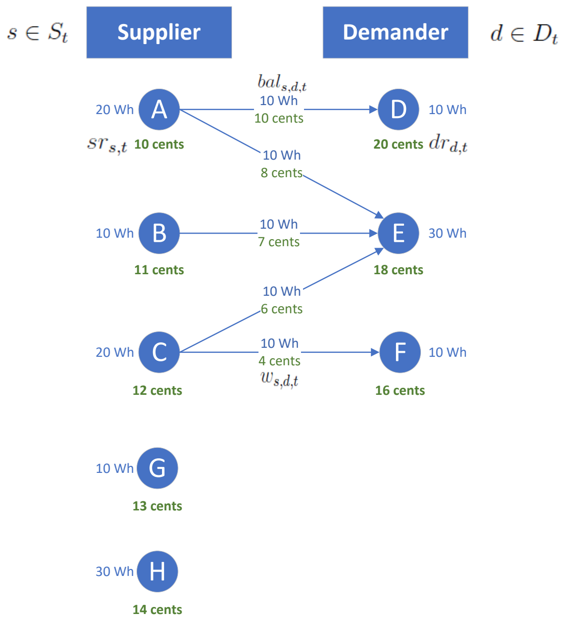


Figure **3.5**. Solution of Internal Energy Exchange used as base for External Bidding Determination

the demanders $d \in D_t$. From the optimal solution of the maximum saving flow algorithm (MSFA), also the savings rate $w_{s,d,t}$ of an ELA can be determined directly. In principle, an improvement is not only possible through the external trading of internally non-tradable energy quantities. Due to the optimal solution of the internal trading quantities with detailed knowledge about the planned P2P connections, it can be determined above which price limit an internal connection generates less monetary benefit than the alternative use of the energy quantities for an external bid on a local market. Figure **3.5** shows a simple internal solution with the necessary details, so that it can be explained how this results in the price limits and quantities for a bid in the external local market.

In the solution of Figure **3.5**, suppliers G and H have a residual supply of energy $\sum_{t \in \mathcal{T}} \sum_{s \in S_t} ol_{t,s}$ equal to 40 kWh. These two suppliers would now have to clear their energy quantities for 13 and 14 cents/kWh respectively via the ESP. Alternatively, the VEU can place a bid on a local energy market that exceeds these 14 cents/kWh. If the bid is successful, this internally unused energy can still be profitably used for local demand of other participants of the local energy market. If the VEU forecasts a realizable price that exceeds 16 cents/kWh, even the existing internal planning can potentially be improved. For example, the lowest edge of the internal solution between supplier C and consumer F achieves a saving of 40 cents. This can only be improved if the achievable market price differs from the tariff values of the two participants involved in the respective ELA. Thus, if the VEU can place a supply bid that is above the tariff value of participant *F*, the saving of the external trade is preferable, if the bid is successful. The reverse is also true if the VEU can alternatively place a demand bid in the market that is below the tariff value of *C*. This principle is simple but effective in identifying the profit-maximizing trading quantities for each price limit. In addition, it is important for the further bidding process to forecast the price development in the local market as robustly as possible. In Table **3.4** it is shown which price limits result for which energy quantities, for the example from the figure.

Price Limit	Demand Quantity	Supply Quantity
$<$ 10 cents	50 kWh	0 kWh
$<$ 11 cents	30 kWh	0 kWh
$<$ 12 cents	20 kWh	0 kWh
$>$ 13 cents	0 kWh	10 kWh
$>$ 14 cents	0 kWh	40 kWh
$>$ 16 cents	0 kWh	50 kWh
$>$ 18 cents	0 kWh	80 kWh
$>$ 20 cents	0 kWh	90 kWh

Table **3.4**. Example of Price Limits in the Bidding Process

A tabular record as in Table **3.4** can be made for each solution of internal energy exchange or can even be integrated directly into the MSFA. All necessary data is available at the time of the individual decision and only needs to be additionally stored so that an evaluation can take place. In the case studies of Chapter 3.1.3, for example, the residual quantities of the individual periods are already presented. Of course, these price limits only determine the point at which the savings of the entire community are increased. The individual participant could theoretically improve his or her individual savings even before that, by deviating from the price limit and trying to trade individually on the local market. However, such scenarios depend on the chosen distribution of savings within the community and is therefore not the subject of this chapter. After the VEU has determined the energy quantity of the bid based on the market price forecast, it is possible for the community to react to both potential outcomes of the bidding process without additional effort. If the bid is accepted in the local market, there is no need to allocate the internal trading partners and the associated energy quantities, as these are part of the decision-making process. If, on the other hand, the bid is not accepted, the VEU can fall back on the previously determined optimal internal use. This no longer needs to be adjusted, unless after the calculation new data became available. Note, that this in any case would require a recalculation. The advantage of this sequential approach is that unnecessarily complicated modeling based on, for example, stochastic optimization or non-linear formulations, can be dispensed with.

3.2.2. Alternative Bidding Decision

As basic reference for auctions and bidding strategies, we refer to the work of McAfee and McMillan (1987), in which classical procedures are given and discussed. Mengelkamp et al. (2017) provide, in turn, an overview of what they consider to be useful market designs in the local environment and the associated overview of possible bidding strategies. Literature also shows that day-ahead scheduling, which is well-used and common in the energy sector, is quite common in the local environment. Thereby, some of the approaches are actually designed to participate in an existing day-ahead market, like in the work of Ferruzzi et al. (2016). While direct participation in existing wholesale structures is unrealistic due to the trading volumes of microgrids or local interconnections, on the other hand, the approach can be applied to an LEM if it follows the basic principles of a day-ahead market. Another criticism of the authors' work, among others, is that they use reallocated strategic costs for their operational cost rates, which should actually be avoided, as explained earlier. Jelenkovic and Budrovic (2015) offers a heuristic approach that does not consider market access, but instead proposes bilateral negotiations between connected microgrids and the DSO to make the best use of the surpluses of microgrid environments. Such direct bilateral negotiations are also a possible approach for the VEU in case LEMs do not emerge, or negotiations with the local DSO seems more appropriate. Iria et al. (2018) formulate two possible optimization opportunities for the supply and demand of a potential aggregator of local prosumers. Since the VEU may also perform the tasks of an aggregator, the proposed stochastic optimization model and control mechanism are applicable in principle for the VEU, although the internal perspective of the community would still need to be integrated. Finally, the work of Yu et al. (2020), which aims to determine optimal bidding strategies of individual prosumers in a distribution-level energy market, presents also an interesting principle. If the VEU can act as a individual participant in the proposed market construct, the clearing scheme is transferable and thus the VEU can also participate in this form of local market design.

3.2.3. Conclusion

The core conclusion of this section is that, based on the optimized internal energy exchange, external trading decisions can be derived in a two-step decision process. The necessity of stochastic optimization is therefore questionable, especially since such approaches are sometimes also applied in two- or multi-stage processes. Advantages of using stochastic optimization arise when price forecasts are difficult to implement, or when the used methods are too inaccurate. However, this cannot be assumed for the energy sector, as forecasting models are proven and consistently used methods in the current market environment. Note, that it is not the aim of this thesis to provide a detailed statement on how established pricing and forecast models will respond to the future local market environment. It is therefore recommended to continue to consider models and methods of stochastic optimization and to apply them alternatively in case a sequential decision based on internal optimization is not robust enough.

For VEUs the consideration of external accesses makes sense only if it is allowed to act as a cooperation in local market structures. The advantage of economies of scale due to the bundled supply and demand volumes may give the VEU an excessively strong influence in local markets. Therefore, it cannot be ruled out that the competition authorities will take regulatory measures or that a cooperation with certain market power will have to participate in higher-level markets. However, this cannot be foreseen at present. An additional external perspective may arise if flexibility is handled by the VEU and there are trading volumes or capacities that can be offered as flexibility. This aspect will be discussed further in Chapter 4.

4. Flexibility Options

In this chapter the possibilities of a virtual economic unit (VEU) for local energy management are extended. So far, the basic setup of the community is to optimally determine the direct internal energy flows in the individual periods. That means the internal energy flows are only possible within the respective time period. In order for the VEU to be able to enhance this basic task, it therefore needs technical capabilities to shift the energy load between time periods. Basically, a load shifting concept describes the process that the energy load occurring at a certain point in time is shifted to another (later) points in time. A distinction can be made between supply-based and demand-based energy load shifting. For supply-based load shifting, the VEU needs the possibility to utilize occurring supply in a later period. For this purpose, energy storage systems (ESSs) must be available, which can charge the energy supply in a specific period. This stored energy can then be discharged at a later time and is available as a supply at that moment. Chapter 4.1 discusses and models this possibility in detail, examines it through case studies and discusses the results. Demand-based load shifting can also be realized by technical devices if they are able to control their demand times. This possibility is subsequently discussed, modeled, and analyzed in Chapter 4.2. In the case of demand-based load shifting, behavioral optimization approaches are also conceivable, which induce an individual to shift its demand. This is also discussed, but a detailed analysis is not provided. Subsequently, in Chapter 4.3, a mixed form is examined in more detail, where both supply and demand shifting is possible. The main discussion here is what practical implementation of load shifting should be used in this case. Finally, in Chapter 4.4, a discussion on the impact of these flexibility-based extensions on VEU is given, together with some topic to further investigation.

4.1. Shift in Supply

The use of ESSs is a widely studied topic in the energy sector and is not limited to the application in local energy management or to economic studies. The storage of electrical energy is usually realized by indirect storage methods[1]. In this process, the electrical energy is converted into mechanical-potential, mechanical-kinetic or electrochemical energy for storage and then converted back to its original form and fed into the grid. During these conversion processes, part of the input energy is lost, which is why storage efficiency plays a crucial role for ESSs. Alternatively, direct storage options[2] can be used. This is done either electrostatically or electromagnetically and has an increased efficiency compared to indirect storage. Due to the current technical requirements for the operation of these direct storage devices, their application and also the amount of electrical energy that can be stored is still severely limited. A complete analysis of possible applications, the possible technical characteristics and the different optimization approaches is outside the scope of this thesis. For a more extensive insight into the topic, we refer to Divya and Østergaard (2009) and Díaz-González (2016). Roberts and Sandberg (2011) and Tushar et al. (2016) discuss the use of energy storage specifically for smart grid concepts. For an overview of the possible integration of energy storage in the context of local markets, see Mengelkamp et al. (2017) or Menniti et al. (2014). Good and Mancarella (2019), on the other hand, analyze energy storage in an energy community (EC) environment.

In the following a specific summary of the most important terms for the further development is given. This selection intentionally does not cover the entire spectrum of topics that can be discussed and modeled. In Chapter 4.3.2 some issues will be addressed additionally in the context of electric vehicles (EVs).

- Charging process

  Physical process in which energy is added to the ESS.
- Discharging process

  Physical process in which energy is extracted from the ESS.
- Storage process

  Collective term that includes both charging and discharging processes.
- Storage capacity

[1]Examples are pumped storage power plants, flywheel storage and batteries
[2]Examples here are double-layer capacitors and superconducting magnetic coils

The storage capacity may be *technically limited* and therefore has a technically maximum value. Deviating from this, however, this value can be undercut by the *available* storage capacity. This limitation of the storage capacity then represents an authorized value that is determined by the respective owner or on the basis of certain regulations. The relevant variable for this thesis is the respective *available* storage capacity.

- State of charge

  The amount of energy that can currently be accessed in the ESS.

- Storage rate

  Each storage process can only convert a certain amount of energy within a specific period of time. This means that the change of the state of charge is limited within each time frame. Depending on the storage process, this can be further specified into charging rate or discharging rate. For the economic questions examined in this thesis, though, this distinction is not necessary.

- Storage efficiency

  There is a technical limitation to the use of energy storage. Through storage processes, part of the origin energy is lost and furthermore stored energy is lost over time in the ESS. Since operational planning is the focus of this thesis only the process-dependent loss is considered. The limited observation period makes explicit modeling of the loss over time unnecessary.

- Storage cycle

  A storage cycle is the recurring sequence of charging, stagnation and discharging of an energy storage device.

ESSs have the advantage that existing supply, i.e. energy production for which there is no direct demand at a certain point in time, can be stored and thus accessed at later times. By this demanded quantities can be produced in advance and storing them when this is more advantageous. This is a proven principle in production management, but the energy production of renewable energy resources (RES) is generally different, as the production times are usually not controllable at all. Energy storage is therefore mandatory to a certain extent, as otherwise the unused or at least stored energy is lost or wasted. However, the sole ability to store energy is not a fully comprehensive solution, as the added value of the ESS depends on the supply and demand quantities as well as the technical specifications of the device. If an ESS is only used by one person or household and the capacity of the device is reached, the effect of lost or wasted energy generation can still occur. In an opposite scenario part of the actual capacity may remain unused. In order to consider this potential of previously unexploited flexibility, the research on distributed storage (DS) discusses how the co-operation and coordination of actually independent energy storage systems can be technically realized and what added value results from this concept (see e.g., Mohd et al. (2008)). For this purpose, these ESSs should be interconnected via the grid infrastructure and follow an objective that offers an economic, technical or ecological added value. Since DS allows several parties to access the connected ESS, it mainly improves the utilization of existing storage capacities and a broader access to stored energy supply. Another advantage results from unused charged energy and/or storage capacities that are kept in reserve. Through such simple safety buffers, local energy storage can thus also increase local flexibility in the event of balance problems within the distribution grids. The ESS can provide missing supply or missing demand for the grid operator or a central unit operator against compensation. For a VEU or comparable communities, DS is therefore an appropriate tool to use more local supply and flexibility internally or to offer the gained flexibility externally. While this thesis primarily examines the internal use, it will also offer a view on the possible external perspective and hereby continue the analysis from Chapter 3.2. The presented two-stage approach there, in which the price limits for external bids are derived on the basis of the internal optimization, already offers a sensible procedure in this case. External bids on markets follow the same principles with integrated energy storage and thus pose similar problems for the VEU. In order for external connections to be discussed at all, the optimized results of internal energy exchange with ESS is essential.

4.1.1. Model Extension

The integration of ESSs into the optimization of a VEU and thus the extension of the basic model considers a set K of accessible and controllable ESS. Each energy storage $k \in K$ can be assigned to a specific member of the community $n \in N$. Note, that this specific assignment is not mandatory[3]. The core decision of the model extension is to determine for each time period $t \in \mathcal{T} := \{1, \ldots, T\}$ and each energy storage k a proper state of charge $soc_{t,k}$. The basis for this decision variable is the state of charge of the previous period $soc_{t-1,k}$. Then, in period t, all discharge processes $dc_{t,k,d}$ by possible

[3]If energy storages are identical in type or if a simplification of the problem is intended, the storages can also be considered as aggregated. In that case set K is omitted and the mathematical formulation abandons the corresponding index.

demanders $d \in D_t$ are subtracted from this base value and all charging processes $ch_{t,k,s}$ by possible suppliers $s \in S_t$ are added. However, the charging processes $ch_{t,k,s}$ must be adjusted to take the storage efficiency of energy storage k into account, which is done by multiplying these values with parameter α_k. The storage balance equation for determining the states of charge can then be formulated as follows:

$$soc_{t,k} = soc_{t-1,k} + \sum_{s \in S_t} ch_{t,k,s} \cdot \alpha_k - \sum_{d \in D_t} dc_{t,k,d} \quad \forall\, k \in K, t \in \mathcal{T}. \tag{4.1}$$

For each storage process, it has to be considered that a part of the originally used energy is lost to the provision process. Therefore, the efficiency α_k only has to be considered at the target of this process. At the starting point of a storage process, on the other hand, it is necessary that the total amount of energy input is taken into account. In the storage-related Equation (4.1), the efficiency α_k therefore has to be considered for charging processes $ch_{t,k,s}$ only. Any discharge process $dc_{t,k,d}$, in contrast, starts at the specific ESS, so the total amount of energy must be considered in its associated storage balance equation (4.1). The storage efficiency α_k must again be considered at the target of a discharge process, i.e., at the energy load balance of demander $d \in D_t$. Since every change in the energy load balance of involved actors $n \in N$ is already recorded by the load balance equation in the basic model, all storage processes must similarly be integrated there. The modification of this equation can be formulated as follows (highlighted in green):

$$\begin{aligned} ol_{t,n} = pl_{t,n} &- \sum_{(n,d) \in B_t} bal_{t,n,d} + \sum_{(s,n) \in B_t} bal_{t,s,n} \\ &- \sum_{(k,n) \in BCh_t} ch_{t,k,n} + \sum_{(k,n) \in BDc_t} dc_{t,k,n} \cdot \alpha_k \quad \forall\, n \in N, t \in \mathcal{T}. \end{aligned} \tag{4.2}$$

The storage processes are again summarized using pair sets to allow a technical subdivision of the participants $n \in N$ into suppliers and demanders within the Equation (4.2). For this purpose, the set BCh_t defines possible pairs in period t between the energy storages $k \in K$ and the suppliers $s \in S_t$ and the set BDc_t the possible pairs in period t between the energy storages $k \in K$ and the consumers $d \in D_t$. Therefore, only suppliers can charge and only consumers can discharge an ESS. However, to ensure that the roles of the participants cannot change due to the storage processes, we need to modify the former constraints of Chapter 3 for role resilience (Equations (3.4) and (3.5), changes highlighted in green)

$$\sum_{d \in D_t} bal_{t,s,d} + \sum_{k \in K} ch_{t,k,s} \leq pl_{t,s} \qquad \forall\, s \in S_t, t = 1, \ldots, T \tag{4.3}$$

$$\sum_{s \in S_t} bal_{t,s,d} + \sum_{k \in K} dc_{t,k,d} \cdot \alpha_k \leq -pl_{t,d} \qquad \forall\, d \in D_t, t \in \mathcal{T}. \tag{4.4}$$

In order to guarantee that the storage levels $soc_{t,k}$ for each period t and each storage device k do not exceed the available storage capacity cap_k of an ESS k, the following constraint is required:

$$0 \leq soc_{t,k} \leq cap_k \quad \forall\, k \in K, t \in \mathcal{T}. \tag{4.5}$$

Furthermore, next to the available capacity an ESS is also limited its storage rate in each period t. For this purpose, a technical periodic capacity $pcap_{t,k}$ parameter is introduced for each energy storage k and each period t. All charging processes $ch_{t,k,s}$ of a storage k in period t by possible suppliers $s \in S_t$ and all discharging processes $dc_{t,k,d}$ of storage k in period t by possible demanders $d \in D_t$ thus have to stay within this periodic capacity $pcap_{t,k}$:

$$0 \leq \sum_{s \in S_t} ch_{t,k,s} + \sum_{d \in D_t} dc_{t,k,d} \leq pcap_{t,k} \quad \forall\, k \in K, t \in \mathcal{T}. \tag{4.6}$$

Finally, the consideration of an initial state of charge ic_k for all energy storages devices k is obligatory from a modeling point of view:

$$soc_{k,0} = ic_k \quad \forall\, k \in K \tag{4.7}$$

4.1.2. Storage Case Studies

This section analyzes the impact of the introduced extension of the VEU environment with energy storage capabilities and the resulting energy supply shift. The realistic scenarios of Chapter 3.1.3 are the basis for the conducted case studies. The aim is to determine how much added value can be generated by storage processes and what impact different parameters can have on this. Part of the study is also to identify how internal energy exchange is affected. Therefore, the 100 participants are assumed to be part of the heterogeneous composed VEU and are connected to a local grid area, with a basic contract for energy exchange services with an external energy service provider (ESP). The local energy generation is assumed to be still based exclusively on photovoltaic (PV) panels and only 50% of participants are equipped with this supply option in the basic seasonal scenarios (one scenario for each of the four seasons). To investigate the impact of different market compositions, the summer scenario is chosen for the analysis and the share of potential suppliers is varied on 25% and 75%. The energy load profiles again are generated by the profile generator of Hoogsteen et al. (2016) and in addition, every PV system owner is now also equipped with an ESS.

All energy storage devices have a randomly chosen available capacity between 4 and 5 kW and their storage efficiency is chosen randomly between 90% to 95%. Although larger storage capacities are also available for a single household, these are normally not applied because the storage will be not fully utilized in normal use. Since this may change in the future with DS, all scenarios are also examined with twice the storage capacity. The storage rate to define the amount of energy, that can be converted in a specific period of time is set to 0.5 kW per time period for all devices. To analyze the influence of the storage rate in more detail, all scenarios are additionally calculated with doubled storage rate values. Subsequently, both the storage capacity and the storage rate are doubled to see how the respective variations affect the behavior within the VEU.

An explicit analysis of the influence of different storage efficiency levels is omitted here, as no significant insights into the system behavior are to be expected. The better the efficiency level of the ESSs, the more likely they are to be used to store energy. It is nevertheless essential to define this degree of energy loss (due to the conversion process) as a parameter. This is because storage efficiency is a technical necessity, which in addition also serves as a performance indicator of individual ESS and therefore offers structural advantages that be used in the further development of potential algorithms. We again us the energy profiles, time periods, fariff structure and distribution parameters used in Chapter 3. For a deeper analysis of the storage influence, a variation of this parameterization is examined for the tariffs, which introduces a day/night distinction. For this, all tariff values (supply and demand rates) of the participants are lowered by 1 cents/kWh or 3 cents/kWh respectively between 6 a.m. and 6 p.m., in order to be able to determine the differences.

The used model (*model-stor.py*) and the data generation (*profiles.py*) are implemented in Python 3.7[4] and CPLEX 12.10 is used to solve the optimization problem.

	Spring	Summer	Autumn	Winter
Basic Savings	72.98 €	96.12 €	42.50 €	14.96 €
DS Savings	180.06 €	204.78 €	130.98 €	19.14 €
DS Savings DC	224.55 €	233.10 €	144.07 €	19.14 €
DS Savings DR	180.06 €	204.78 €	131.17 €	19.16 €
DS Savings DCR	228.05 €	233.13 €	145.50 €	19.16 €
Basic ESP Sale	1,554.07 kWh	1,801.33 kWh	637.88 kWh	15.97 kWh
ESP Sale DS	887.88 kWh	1,087.00 kWh	100.50 kWh	0.00 kWh
ESP Sale DC	557.60 kWh	874.35 kWh	0.52 kWh	0.00 kWh
ESP Sale DR	887.88 kWh	1,087.00 kWh	99.98 kWh	0.00 kWh
ESP Sale DCR	526.11 kWh	874.58 kWh	0.00 kWh	0.00 kWh
Basic ELA	369.55 kWh	485.52 kWh	215.47 kWh	77.03 kWh
ELA Change DS	-0.12%	0.0%	-3.57%	-55.43%
ELA Change DC	-0.27%	0.0%	-7.99%	-55.43%
ELA Energy DR	-0.12%	0.0%	-3.83%	-55.92%
ELA Energy DCR	-0.03%	0.0%	-7.24%	-57.42%
Charge Amount DS	666.62 kWh	714.33 kWh	545.07 kWh	58.66 kWh
Charge Change DC	33.17%	22.94%	16.73%	0.00%
Charge Change DR	0.00%	0.00%	0.20%	0.64%
Charge Change DCR	35.16%	22.92%	16.59%	2.55%

Table **4.1**. Seasonal Results with ESS

For a better overview despite the extensive results, the analysis is structured as follows:

- Seasonal differences in savings values
- ELA changes in particular
- Variation of storage-related parameters
- Changes with price differentiations
- Results for different market compositions
- Findings on storage utilization.

[4]http://www.python.org

- **Seasonal differences in savings values**

  Table **4.1** shows the results achieved in the comparison of the four seasons. The table contains the resulting optimal savings for the VEU balance for each seasonal scenario without ESSs as comparative value in the first row. The results with active DS are shown in the second row. At first glance, the optimal savings values can be significantly improved with active storage management, even in the winter scenario by a small margin (28%). The increase in savings in the autumn scenario is particularly noteworthy (at 208%), while lower relative increases in savings are observed in summer (113%) and spring (147%). In absolute terms, by contrast, summer (+ 108.66 €) and spring (+ 107.08 €) are still stronger than autumn (+ 88.48 €). This difference is mainly based on the fact that the energy production by the PV systems differs in the individual scenarios. In summer, for example, the aggregated and also individual energy production is higher, so that higher savings can already be achieved through the sole use of energy load adjustment (ELA). The relative increase potential is thus lower than in autumn. Accordingly, planning horizons in which there is period-specific and overall low energy supply, can benefit disproportionately from integrated ESS, as planning horizons with higher energy supply can already achieve meaningful savings through the use of ELA.

- **ELA changes in particular**

  However, this only applies as long as there is enough additional supply overall, as the winter scenario shows. The comparatively low residual supply there is not only completely utilized (row 'ESP Sale DS'), but also leads to a situation where ESSs are used to replace low-saving ELA connections in the individual periods. Overall, the amount of energy exchanged through direct ELA connections decreases by more than half in winter (row 'ELA Change DS'). The already small increase in savings in winter is thus now largely based on the substitution of ELA between participants, which can be seen from the load values (row 'Charge Amount DS'). In summer, this substitution effect does not exist at all, and in spring only minor influences of this kind can be observed. This leads to the conclusion that more available energy storage capacity will be utilized to replace ELA connections if there is less residual supply available (row 'Basic ESP Sale'). This is due to the linear effect of decreasing incremental savings for the available residual supply when using ELA, which is discussed in Chapter 3.1.2 and used to apply the maximum flow algorithm. Note, that for a better overview, the total energy quantities available are not listed in the table, but can be derived from the surpluses available so far (row 'Basic ESP Sale' in Table **4.1** and the original energy quantities exchanged via ELA (row 'Basic ELA')[5].

- **Variation of storage-related parameters**

  That the use of ESS has a decreasing marginal benefit is shown by the variation of the storage parameters. Although doubling the storage capacity also leads to an increase in the savings achieved (row 'DS Savings DC' in Table **4.1**) proportionally, these increases are much smaller than before. The additional storage capacity can only utilize less lucrative residual supply, so that only small amounts of additional energy are stored (row 'Charge Change DC') and the substitution of ELA connections between the participants (row 'ELA Change DC') is increased throughout all scenarios. This effect occurs even though there is still energy available in spring and summer that could be stored (line 'ESP Sale DC'). In summer, however, there is also a demand bottleneck, as the achievable demand can be fully served by the internal energy exchange.[6] Another explanation for this effect might be that the storage rate is a limiting factor for the increased storage capacity as simply not enough energy can be charged or discharged during the periods.

  However, the sole doubling of the storage rate has no significant influence on the use of ESSs. Only in autumn and winter is there any effect on savings measurable at all (row 'DS Savings DR'), based on a small increase in charge quantities (row 'Charge Change DR') and the changes in the ELA substitutions (row 'ELA Energy DR'). In autumn, due to the increased storage rate, even additional amounts of energy can be utilized for local demand (row 'ESP Sale DR').

  If both parameter changes are combined, the increases in savings (row 'DS Savings DCR') are more significant, so that in principle it can be said that the use of larger storage capacities with the simultaneous use of devices with better storage rates does have advantages. However, the influence of the storage rate is still a minor factor compared to the numbers presented of the sole doubling of storage capacity. Additionally, the composition of the small savings increase in summer is quite astonishing compared to doubling the storage capacity alone, as the amount of energy sold to external ESP increases (row 'ESP Sale DCR') and

[5] Alternatively, this data is also available in Chapter 3.1.3 and the digital appendix.

[6] This is evident from the $ol_{t,n}$ values of the solution, since overall demand remains available in the planning horizon (at the beginning), but cannot be served by internal energy exchange with ELA or ESS.

the amount of energy charged into the energy storage decreases (row 'Charge Change DCR'). A change in the substitution of ELA, on the other hand, is still not to be considered (row 'ELA Energy DCR'). This indicates that the additional revenue is based entirely on an optimization of the storage processes due to the storage rate, which then even leads to more energy being sold to external ESPs again. A similar observation can also be made in autumn and spring, where the increase of both parameters leads to lower charging quantities into the ESSs, which indicates the optimization of the storage processes again. In contrast, in these cases the energy is used to re-establish more ELAs between participants (row 'ELA Energy DCR'). This ultimately leads to even less energy being sold to the ESP and thus being used locally.

	Summer	Summer N1	Summer N3	Autumn	Autumn N1	Autumn N3
Basic Savings	96.12 €	96.12 €	96.12 €	42.50 €	42.50 €	42.50 €
DS Savings	204.78 €	211.76 €	225.93 €	130.98 €	135.61 €	145.86 €
Basic ELA	485.52 kWh	485.52 kWh	485.52 kWh	215.47 kWh	215.47 kWh	215.47 kWh
ELA Change DS	0.00%	-0.41%	-0.51%	-3.57%	-6.00%	-14.14%
Charge Amount DS	714.33 kWh	716.79 kWh	717.41 kWh	545.07 kWh	550.32 kWh	567.84 kWh
ESP Sale	1,801.33 kWh	1,801.33 kWh	1,801.33 kWh	637.88 kWh	637.88 kWh	637.88 kWh
ESP Sale DS	1,087.00 kWh	1,086.54 kWh	1,086.42 kWh	100.50 kWh	100.50 kWh	100.50 kWh

Table **4.2**. Price Deviation Results with ESS

- **Changes with price differentiations**

  The results for the consideration of price differentiations within the planning horizon are shown in Table **4.2**. The comparison values of both respective base scenarios are listed in Columns 1 and 4 and the first impression is that the savings can be improved by applying the pre-defined day-night tariff differentiations (row 'DS Savings'). The increase in savings is also lower if the price reduction is only 1 cents/kWh in the defined night time (scenarios with 'N1' in Columns 2 and 5), compared to a price reduction of 3 cents/kWh (scenarios with 'N3' in Columns 3 and 6). It is not surprising that an increase in price reduction also leads to an increase in savings, but a more important insight is that in all cases this increase in savings is significantly influenced by the substitution of period-specific ELA (row 'ELA Change DS') with additional storage processes (row 'Charge Amount DS'), especially in autumn.

  At the same time, only in summer small amounts of the still available local energy (row 'ESP Sale DS') is additionally used at all. It is therefore obvious that in the case of a temporary price reduction in this specific time frame, an attempt is made to store the available energy rather than to use it during the periods themselves. This is not a surprising correlation, since the price reduction falls exactly in the time frame in which the ELAs are utilized. Therefore, the margin for the time-independent storage processes is more competitive with the ELA margins. On the other hand, no general trend can be derived from this study, except that the size of the price difference amplifies the corresponding response to that price difference. However, it is obvious that the timing or the direction of the price difference (increase or decrease of the price) may be another aspect that should be further investigated. Therefore, this will be analyzed in the case study on demand-driven load shifting in Chapter 4.2.2.

	Summer	Summer 25	Summer 75
Basic Savings	96.12 €	128.70 €	64.75 €
DS Savings	204.78 €	184.50 €	191.19 €
DS Savings DC	233.10 €	208.78 €	193.05 €
DS Savings DR	204.78 €	184.50 €	191.19 €
DS Savings DCR	233.13 €	208.94 €	193.12 €
Basic ESP Sale	1,801.33 kWh	529.81 kWh	3,216.12 kWh
ESP Sale DS	1,087.00 kWh	190.85 kWh	2,394.69 kWh
ESP Sale DC	874.35 kWh	21.41 kWh	2,411.38 kWh
ESP Sale DR	1,087.00 kWh	190.85 kWh	2,394.69 kWh
ESP Sale DCR	874.58 kWh	21.09 kWh	2,411.97 kWh
Basic ELA	485.52 kWh	648.42 kWh	317.02 kWh
ELA Change DS	0.0%	-0.73%	-0.18%
ELA Change DC	0.0%	-1.81%	-0.90%
ELA Energy DR	0.0%	-0.73%	-0.18%
ELA Energy DCR	0.0%	-1.98%	-0.90%
Charge Quantity	659.02 kWh	343.72 kWh	821.99 kWh
Charge Change DC	22.94%	33.91%	1.78%
Charge Change DR	0.00%	0.00%	0.00%
Charge Change DCR	22.92%	34.10%	1.86%

Table **4.3**. Composition Results with ESS

- **Results for different market compositions**

  The market composition of suppliers and demanders in the VEU is a very influential factor for internal energy exchange, as the case study in Chapter 3.1 shows. For a storage extension, it is therefore interesting to see whether the impressions can be confirmed or divergent insights can be gained. For the purpose of clarity only the corresponding results for the variation of the summer scenario is shown in Table **4.3**.[7]. The analysis of the varied market compositions essentially

[7]Further scenarios are available in the digital appendix in the collected results.

confirms the observations from the seasonal scenario comparison and that the market composition retains a significant influence on the behavior of the VEU.

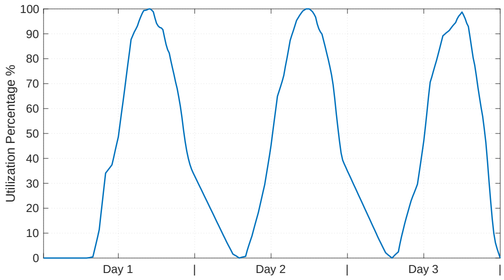
If the fraction of possible suppliers is reduced to 25% (column 2 in Table **4.3**), the total available energy supply decreases and energy demand increases in turn. In principle, this has a beneficial effect on total VEU savings (row 'Basic Savings'), since the reduced energy supply can serve more lucrative demand. Therefore, the amount of ELAs rises (row 'Basic ELA') and yields higher margins than in the baseline scenario (column 1). In turn, the reduced energy supply becomes a limiting factor for the use of ESSs, so that the achievable savings increase by ESSs is lower (row 'DS Savings'). Another limiting factor is the total available storage capacity, since only suppliers are equipped with ESSs. Therefore, much less energy is charged overall (row 'Charge Quantity'), but there is also still supply available (rows with 'ESP Sale'). Even the doubling of the total capacity does not exceed the remaining supply, but instead leads to more substitutions of ELA rows with 'ELA Change') in order to use existing capacities.

The increase in the fraction of possible suppliers to 75%, in contrast, creates a significant oversupply of energy, which initially leads to a substantial increase in savings when ESSs are taken into account (row 'DS Savings'). However, the low demand in the system in general is then the limiting factor, which becomes obvious with the minimally increased savings for doubling the storage capacity (row 'DS Savings DC') in comparison. In fact, despite the theoretically available energy quantities (rows with 'ESP Sale'), the increase in savings there is mainly explained by substituting ELAs. Furthermore, the minimal increase in charging activity results in more energy being sold once again to external ESPs. An imbalance between supply and demand therefore still leads to a rapid shortage or bottleneck on either side, but the use of ESSs helps to mitigate these extremes.

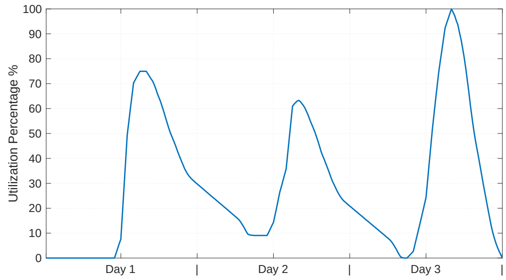
The variations in market composition therefore also offer the opportunity to fundamentally question the purely internal use of storage capacities. Especially in a community with such large temporary supply or demand surpluses, it can happen that ESSs are not used to their full extent internally. If the VEU anticipates this circumstance through the model, it can actively use the advantage of free capacities or derive flexible energy supply (rows with 'ESP Sale') and offer this available flexibility externally. In addition, with existing local flexibility markets (LFMs) it will be possible that the energy is still be used locally.

To determine price limits that make participation in such a LFM attractive to

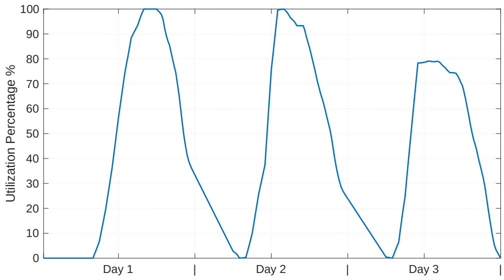
VEU can again be decided on the basis of internal planning like in Chapter 3.2. All necessary tariff data $v_(n, t)$ and optimized load profiles $ol_(t, n)$ are available. The data can also be used to determine potential improvements in the optimized charge $ch_{t,k,s}$ and discharge $dc_{t,k,d}$ quantities. However, as there is no direct link between a charging process and the discharging process in the model, and thus also not between two participants, the identification of exact price limits for external trading is not quite as simple as in Chapter 3.2. The absence of a direct connection may also leads to problems for a later distribution of the savings. Therefore, Chapter 4.1.3 analyzes the problem in more detail and aim to develop an effective algorithm to identify an indirect connection between two participants when storage processes are used while optimally solving the problem at the same time. A more detailed analysis of the optimized individual results already shows further structural characteristics of the problem, which are necessary for a realization for the desired algorithm.



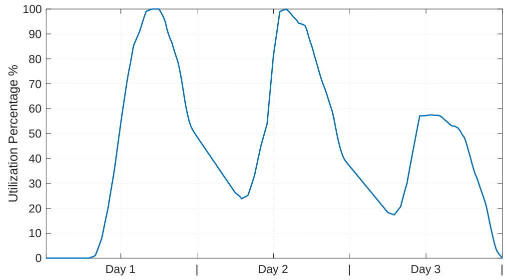
(a) Summer Scenario



(b) Autumn Scenario



(c) Spring Scenario



(d) Spring DCR Scenario

Figure **4.1**. Storage Utilizations

- **Findings on storage utilization**

  Figures **4.1** shows the utilization curves of the aggregated ESSs from different scenarios, each representing a planning horizon over three calculated days. Due to the natural production cycle of PV systems, there are observable daily charge cycles that also follow this pattern. First, the energy storage device is charged during a charging phase until around afternoon, as far as possible or appropriate. After the charging phase, there may be a stagnation phase in which no storage processes are used at all for some time. This phase is not always present and have no influence on the system, but is followed by the more important discharge phase, which lasts into the night or morning hours until a new charge cycle begins. Note that a storage process that deviates from the respective phase of the storage cycle can never be observed in the solution data, because the storage rate is a limiting factor for the system. This means the system will use the limited periodic capacity in only one way. The curve that can be seen in the first figure, **4.1**a, shows a very common utilization of the ESSs in summer. This always leads to closed storage cycles in which the best possible charging of the energy storage is achieved, followed by a complete discharge of the stored energy before a new storage cycle begins. This indicates that in each storage cycle, the stored energy must be consumed in the same cycle in order to achieve the maximum saving.

In the second partial figure **4.1**b with the utilization curve of autumn, the situation is different. Between Day 1 and Day 2, there are energy amounts that are kept in the energy storage and not used in the same cycle. A complete discharge in each cycle is therefore no longer advantageous and this must be taken into account with regard to an optimal design of the internal energy flows of the VEU. With a planning horizon of only one day, the significance for operational use is much lower, as no cross-cycle utilization scenario can occur. With an extended planning horizon, on the other hand, such effects can not only be taken into account, but above all the right conclusions can be drawn from them. Overall, the maximum saving result when such cross-cycle utilization occurs is based on the fact that the maximum available energy may not be kept locally. It is only more economical to hold the energy longer than to use it in the same cycle. In the curve shown, a shortage of energy supply is responsible for this occurring effect and reducing the savings potential of using the energy in the same cycle. The VEU can therefore analyze the existing results and identify the reason for the cross-cycles if, for example, they want to keep more energy local with possible short-term solutions.

Figure **4.1**c does not show a highly deviating utilization curve in spring, even if the storage is not fully loaded on Day 3. The course of the curve, however, exposes another very important detail why it makes sense to directly consider several days in the planning. The last planning day will always lead to a complete discharge of the energy storage. Storing energy over the planning horizon is a loss due to the model's objective function, as the amount of energy can alternatively be sold to the ESP. Therefore, it is not possible that an optimal solution still holds energy quantities at the end of the planning horizon without a corresponding restriction that requires a minimum state of charge. However, for more precise detailed planning and in order to better deal with deviations, it is more appropriate to use the rolling planning concept previously mentioned instead of choosing short planning horizons, which is confirmed once again here.

Figure **4.1**d additionally enhances the understanding of the cross-cycle charging of the ESS. While in autumn it still looks as if such an effect can only occur if the ESSs cannot be fully charged, the curve in spring with doubled storage capacity and storage rate is clearly different. On Day 1 and 2, full charging takes place and yet the energy storage has cross-cycle utilization present. These then remain active on Day 3 before full discharge occurs again at the end of the planning horizon. It is therefore not easy to predict what the optimal utilization patterns will ultimately look like, at least if a longer period is considered. However, this question will still be essential for a potential algorithm, as shown in Chapter 4.1.3.

The individual utilizations give additional insights that are important for further consideration. Table **4.4** shows an excerpt of the solution data from the spring scenario, in which the identification of the ESS is given in the first row and the associated efficiency levels in the second row. This is then followed by the utilizations between Period 31 and Period 40. All storage devices receive their first charge during the displayed time interval, which raises the utilization degree above 0. It is of interest that it can be clearly seen that the two most inefficient energy storage devices (53S and 56S) are charged before the two more efficient energy storage devices. This does not always have to be the case, but it shows that the preference for using the more efficient storage units is not the time aspect. Thus, for a greedy-based solution approach, the best storage devices does not need to be loaded first, but clearly with the profit-maximizing loadings whenever they occur. Determining exactly which ones these are must be examined in the next section.

Storage	53S	40S	56S	71S
Efficiency	90%	94%	90%	91%
Period 31	0	0	0	0
Period 32	0	0	0	0
Period 33	0,044	0	0	0
Period 34	0,044	0	0	0
Period 35	0,044	0	0,019	0
Period 36	0,044	0	0,030	0,041
Period 37	0,044	0	0,102	0,041
Period 38	0,044	0,109	0,102	0,122
Period 39	0,144	0,189	0,145	0,122
Period 40	0,144	0,189	0,245	0,183

Table **4.4**. Individual Storage Utilization (excerpt from solution data of the spring scenario)

4.1.3. Algorithm Possibilities

The integration of ESS does not change the main objective of a VEU in principle. The internal energy exchange is only extended, which is why the objective function remains unchanged. The actual integration is implemented in the modified load balance equation (4.2) which now enables a different composition of the savings-related optimized load profiles of the participants $ol_{t,n}$. In addition to the period-specific energy exchange through the ELA, the alternative for delayed energy exchange through the storage processes is included there. The resulting overall problem is then composed of two competing subproblems and with the goal to optimize this local energy exchange. The new delayed energy exchange sub-problem thereby decides which storage processes are setup to influence the resources available by the storage in which period. The resource competition for capacity between different periods is the challenge for making optimal decisions about which storage processes should be established in a given period. This is especially the case if an efficient and fast method is wanted as an alternative for the available linear program.

In literature, optimization models that consider ESS are often formulated as mixed-integer program and alternatively solved with dynamic program approaches. Such dynamic program formulations can be used for the presented problem as well. In this thesis, however, the structural insights of the linear program solutions are used instead to achieve opportunities for an effectively applicable method. The aim of this method is to complement the assignment of the maximum saving flow algorithm (MSFA) presented in Chapter 3.1.2. The advantage of such an extension would be that it allows an allocation between supplier and demander also for storage processes, which is useful for subsequent distribution issues within a VEU.

From the case studies in Chapter 4.1.2, it can be concluded that at the end of the planning horizon, the mathematical model will always empty all ESSs, so that $\sum_{k\in K} soc_{T,k} = 0$. As long as there is no constraint that requires a minimum state of charge, it is always more advantageous to use remaining energy quantities that are still available in some ESS. If initially the storages are also discharged ($\sum_{k\in K} ic_k = 0$), the assumption can be made that all storage processes can be related to suppliers and demanders. Each charging process $ch_{t,k,s}$ in period t from supplier s to storage k can then be directly assigned at least to one time-delayed discharging process $dc_{t+x,k,d}$ from storage k to a demander d within a time delay $x \in \{1, \ldots, T-t\}$. If this indirect allocation of the energy flows is possible, this substitutes the decision about individual storage processes. Alternatively, decisions can then be made about the time-delayed P2P connections between two participants, which in principle represents a greedily solvable linear problem and can be solved with the MSFA, among others. Figure **4.2** illustrates the difference of the period-specific ELA and the cross-period delayed energy load adjustment (DELA). However, since DELAs can only be established by using the limited resource of ESSs, this property can not directly be integrated in a successful implementation.

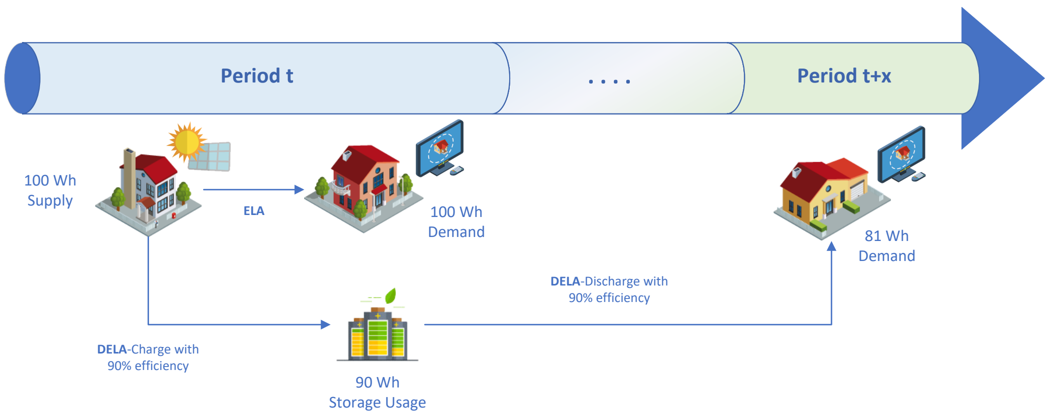


Figure **4.2**. Difference between ELA and DELA

Figure **4.2** shows, how the efficiency α_k will affect the energy exchange of a DELA compared to a ELA between the same participants. Alternatively, this efficiency loss due to α_k can also be taken into account when determining the savings rate for a

DELA.[8] This savings rate depends on the difference between the demand and supply rates of the associated participants in the particular periods and is therefore given by $w_{s,d,t}^{DELA} = (dr_{d,u} - sr_{s,t})$ with $u \in \{t+1, \ldots, T\}$. If now the efficiency loss is considered, the effective achievable savings rate is $\tilde{w}_{s,d,t}^{DELA} = w_{s,d,t}^{DELA} \cdot \alpha_k^2$ (the loss has to be considered for both storage processes). From this general consideration and the insights of the case studies from Chapter 4.1.2, two principles can be derived that could provide orientation for an algorithm. An ELA will be more advantageous than alternative DELA until the effective savings rate $\tilde{w}_{s,d,t}^{DELA}$ exceeds its own savings rate $w_{s,d,t}^{ELA}$. The substitution of an ELA with a DELA also only achieves an savings increase, given by $\Delta\tilde{w}_{s,d,t}^{DELA} = \tilde{w}_{s,d,t}^{DELA} - w_{s,d,t}^{ELA}$. This in turn implies that the system will prioritize DELAs that do not substitute ELAs until their savings rate is lower than the maximum possible savings increase $\Delta\tilde{w}_{s,d,t}^{DELA}$ of a DELA that is replacing an ELA. From these insights, a rough sequential framework can already be derived, which determines feasible P2P connections. In the next section before proposing an alternative method for allocating the savings in the storage processes. The explanations of the extended MSFA can be found in Appendix C.

It is acknowledged, that there may be storage processes where no allocation between supplier and demander is possible. Due to the savings-maximizing objective function, for charging processes $ch_{t,k,s}$ such a situation can only occur, if restriction demands a minimum state of charge at the end of the planning horizon. For discharges $dc_{t,k,d}$ in turn a allocation between supplier and demander is prevented, if there is an initial state of charge in the planning horizon $ic_k > 0$. In this case, an allocation can still be forced by having a dummy supplier in period 0 and a dummy demander in period $T + 1$.

4.1.4. Charge Cycles

To determine an optimal selection of DELAs is at first sight a basically simple combinatorial problem. It has even similarities with the well-known knapsack problem. The limited storage capacity (*permissible weight in the knapsack*) is to be optimally filled with available DELAs that generate a saving (*worth*) for a certain share of the storage capacity (*weight*). Since the two decision-relevant parameters, *weight* and *worth*, are usually independent of each other for a typical knapsack problem, the solution of this problem type is known to be NP-hard. Therefore, a simple standard approach like

[8] Since the saving of all P2P connections is based on the amount of energy consumed times the savings rate.

e.g. a greedy-based approach cannot determine the globally optimal solution with certainty. However, in the case of ESSs and the examined DELA, there is a linear dependency between the storage capacity claimed by the DELA and the savings that can be achieved as a consequence. This means that a procedure such as the MSFA in turn may be able to determine a globally optimal solution. What makes this problem more complicated is that an additional weight has to be considered here. This time-related weight is needed since a DELA has to remain in the ESS for a certain period of time. This duration of a DELA is independent of its yield and may block other more favorable DELAs. The complicating factor for a greedy-based approach reappear and the aim therefore must be to structurally eliminate the temporal component so that only linear dependencies continue to exist.

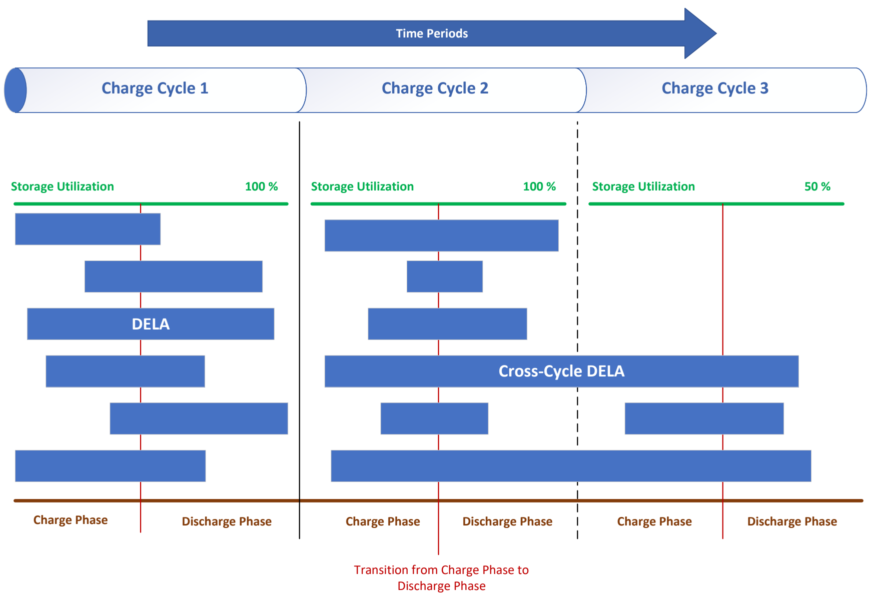


Figure **4.3**. Charge Cycle

Figure **4.3** illustrates that this desired structural feature can be observed when the well-known phenomenon of charge cycles is present. Each charge cycle is always divided into two phases that follow a fixed sequence and are strictly separated from each other. A charging phase is always followed by a discharging phase before a new cycle begins. If ESS are considered in combination with PV systems, these charge cycles normally follow a 24-hour rhythm. This begins with the charging phase when energy production starts in the morning and then leads into the discharging phase, which starts at the end of energy production and can last overnight. If the planning is limited to one charge cycle, the DELA will utilize the storage as in charge cycle 1

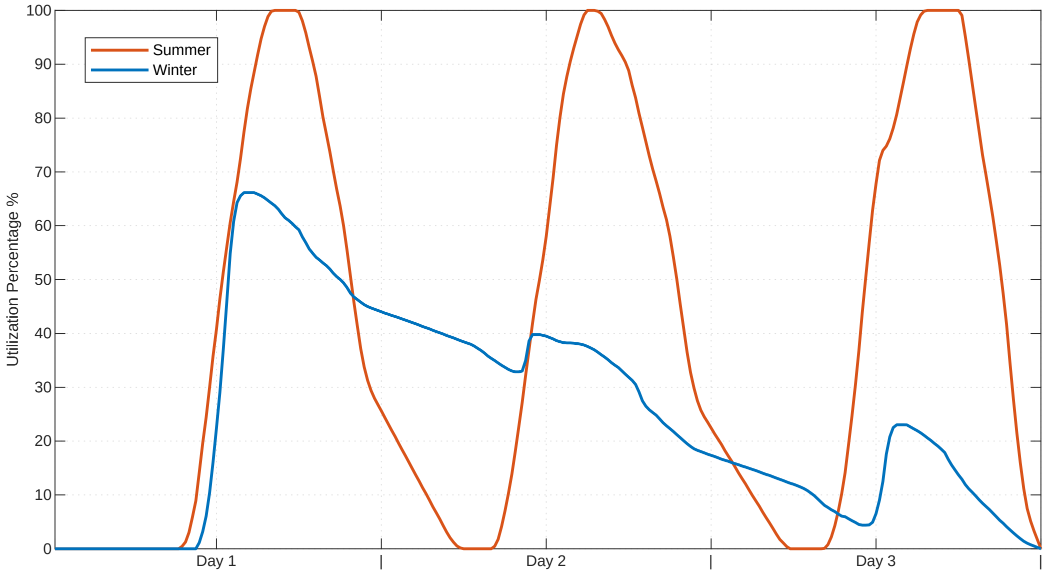


Figure **4.4**. Example for Storage Utilization

of the figure. In this case, the DELAs are in direct competition with each other, since they have exactly one charging and discharging process within the cycle. Each DELA can therefore be evaluated independently of time and purely by its savings, and the time-related component described above does not exist.

The time-related problem becomes present only if several successive charge cycles are considered and planned simultaneously. In the figure, this can be seen in charge cycles 2 and 3, in which cross-cycle DELAs can occur. These are DELA whose charging and discharging processes are in different charge cycles. A cross-cycle DELA therefore utilizes the storage over a longer period of time and thus competes with all other potential DELAs in the involved charge cycles. In the same time, several shorter DELAs could be more lucrative overall, the time-related component is present and complicates the decision process. The fact that an optimal solution may include cross-cycle DELAs or longer holding periods in general can be seen in Figure **4.4**.[9] The storage utilization in summer shows a daily complete charging and discharging of the ESS in this case, which corresponds to the described ordinary charge cycle. In winter, on the other hand, the ESS are fully discharged only at the end of the planning horizon and fractions of the stored energy are kept longer for result-maximizing use.

This indicates that the time-related component must be considered again if the planning horizon covers several days or multiple charge cycles. A one-day or one-cycle

[9]This finding is also discussed in Chapter 4.1.2 in the results for the storage utilization.

schedule would not be desirable either, because in this case such result-maximizing cross-cycle DELAs will never occur, as explained before. A methodological alternative to the model must therefore be able to determine whether one cross cycle DELA is more profitable than two single cycle DELAs for an optimal decision for the DELAs. However, this aspect is not further treated in this thesis. Consequently, a feasible distribution of storage-related savings cannot be based on the exact allocation of participants to DELAs, as is the case with ELA, since the results provided by the model do not determine such information. Intuitively, the savings can also be divided by the respective share of participants based on their amount of energy charged and discharged. The problem in this context is that such a saving distribution rely on the values for the charging $ch_{t,k,s}$ and discharging $dc_{t,k,d}$ variables. Why this can lead to inaccuracies in the distribution is explained in more detail in the next section.

4.1.5. Saving Distribution with ESS

The critical aspect in the determination of the charging $ch_{t,k,s}$ and discharging $dc_{t,k,d}$ variables in the model is the relationship between the origin and the target of each storage process. The efficiency α_k has to be considered for charging processes $ch_{t,k,s}$ only in the storage balance (Equation (4.1)):

$$soc_{t,k} = soc_{t-1,k} + \sum_{s \in S_t} ch_{t,k,s} \cdot \alpha_k - \sum_{d \in D_t} dc_{t,k,d} \quad \forall\, k \in K, t \in \mathcal{T}. \tag{4.8}$$

In contrast, for discharging processes $dc_{t,k,d}$ the efficiency α_k is only considered at the target of the discharge process, i.e, the energy load balance of consumer $d \in D_t$ (Equation (4.2)):

$$\begin{aligned} ol_{t,n} = pl_{t,n} - \sum_{(n,d) \in B_t} bal_{t,n,d} + \sum_{(s,n) \in B_t} bal_{t,s,n} \\ - \sum_{(k,n) \in BCh_t} ch_{t,k,n} + \sum_{(k,n) \in BDc_t} dc_{t,k,n} \cdot \alpha_k \quad \forall\, n \in N, t \in \mathcal{T}. \end{aligned} \tag{4.9}$$

This is due to the fact that the energy loss that occurs in the storage processes must be taken into account only once, namely at the target of the process. However, this also means that in the values of charging $ch_{t,k,s}$ and discharging $dc_{t,k,d}$ variables the storage efficiency α_k is not directly involved, but considered by modeling the two balances. The values therefore do not correspond to what the consumer actually received in the end (but in contrast, consider the amount of energy that the charging supplier expends). While it is quite possible to accept an saving distribution based on the discharging $dc_{t,k,d}$ variables to determine the share of a participant. This thesis would also like to provide an adjusted variant where the storage efficiency α_k is taken into account. The adjusted savings distribution procedure therefore determine the specific share of each ESS in the total savings and consider the storage efficiency α_k for the discharging processes in this calculation:

$$sav_k = \sum_{t \in \mathcal{T}} \sum_{d \in D_t} v_{t,d} \cdot dc_{t,k,d} \cdot \alpha_k - \sum_{t \in \mathcal{T}} \sum_{s \in S_t} v_{t,s} \cdot ch_{t,k,s} \quad \forall\, k \in K. \tag{4.10}$$

This calculation of storage-related savings can then be done iteratively for each ESS. All storage-specific savings values sav_k are then divided between the two groups (suppliers who charge the ESS and consumers who discharge the ESS) that are responsible for the savings. Therefore, the benefit for the involved participants involved can no longer be determined individually or on the basis of a P2P connection, since there are no direct links between participants. Alternatively, a generally applicable distribution may be used[10] or a separate distribution may be defined for each ESS, if there is a sensible justification for this. In the context of this thesis, this topic is not further analyzed and only a choice of the generally applicable distribution is provided in the implementation.

Based on the savings distribution over the two relevant groups of storage processes (charging and discharging), it will be determined which share individual participants have contributed to this. According to this share, the savings of the charging suppliers and the discharging consumers are then distributed. In the numerical results, this corrected distribution (Sheet 'Savings_Distribution (Storage)') as well as the simple intuitive distribution (Sheet 'HouseHoldStats') are presented. The total storage-specific part of the savings is fully distributed in both cases, but for the individual participants there are marginal deviations in each case due to the provided correction. A VEU can decide which procedure they will follow.

[10]For example, with a specification that both sides of the involved storage processes achieve a share of 50% savings each

4.1.6. Storage Discussion

In summary, it is evident that a VEU with the ability to shift available energy supply to other periods is better positioned and more flexible. The storage case studies in Chapter 4.1.2 have shown that the storage processes of the ESSs offer significant added value compared to a system limited to purely periodic energy exchange. The achievable savings values even significantly exceed the possibilities of period-specific ELA in most cases, although this is not a universally valid statement. Despite the energy loss that cannot be avoided during the conversion processes, the integration of ESSs is therefore overall recommendable. The main advantage is that the stored energy can always be used for the most lucrative demanders that are available throughout the rest of the planning period. This can also be seen by the fact that the energy demand of the participants with the highest ESP tariff values are served first in descending order. It has been shown that the extent of achievable savings depends on three key factors:

1. Total and periodic energy supply and demand quantities
2. Available storage capacities of related ESS
3. Storage rate of related ESS.

The available total and periodic supply as well as demand quantities limits the potential of savings through storage processes, just as in the case with period-specific energy exchange. If the period-specific amounts of available energy are not a limiting factor, the technical characteristics of the ESSs constrain the achievable savings. Thereby, the available capacity is by far the most important factor, which clearly dominates the storage rate, as even a decreasing marginal utility can be seen with increased capacity. The subordinate role of the storage rate as a technical parameter is reflected in the case studies by the fact that it rarely occurs as a limiting factor in the periods. This does not mean that the storage rate has no influence on the system at all. Indeed, if the ESS is not able to use the available capacities due to insufficient storage rates, there is a general problem with the used equipment. Faster storage operations are quite capable of further optimizing local power flows, even if this is not significantly monetarily measurable. Hence, for realistic scenario values, the storage rate will always be secondary to pure storage capacity, and also for investment decisions the capacity should be clearly prioritized. Finally, the application of DS makes it reasonable to apply larger capacities in the residential environment, as the ESS can be used more extensively due to the increased energy supply and demand. Furthermore, the operational decisions made within the framework of VEU optimization for a ESS can also be relevant for strategic decisions, such as future investments. The influence and monetary added value of new or upgraded devices can thus be easily evaluated for different scenarios and an estimate of the payback period can be given. In the strategic planning, details such as the lifetime of an ESS must also be taken into account. For operational planning, these details can still be neglected due to the short planning horizon.

The importance of a multi-day planning horizon should also be emphasized, as the analysis revealed. The longer planning horizon makes sense not only because of the day-ahead planning that is common in the energy sector, but also as it can add value here. The utilization curves of the ESS show that by operationally optimizing over more than just one day, economically viable periods can be identified and considerations can be made where energy should remain in storage for a longer period. On the other hand, from a technical perspective, it may be determined whether long-term holding periods of energy have a negative impact on the life-cycle of the involved ESS. However, such an analysis is outside the scope of this work, but the data of the current optimal solution can in principle be used for such an analysis as long-term holding periods can be identified and also the average holding times in the ESSs. Furthermore, it is correct that long holding times lead to less energy being used locally, because the available capacity is then not fully utilized within a charge cycle. This is a negative effect from an ecological point of view, even if it may make economic sense. Thus, depending on the objective of the VEU, there could be an environmental constraint here that forces a daily maximum use of the ESS. However, the more reasonable alternative is to worth the economically optimal solution and use the analysis of the data to respond appropriately. If long-term observations suggest or indicate that there is a structural problem for this operational behavior, investments could be initiated, for example. Alternatively, remaining local energy or residual capacity of the ESS can be traded in local markets such as local energy market (LEM) and LFM. In this way, energy continues to be utilized locally, but with the added benefit of maximizing savings for the participants. As described in Chapter 3.2, the information from internal optimization is a good starting point for making meaningful external decisions. This is also valid when an ESS is taken into account. The values that have to be minimally achieved in an external auction market for certain energy quantities can also be derived in this case and only a well predicted price decision has to be made for the related energy quantities.

The charge cycles of an ESS can also be observed in the storage utilizations. These cycles allow, in principle, to eliminate the time-related component in the development of an algorithm, so that it can find the optimal solution by applying an extension of the MSFA. However, so far this only applies if the planning horizon is limited to one day and there is therefore only one charge cycle. A multi-day consideration in turn results in several charge cycles and an optimal selection of DELA is then no longer possible if the type of charge cycle cannot be clearly identified. Although in this thesis this important intermediate step is not solved, it does provide alternative approaches for the individual distribution of the achieved savings based on the optimal solution of the model. The savings distribution approach given in this thesis provides results that take into account the varying efficiency of individual ESS and apply them correctly to the discharge operations involved.

4.2. Shift in Demand

Demand side management (DSM) provides consumers, and thus also communities in which they participate, with a concrete plan for a specific part of the occurring energy demand, namely, for smart or controllable devices. As indicated in Figure **4.5**, non-time-critical tasks of such devices whose scheduling has a certain flexibility can be used for this purpose. In the figure, the execution time (orange) of the task must be scheduled in a fixed time frame (green) in a way that the resulting energy demand of the scheduled task can be served cost-efficiently. This flexibility offers the possibility to shift the demand into periods that are favorable for the individual participant, but also that a VEU may control the demand in a way that it can better utilize times of local energy production.

Generally, in the context of DSM, devices with power consumption are divided into fixed, shiftable, and elastic applications, see e.g. in Barbato and Capone (2014). This classification may be valid from a purely technical point of view, but in this thesis a classification of devices is chosen that is based on modeling aspects:

Fixed devices are devices whose power consumption cannot be shifted in time. These include, for example, TV devices or personal computers whose tasks (here entertainment or work) cannot be postponed and which consume electricity as long as the task is in progress.[11]

Shiftable devices are devices whose power consumption can be shifted to other time periods. Their need that triggers consumption does not necessarily have to be satisfied

[11]Note, that the consumption value can fluctuate over time and does not have to be constant.

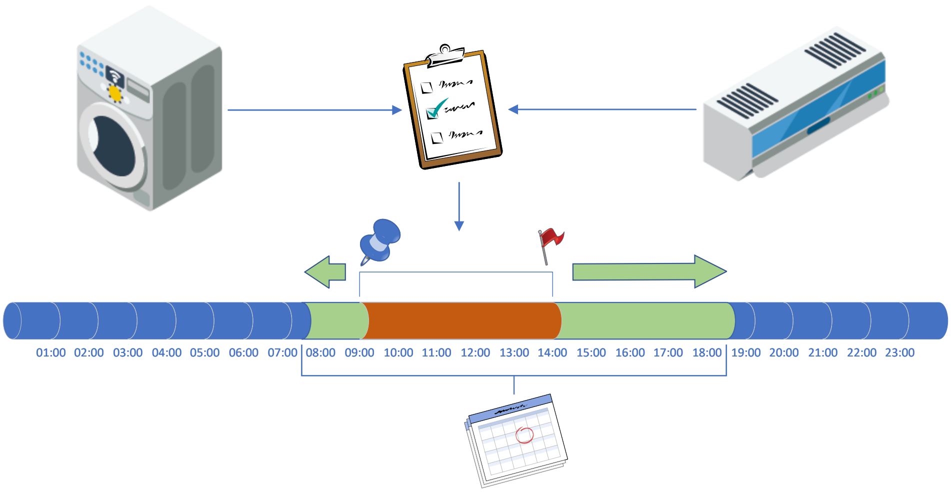


Figure **4.5**. Demand Side Management

at a specific time. A practical example of this is the washing machine. Its task is to wash the laundry, but it is not relevant when exactly this is done, it is only necessary that it is done within a certain time frame. Deciding on the start time for a job on a shiftable device is therefore a valid optimization approach.

Comfort devices are also devices whose power consumption can be shifted to other time periods. They basically behave like shiftable devices but differ in one central point – the comfort of the user must be taken into account. Hence, when choosing the start time for a task of such a device, a time has to be chosen that satisfies the demand at the lowest possible cost, while not compromising a certain level of comfort for the user. This category mainly includes devices from the area of heating, cooling, ventilation, and air conditioning.

The often used category of *elastic devices*, like in Barbato and Capone (2014), is replaced in this thesis by the more appropriate category of *comfort devices*. The reason for this is that elastic devices either are part of the fixed or shiftable dvices or if this is not the case, the actual characteristic for a distinction is the considered comfort of the user. That means, shiftable devices and comfort devices differ practically only by the attitude of the concerned user of this device. If the user defines the time frame for a possible shift, it is a Shiftable Device. If, on the other hand, the user only determines which comfort level he wants to keep and let the system vary the time frame, it is a comfort device. The most important category for the integration of DSM in this thesis are shiftable devices, as the consumption of *fixed devices* can already be aggregated in the parameter for predicted load $pl_{t,n}$. The category of comfort devices in turn has a strongly subjective component – the comfort values of a user. These hard-to-quantify values need to be estimated or require empirical studies for a meaningful evaluation of the desired comfort. Even if empirical information is available, a non-linear formulation with extensive modeling depth (see i.e. Schlereth and Skiera (2012)) may be needed.

Thus, integrating this level of complexity, should only be considered if this step provides added value. The time frame of comfort-based load shifting is often rather limited, because the device user continues to have a desire that needs to be satisfied. For example, it may be advantageous to start the heating or air conditioning half an hour later and delay the desired temperature for a short time. The device user only forgoes immediate satisfaction, and therefore comfort, because he places the monetary incentive above this abstract comfort value. The economic impact may be rather small in this case when considering DSM only, because the time frames for the shift are comprehensively short. The exception, of course, is if the energy load shift hits exactly the period in which there is a price shift or more internal supply that can then be used. This changes if the focus is placed on demand response (DR) instead of an investigation of DSM. In this case, the specific objective of the analysis and optimization is the targeted change of consumer behavior through dynamic pricing. Since comfort is an important factor in DR approaches anyway and the complexity required for comfort devices is therefore an integral part in any case, it does not need to be integrated additionally. However, since this thesis only examines approaches to DSM and the economic added value without dynamic pricing is low, the explicit modelling of comfort devices is not included.

Another special device, that is sometimes categorized as a DSM (elastic) device is the EV. Since such a vehicle is not a purely demand-driven device, but offers a way to shift supply to other time periods, it is treated separately in this thesis. This device is therefore not be discussed and modelled in the context of DSM, but treated separately in Chapter 4.3.

In order to integrate shiftable devices into the existing model, data and relationships must be considered first:

- Which household has which devices
- What kind of tasks occur for the device
- Number of tasks for the device in the planning horizon
- Acceptable time windows for the tasks (earliest start and latest end times)

- The power consumption of the tasks over time
- The duration of the tasks.

This means that the needed data can be limited to the following:

- Participants
- Periods
- Devices
- Tasks
- Task types.

For a better overview of the possible data provision and how tasks can be designed, a small example is given. Consider a participant who plans two different jobs for the washing machine for the next day. Both jobs can be scheduled in the same flexible time frame and there is no specific preference. It is assumed that the set-up for a task is included in the duration times of the jobs, so set-up times do not have to be considered separately. Since the two jobs can not overlap in time, a sequence of the two jobs has to be determined. This can be forced directly by the system, either by asking the participant to make a selection when entering the job details or by the system itself by deciding which job is to be given priority. Alternatively, the system can determine the optimal sequence through the model.

4.2.1. DSM Model Extension

The sets for participants $n \in N$ and periods $t \in \mathcal{T} := \{1, \ldots, T\}$ are already present in the model of the basic formulation. For the optimization objective, the set of all tasks $j \in J$ is of central importance, since the optimal scheduling of the tasks is the objective of this DSM-related subproblem. For these sets, binary decision variables $x_{j,t}$ can now determine in which period t a job j should be started. A job j with the earliest possible start time ST_j, the latest possible end time ET_j and the job duration of du_j needs to start precisely once in its time interval, which can be formally guaranteed by the following constraint:

$$\sum_{t=ST_j}^{ET_j - du_j + 1} x_{j,t} = 1 \quad \forall\, j \in J. \tag{4.11}$$

From the determination of the $x_{j,t}$ values, the energy consumption $sl_{t,n}$ in the corresponding periods t for all tasks of a participant n can be obtained. This requires that the model receives information about which participant $n \in N$ is assigned a task $j \in J$ and is given by the binary parameter $y_{n,j}$, that takes the value 1 if this assignment exists. The determination of the $sl_{t,n}$ values is then based on the summed periodic energy values jl_j of all tasks $j \in J$, if these can be assigned to a certain participant with $y_{n,j} = 1$. However, this should only apply to the periods $t \in \mathcal{T}$ that are in the selected time frame of the job, which is guaranteed by multiplication with the decision variable $x_{t,j}$. In order to ensure that all periods in the time frame are recognized by the one-time decision variable $x_{t,j} = 1$, a summation method known from scheduling is used. Since the decision variable $x_{j,t}$ can only have the value 1 once, due to the model, the summation is therefore formulated in such a way that the value must be 1 as long as a period t is within the operational time frame of the job. This leads to the following equation for the $sl_{t,n}$ values:

$$sl_{t,n} = \sum_{j \in J | y_{n,j}=1} jl_j \cdot \sum_{u=\max(ST_j, t-du_j+1)}^{\min(t, ET_j)} x_{j,u} \quad \forall\, n \in N, t \in \mathcal{T}. \tag{4.12}$$

In case data provisioning does not prevent simultaneous execution of two tasks on one device, the model requires a set of all devices $m \in M$ and the binary parameter $z_{m,j}$, which will take the value 1 if a task j is assigned to the device m. To avoid that a device is occupied by more than one task at the same time, all decision variables $x_{j,t}$ where job j is assigned to a device m must be summed up so that the sum is less than or equal to one in a given time frame. For a valid consideration of the operational time windows of the jobs, the summation method used in Equation (4.12) can be used again. This leads to the following constraint:

$$\sum_{j \in J | z_{m,j}=1} \sum_{u=\max(ST_j, t-du_j+1)}^{\min(t, ET_j)} x_{j,u} \leq 1 \quad \forall\, m \in M, t \in \mathcal{T}. \tag{4.13}$$

Finally, the values $sl_{t,n}$ for the periodic energy demand of the DSM devices of participant n have to be integrated in the basic model from Chapter 3.1.1 or the extended model with ESS from Chapter 4.1.1. A core issue with this integration is that a role change of the participants from supplier to demander or vice versa is not allowed. This is necessary as otherwise the participant with the best conditions could purchase the whole energy demand of the VEU by its external ESP and distribute it via the ELA mechanism. Since negative values represent the energy consumption in the model, this implies that it should not be possible for supplier to have negative values. However, the additional energy consumption of the DSM devices $sl_{t,s}$ could lead to such negative optimized energy load values $ol_{t,s}$ for a supplier $s \in S_t$, if $sl_{t,s} > pl_{t,s}$. This would be considered infeasible, and it must therefore be possible for a supplier to cover the energy consumption $sl_{t,n}$ not only by its own energy production. The condition for such a division of the DSM energy consumption is given in the modification of the load balance equation (3.2) or (4.2) if ESS are considered (additions are highlighted in green):

$$\begin{aligned} ol_{t,n} = pl_{t,n} - sl_{t,n} + hc_{t,n} - \sum_{(n,d)\in B_t} bal_{t,n,d} + \sum_{(s,n)\in B_t} bal_{t,s,n} \\ - \sum_{(k,n)\in BCh_t} ch_{t,k,n} + \sum_{(k,n)\in BDc_t} dc_{t,k,n} \cdot \alpha_k \quad \forall\, n \in N, t \in \mathcal{T}. \end{aligned} \tag{4.14}$$

Next to the energy consumption of the DSM devices $sl_{t,n}$ in period t for participant n, here also the decision variable $hc_{t,n}$ is introduced. This dependent auxiliary variable is intended to allow that the required amount of energy for $sl_{t,n}$ does not necessarily have to be included in the values of the optimized energy load. These parts or even the total amount of energy required for $sl_{t,n}$ must therefore also be considered separately in the objective function:

$$\max Z = \sum_{n\in N}\sum_{t\in\mathcal{T}} v_{t,n}(ol_{t,n}) - \sum_{n\in N}\sum_{t\in\mathcal{T}} dr_{t,n} \cdot hc_{t,n}. \tag{4.15}$$

Since the energy quantities of the auxiliary variable $hc_{t,n}$ are always settled at the demand rate $dr_{t,n}$ of the participant n in the period t, this variable will only take positive values if this is unavoidable. Such necessity can be enforced by constraining the optimized load profiles $ol_{t,s}$ of all supplier s in every period t to be greater than or equal to 0:

$$ol_{t,s} \geq 0 \quad \forall\, s \in S_t, t \in \mathcal{T}. \tag{4.16}$$

Together with the load balance equation, the case of negatively optimized load profiles is prevented and at the same time a separate accounting via the auxiliary variable $hc_{t,n}$ is enforced. This limitation was previously not necessary in the model, because the role association restrictions (4.3) and (4.4) automatically enforced these limits. In contrast, these two constraints have so far only been responsible for the balance between internal supply and internal demand. In this case, this is no longer possible. The additional energy consumption $sl_{t,n}$ of the DSM devices places different requirements on these two restrictions. It must be possible for demanders to satisfy this energy consumption by internal energy exchange as well, which is why the limit $-pl_{t,d}$ must be increased by the additional $sl_{t,n}$. The energy supply, on the other hand, should not be restricted by the additional energy consumption, but allow optional utilization of the energy for self-consumption or for internal energy exchange. Therefore, this value is completely ignored at this point and restrictions on the change in role are formulated as (changes highlighted in green):

$$\sum_{d \in D_t} bal_{t,s,d} + \sum_{k \in STOR} ch_{t,k,s} \leq pl_{t,s} \qquad \forall\, s \in S_t, t \in \mathcal{T} \tag{4.17}$$

$$\sum_{s \in S_t} bal_{t,s,d} + \sum_{k \in STOR} dc_{t,k,d} \cdot \alpha_k \leq -pl_{t,d} + sl_{t,d} \qquad \forall\, d \in D_t, t \in \mathcal{T}. \tag{4.18}$$

The integration of DSM devices can be realized in other ways as well and offer a different point of view. For example, one way assume that the total energy consumption of the DSM devices is always settled via the ESP. This significantly reduces the complexity of the model and also leads to identical economic interpretations of the system behavior. However, as a result no statement can be made about which additional energy quantities could be satisfied by self-consumption. Furthermore, if the number of jobs and periods is moderate, it is possible to consider generating all possible schedules (i.e., the x-vectors) a-priori and then formulate the scheduling subproblem as a scheduling selection problem. This type of formulation may lead to a faster solution in certain circumstances, but in any case opens up other possibilities for alternative heuristic solution approaches, such as e.g. column generation approaches.

4.2.2. DSM Case Studies

In this section, the extension of the VEU environment when it is able to control DSM devices is analyzed. For this purpose, the spring and summer scenarios from the previous case studies in 3.1.3 and 4.1.2 are used as basis data for the presented results. In addition, for each of the 100 participants two DSM devices (a washing machine and a dishwasher) are present. For each of these devices, a random number of daily jobs is generated within the planning horizon. Hereby no or one dishwasher task and up to two washing machine tasks each day are created. Furthermore, every DSM device has specific settings to define different task types that can be customized. In the following study there are two individualized task types for each DSM device, an 'eco' and 'normal' program for the dishwasher, and a '40°' and a '60°' program for the washing machine. For the customization of these task types, the energy consumption and duration of the task can be varied. The data variation used in this case study is based on data for commercially available devices and is randomly assigned to each task type on every DSM device. The potential time windows for each job can also be freely specified. For simplicity and a realistic scheduling period, a daily time frame between 8 a.m. and 8 p.m. is chosen for all generated jobs in the case study. By this there is a high number of potential time frames to schedule the jobs. Both basic scenarios (spring and summer) are initially analyzed without an ESS. The analysis is done in two steps, whereby in each case a distinction is made between the results with fixed schedules of the jobs and optimized schedules in order to evaluate the influences of the optimization. The same is then done for the combined use with the ESS. The randomly generated dataset for the analysis consider 87 DSM devices for 69 participants with 190 tasks in total. The influence of the number of tasks on the achieved results is not further analysed, as no unexpected outcomes have been found.[12]. The main conclusion is simply that the more tasks, the higher the potential savings, as long as the supply in the planning horizon can satisfy this demand. Finally, for the spring scenario, an analysis with price deviations is performed by generally raising and lowering the demand price by 3 cents/kWh between 8 a.m. and 4 p.m.

The used model for DSM devices without an ESS is *model-DSM.py* with optional fixed schedule and price deviations. The model *model-DSM-ESS.py* is used if ESSs are considered with also the optional fixed schedule and price deviations. All models and the data generation (*profiles.py*) are implemented in Python 3.7[13] and CPLEX 12.10 is used to solve the optimization problem.

Table **4.5** shows the results for the two seasonal scenarios with 190 tasks that need to be scheduled on the DSM devices. The first five rows show the results without ESSs and the rows thereafter show the results when ESSs are considered. For both seasons, the optimized solutions (column 'Spring Optimal Jobs' and 'Summer Optimal Jobs' of **4.5**) and the solutions with fixed schedule (columns 'Spring Fix Jobs' and 'Summer Fix Jobs') are given. At first glance, it can be seen that the savings can already be

[12]The summer scenario with 252 DSM tasks can be viewed in the appendix, for example.
[13]http://www.python.org

	Spring Fix Tasks	Spring Optimal Tasks	Summer Fix Tasks	Summer Optimal Tasks
ELA Savings	133.40 €	158.14 €	182.43 €	189.76 €
ELA Share	99.60 €	109.66 €	136.17 €	137.06 €
OC Share	33.80 €	48.48 €	46.26 €	52.70 €
ELA	508.14 kWh	562.37 kWh	701.07 kWh	704.04 Wh
ESP Sale	1,239.83 kWh	1,107.68 kWh	1,345.15 kWh	1,307.40 kWh
ESS Savings	234.07 €	243.84 €	288.30 €	291.94 €
ELA Share ESS	98.81 €	106.21 €	132.71 €	133.30 €
ESS Share	99.75 €	89.32 €	108.50 €	105.87 €
OC Share ESS	35.51 €	48.31 €	47.09 €	52.77 €
ELA ESS	515.02 kWh	556.34 kWh	700.33 kWh	703.68 kWh
ESP Sale ESS	619.19 kWh	582.67 kWh	636.18 kWh	622.01 kWh
Charge Amount	604.39 kWh	532.27 kWh	705.12 kWh	685.43 kWh

Table **4.5**. DSM Seasonal Results

improved without an ESS (row 'ELA Savings') if the schedules of DSM devices are optimized.[14]. However, the increase in savings due to schedule optimization is significantly higher in the spring than in the summer. The difference here can be explained by two interpretations. In summer, the energy supply in each period may be so large that the additional energy demand of the DSM devices can already be satisfied simply by the internal energy exchange (row 'ELA Share') and the own consumption of suppliers (row 'OC Share') without optimizing the schedule. Optimization of the schedule can therefore only shift a few jobs in time so that additional savings can be generated. In spring, on the other hand, the energy supply in individual periods is lower and the fixed schedule offers much more potential to be improved. This is again reflected in the increase in savings from internal energy exchanges (row 'ELA Share') in general and from suppliers' own consumption (row 'OC Share') in spring. Alternatively, the situation can also be argued from the demand perspective. This savings increase can also be seen in the rising energy quantities for the internal energy exchange (row 'ELA') and the decreasing energy quantities that have to be processed via the ESP (row 'ESP Sale').

A further improvement in savings occurs when ESSs are available (row 'ESS Savings'), allowing an additional shift of the energy supply. The overall demand of DSM devices can now be more flexibly allocated and served. However, this is already evident with a fixed schedule, so optimizing the schedule can no longer achieve a larger increase in savings in the spring either. With a fixed schedule, the VEU then simply makes more use of the possibility of shifting the energy supply. The differences to the op-

[14] The significant savings difference compared to the baseline scenarios without DSM devices from the case study in Chapter 3.1.3 results from the additional demand that is now available and can be served internally during the supply-rich periods.

timized schedule are therefore also reflected in the share of savings from the storage processes (row 'ESS Share'), which decrease both in summer and in spring. In both seasons, the savings increase of the optimized schedule is due to the increase of internal energy exchange (row 'ELA Share ESS') and self-consumption of the suppliers (row 'OC Share ESS'). What is also noteworthy is the strong relative and absolute increase in self-consumption compared to the increase of ELA. This can be explained by the corresponding instance values and does not indicate a general preference for self-consumption. It is rather plausible that the internal energy exchange through ELA is already highly optimized without the shifted demand. Therefore the potential for additional ELA and savings is simply lower. Nevertheless, the potential is present and can also lead to significant increases, as the spring data again demonstrates.

The trends in savings are also evident in the associated energy quantities. In both seasons, the amount of energy that must be handled with the ESP is reduced (row 'ESP Sale ESS') and in each scenario there is an increase in the amount of energy traded internally (row 'ELA ESS') and a decrease in the use of ESSs (row 'Charge Amount'). To some extent, the tasks of the DSM devices are thus shifted in such a way that self-sufficiency and internal energy exchange are more likely to be provided. However, considering the efficiency loss of ESS, this prioritization of ELA is understandable. An interesting side effect that underscores this is that the absolute share of self-sufficiency in savings changes only slightly. The values are relatively stable and are not significantly affected by the presence of an ESS. So, if self-consumption prevails over internal energy exchange, storage processes will normally not influence this. The overall impact of ESSs to the VEU, however, is shown by the increase in total achievable savings (comparing the 'ESS Savings' and 'ELA Savings' rows). The combination of both load shifting strategies, on the other hand, can achieve an even better balance between periodic energy supply and demand. It significantly expands the possibilities of the VEU and brings more energy supply and demand together, which otherwise would not be achievable. Hereby also the scheduling of tasks is distributed more broadly, as illustrated in Figure **4.6**.

Figure **4.6** shows the start times of the jobs (decision variable $x_{j,t} = 1$) in the optimized schedules in the fall scenario. With the use of an ESS, the optimization distributes the jobs more evenly on Day 1 and 3. On Day 2, there is an adjustment and slight smoothing in the number of job starts in a specific period, however, there remains a clear concentration at the beginning of the allowed periods. This concentrated scheduling at the beginning of the allowed period occurs when the system is indifferent and no savings

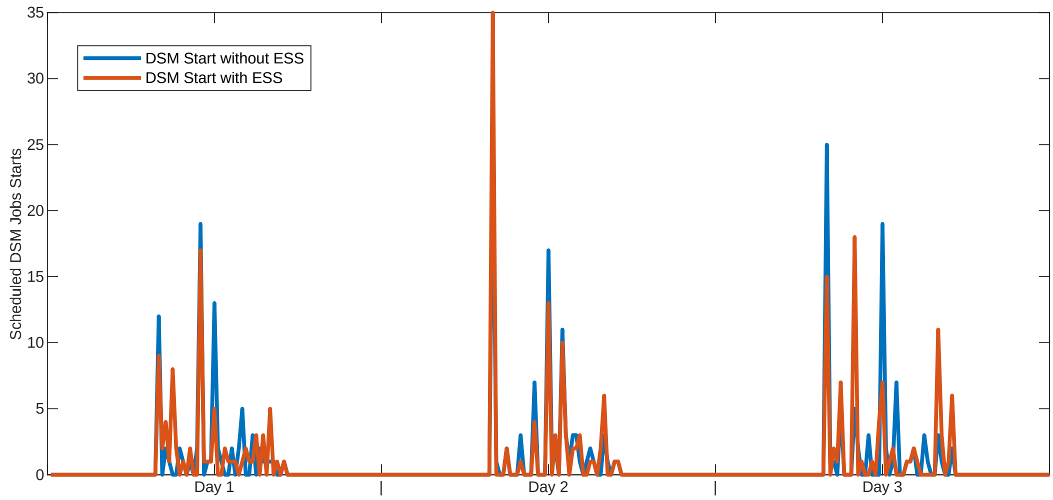


Figure **4.6**. Optimized DSM Job Start Times in Autumn

can be generated by shifting this demand. The share that each energy load shifting scheme of the VEU eventually contributes to the savings is situation-dependent and will differ at least seasonally. Depending on the daily constellation, though, differences can already be identified there. A generally valid recommendation for how the VEU should be structured for the use of DSM can therefore not be given. It is important to recognize additional saving potentials and that the VEU reacts to long-term structural conditions and not to short-term deviations. For example, it makes little sense to react to a one-time high number of tasks and thus increased demand if no general trend towards permanently increased demand can be verified. For evaluating such trends or structural opportunities to achieve more savings, operational planning can be used with the tools provided.

In the given results, however, the basic benefit of optimizing DSM devices becomes clear. Due to the energy losses of ESSs, the load shifts can be applied in a way that ELAs are prioritized and can be used to a higher extent. Nevertheless, the combined flexibility of energy supply and demand shifts is always preferable. The ESS, on the other hand, can develop a stronger influence precisely when ELAs are less lucrative, as the case study on price deviations shows.

The results for the impact of price deviations are shown in Table **4.6**. The first column shows the comparison values of the baseline scenario in spring with optimized schedules, while the second column shows the results for the same scenario with optimized schedules but with 3 cent higher demand tariffs between 8 a.m. and 4 p.m.. In

	Spring Optimal Jobs	Deviation +3 cents	Deviation -3 cents
ELA Savings	158.14 €	158.78 €	137.54 €
ELA Share	109.66 €	123.44 €	96.43 €
OC Share	48.48 €	55.14 €	41.11 €
ELA	562.37 kWh	565.22 kWh	562.37 kWh
ESP Sale	1,107.68 kWh	1,107.00 kWh	1,107.27 kWh
ESS Savings	243.84 €	264.45 €	223.80 €
ELA Share	106.21 €	120.73 €	88.70 €
ESS Share	89.32 €	90.22 €	96.16 €
OC Share	48.31 €	53.50 €	38.94 €
ELA ESS	556.34 kWh	564.74 kWh	518.29 kWh
ESP Sale ESS	582.67 kWh	584.05 kWh	583.16 kWh
Charge Amount	532.27 kWh	532.17 kWh	585.25 kWh

Table **4.6**. DSM Price Deviation Results

contrast, the third column presents the results with 3 cent lower demand tariffs in the same time frame. The differences in the savings values (rows 'Savings' and 'ESS Savings') between the scenarios can be explained to a large extent by the different price levels and do not allow any further conclusions. Consequently, the differences must be derived from other values, such as changes in the shares of savings. If ESSs are not considered, there only minor changes in the energy quantities for the internal energy exchange via ELA (row 'ELA') and the energy quantities settled via the ESP (row 'ESP Sale') can be explained due to the price deviation. For example, an increase in the amount of energy exchanged internally with an ELA is observed only in one scenario (+3 deviation), while in both cases the amount of external energy decreases slightly. This suggests that in the second scenario, the reduction in the amount of external energy indicates increased self-consumption. The small influence of the price deviation without ESSs could be expected because ELAs only exchange energy within a period. Since these are optimized schedules, price adjustments without ESSs have only few possibilities to significantly influence the schedules. Only if the time frames for the price change are more favorable, a larger deviation can occur to a greater extent.

On the other hand, the impact of price deviation increases significantly when ESSs are available. It can be observed that there is also a key difference between the two directions of the price deviation by considering the respective shares of the savings (rows 'ELA Share' and 'ESS Share'). If the demand tariffs increases by 3 cent in the decision-relevant period for the scheduling of the DSM devices, the dominance of the ELA is further enhanced. Due to the temporarily increased price, the savings increase in general (row 'ESS Savings'), but the share of ELAs in these savings increases significantly more (row 'ELA Share') and ELAs also rise (row 'ELA ESS'). The absolute value of savings from storage processes (row 'ESS Share') also increases marginally, but the total amount of energy stored (row 'Charge Amount') decreases. The free amount of energy is mainly used for new ELAs (row 'ELA ESS') and the energy amount exchanged via the ESP (row 'ESP Sale') increases marginally.

The exact opposite can be observed when the demand tariffs decrease by 3 cent compared to the spring results without price variation. Savings from ELA are then less attractive, which means that the overall decrease in savings (row 'ESS Savings') manifests itself only in the share of ELA (row 'ELA Share'). The absolute savings from storage processes even increases marginally (row 'ESS Share'). The associated energy quantities confirm this inverted result. Although the VEU has no influence on price variations in the contracts of the participants with their ESP, this is nevertheless an interesting observation. The VEU can react specifically to such individual time periods, depending on the optimal *internal* schedule of the DSM devices. For example, if there is an advantage to using more local supply or local storage capacity during this time period, external local markets could be used here temporarily. The price bounds which are attractive for bids can again be taken from these optimal internal solutions.

4.2.3. DSM Discussion

The formulation of a mixed-integer program to solve the overall planning problem for the VEU with integrated DSM leads to an increase in computation time. It is noticeable that with a realistic number of tasks in the planning period, the model requires more time to compute the combinatorial capabilities of the ESS than to schedule the DSM devices. This can be verified by comparing the computation times, which are around 500 seconds with ESSs, while they are only around 50 seconds without.[15] This is explained by the problem structure of the DSM subproblem, which allows only a relatively small number of effectively selectable decision variables for each job due to the time windows for the jobs. Modern solvers like the used CPLEX are then able to solve the mixed-integer program-based decisions of the model very fast. A branch-and-cut approach is used, which requires only a few iterations due to various presolve procedures[16] to find the optimal solution or nearly optimal solution. To speed up the computation, the solver was instructed to abort if no significant improvements were obtained in an iteration. The overall impact of demand-driven load shifts for VEU is smaller compared to supply-driven load shifting using ESS. This thesis therefore sees no need or concrete added value to provide an alternative methodology to fur-

[15] A significant increase in calculation times can also already be seen in the case study on storage.
[16] Which procedures and cuts exactly are implemented is not conveyed by the solver

ther improve the computation times. This level of solution quality with equally short computation time provided by modern solvers can rarely be improved if the problem structure can be well-recognized and exploited. The implemented heuristic methods, which were examined in the context of the thesis, are therefore not able to improve the evaluation decisively.

Similarities of the presented models to that of the research area of production management opens up numerous possibilities for optimizing the job schedule heuristically, if this is desired. In the following, a short overview of alternative methods is given. For example, one well-known approach is the relax-and-fix approach. Belvaux and Wolsey (2000) use a basic form of relax-and-fix in their sophisticated lot-sizing solver, or Stadtler (2003) uses a time-oriented relax-and-fix for the multilevel capacitated lot-sizing problem. This concept originates from Maes and van Wassenhove and is initially based on the relaxation of the mixed-integer program and hence all binary decision variables. The optimal solution of the relaxed problem can be used to iteratively fix individual decision variables. The iterative process is applied until all binary decision variables are integer. The rules for selecting the decision variables to be fixed can be designed very differently and has to be decided for the concrete problem on the basis of priority rules.

Priority rules are often used in scheduling to determine a simple sequence, which may provide very good results in certain cases. A simple example here would be to sort the demanders in descending order according to their ESP tariff values $dr_{t,n}$. The tasks of the first demand agent in this list are then fixed in the periods t in which the relaxed variable value for the starting period of the job $x_{j,t}$ is highest. The whole procedure can then be repeated for other tasks until a termination criterion is reached.

Another alternative is a fix-and-optimize approach, where certain decision variables are already fixed before the model is solved without relaxation. The priority rule described above would also be applicable here to select the decision variables of prioritized demanders to be fixed. In this method, the individual decision steps can also be designed in a variable way. More details on how the method can basically be applied and which variations are possible, are given, among others, by Helber and Sahling (2010) and Sahling et al. (2009).

It become apparent, that the possibilities of DSM optimization depend very much on the respective instances. Therefore, it seems reasonable to examine the participant's information about the tasks already when provisioning the potential improvement possibilities. If, for example, it can be shown directly to the participant that an additional saving can be generated by moving a task outside the actually selected time period, it is up to the participant to decide whether or not to agree to this change. This interactive approach can also replace the possible planning of comfort-based devices by abstract comfort analysis and modeling. By providing the potential savings, the involved participant can decide directly on his current perception, while transmitting the data needed for optimization. The interaction with the participant seems to be more involving from a practical point of view and is also preferred according to the findings of this thesis. A change in the participant's behavior is then not predicted based on abstract values but is concretely coordinated through active participation.

4.3. Special Case of Electric Vehicles

Electric vehicles provide a specific challenge but also added value to local energy management. Their primary task is the transport of people but they consume a certain amount of electrical energy to fulfil this task. Hence, EVs can be classified primarily as energy consumers and the challenge for the infrastructure is to satisfy the huge temporary demand peak, which may appear. The problem is not the individual demand of one EV, but with an increasing number of such vehicles, the impact on the distribution grids will be significant and the need for smart local energy management rises (see e.g., Clement-Nyns et al. (2011)). In addition, since EVs have an ESS (which provides the energy for driving), they can temporarily also be used as fully functional DS to shift energy supply as long as they are connected to the local grid infrastructure. This makes EVs a special asset for energy load shifting, as they allow both the demand and the supply of energy load to be shifted to other times. In literature, this is often refers to as vehicle-to-grid concept (see e.g., Liu et al. (2013) or Tan et al. (2016)). For instance, Kriukov et al. (2014) explores an exclusive market form for EVs that could be applied at a parking facility. Furthermore, in microgrid research, EVs are integrated as an additional flexibility option for the energy supply, as e.g., in Eseye et al. (2019) or Mohan et al. (2015). However, there are also studies that analyze only the demand-related part of an EV (e.g. Soares et al. (2014) introduce the combination of EVs with a DR concept). The problem with the usage of EVs in local energy management is the volatile usability of the vehicle, which is difficult to schedule. As mentioned, the primary task makes the vehicles a utility that also must be available spontaneously. To a certain extent, this contradicts rigid planning in which the vehicles' energy storage has to be available. Thus, a more flexible planning approach seems to be preferable.

For this, there are various aspects need to be considered and can make the problem very complex. Before discussing the details further, we summarize some key points that are generally valid for the modeling:

- If an EV is connected to the local controllable grid, it is *on-grid*
- If an EV is connected to a foreign grid or is in motion, it is *off-grid*
- If an EV changes to the *on-grid* state, it must have been *off-grid*
- It must be possible to update the state of charge of the EV when changing to the *on-grid* state
- If an EV changes to the state *off-grid*, it must have been *on-grid*
- A minimum state of charge may be required to ensure functionality when switching to *off-grid* status

From a local grid perspective there are only two states in which an EV can be, and they always alternate with each other. In order to apply an optimization approach, the times for these state changes must be known next to the goal of the optimization. This scheduling aspect is thus part of the overall problem and can either be given or ultimately solved by the model. In contrast to DSM devices, the decision whether to consider a changing task as part of the optimization or as given parameter is not straightforward. Basic tasks, such as driving to work, can be planned well, but do not offer scope for a large time shift and therefore have less economic impact for the decision. The trip to the store with the second car, on the other hand, has more potential. This off-grid period can be shifted to some extend. Therefore, the different applications and use of an EV complicate the question of whether scheduling optimization of an EV is useful or not. In theory, a shiftable schedule for EVs not only shifts energy demand, but also offers a potential to shift energy supply. This means that even small time shifts can have a stronger economic impact than, for example, the purely demand-based shift of DSM devices. This is especially true if there are high energy surpluses, which can then be utilized by the temporarily available storage capacity. Integrating this in an DR concept that generates behavioral change through monetary incentive could therefore yield interesting results. In contrast, due to the significant increase in complexity already discussed in Chapter 4.2, the added value of the explicit modeling of this scheduling aspect is still questionable under a practical point of view and out of scope of this thesis.

To use an EV of an individual participant, the VEU has to ensure that only on-grid times are submitted at which the vehicle is certainly not needed and fully applicable. Deviations from this could result in imbalances for the VEU, which in case of unscheduled use may lead to compensation charges by the community. This means that participants have to actively decide and communicate on-grid times to the VEU. In this case it is possible to directly notify the involved participant of potential benefits if he adjusts this submitted schedule. This requires modeling of such extensions, so that the model can solve different instances (with deviating schedules) based on the origin input of the participants. Based on an efficient formulation, further analyses of an optimal solution is also conceivable by identifying periods with continued high energy surpluses and actively notifying participants of additional savings opportunities if they can provide their EV.

The following parts of the thesis focus only on modeling the effects of the temporarily available EV to provide the flexible formulation needed. However, a deviation from the fixed schedule is theoretically still possible due to the volatile nature of the primary purpose of an EV. In addition, there are more possible aspects to consider for a detailed assessment of this issue than the practical implications. These are discussed further in Chapter 4.3.2.

4.3.1. EV Model Extension

The temporary availability of the EV and thus the consideration of the off-grid state can be integrated without further modifications in the current formulation. For this, the parameter for the storage rate $pcap_{t,k}$ is set to 0 in periods in which the EV is scheduled to be off-grid. This effectively prevents communication or energy exchange with this energy storage device during this time frame. The necessary information thus is included in the data preparation and the constraint can be considered unmodified (4.6):

$$0 \leq \sum_{s \in S_t} ch_{t,k,s} + \sum_{d \in D_t} dc_{t,k,d} \leq pcap_{t,k} \quad \forall\, k \in K, t \in \mathcal{T}. \tag{4.19}$$

If the EV is on-grid and can thus be used like a normal ESS, the given storage rate $pcap_{t,k}$ is used as the parameter. When an EV returns to the local controllable grid infrastructure, the state of charge may have to be updated, due to external charging activities or energy consumption during driving. Therefore, the balance constraint for the determination of the state of charge values needs to integrate the parameter $stu_{t,k}$ to introduce temporary planned changes in period t to the state of charge of energy storage k. These predicted changes introduce new uncertainties, as it is not clear whether these changes will actually occur at the predicted level. This already suggests that with the use of EVs the continuous re-evaluation through a rolling planning approach of the model may be useful to better address the current data situation. The formal change to the storage balance equation (4.1) can be formulated as follows (changes highlighted in green):

$$soc_{t,k} = soc_{t-1,k} + \sum_{s \in S_t} ch_{t,k,s} \cdot \alpha_k - \sum_{d \in D_t} dc_{t,k,d} + stu_{t,k} \quad \forall\, k \in K, t \in \mathcal{T}. \tag{4.20}$$

The advantage of introducing the parameter $stu_{t,k}$ is that it can also be used for events that affect the state of charge of each ESS. This means that changes can also be planned and thus considered for the state of charge of stationary storage. An example would be that the VEU has offered a fraction of the total available storage capacity for external energy usage and therefore needs to consider this charging for the internal planning process. The interesting side effect is that the temporary external energy is theoretically usable for a VEU if a fixed time frame has been negotiated. The only requirement is to ensure that the required amount of energy is available again in the ESS in question when a fixed time frame exists and is about to expire.

The minimum state of charge $mcap_{t,k}$ of the energy storage k in period t is the last detail that has to be modelled for a basic integration of EV. This thesis assumes that a minimum state of charge indicates that this lower bound should be available at the beginning of a period, i.e. already be reached at the end of the previous period. This leads to the following constraint:

$$soc_{t-1,k} \geq mcap_{t,k} \quad \forall\, k \in K, t = 2, \ldots, T+1 \tag{4.21}$$

The parameter $mcap_{t,k}$ can also be used for other ESSs to ensure that a temporarily necessary state of charge is reached. For the EV, this lower bound can be used to ensure that the vehicle is in a planned state of charge at the time of grid disconnection.

4.3.2. Potential Extensions

This section will address in more detail other potential extensions that can be considered in the context of EVs, but also partially for ESSs in general. One aspect that has not yet been considered in the modeling approach is the technical aspect of variable

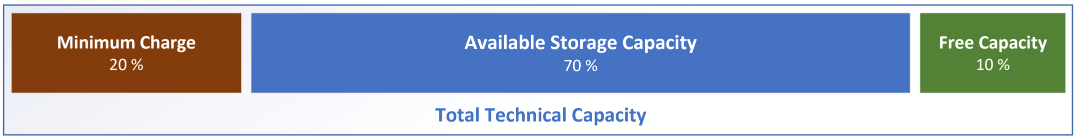


Figure **4.7**. Available Storage Bounds

storage rates for an ESS. Particularly with EVs, very high storage rates are possible in order to ensure rapid charging of the battery and thereby usability. Which storage rate is actually used depends also on the charging station used. For a VEU this distinction is less relevant, since it can be assumed that the involved participant always uses the same own charging station. A separate formulation is not necessary for this, since different storage rates can already be integrated by the parameter $pcap_{t,k}$. However, there can also be a variation of the storage rate when certain states of charge are reached in order to protect the ESS. Such a flexible state-of-charge-aligned storage rate has direct consequences for modeling, as it leads to a piecewise-linear parameter $pcap_{t,k}$ that depends on the variable $soc_{t,k}$. Alternatively, one may chose to ignore this technical aspect to avoid the associated increase in complexity. For this purpose, the available capacity cap_k only has to be determined in such a way that no variable storage rates occur within certain limits. The important aspect here is that an available capacity can be a limitation not only to one side of the state of charge, but to both sides at the same time. Figure **4.7** illustrates this.

For the optimization objective of the VEU, such a limitation on the possible use of the ESS still provides sufficient usable capacity, but as a side effect it opens up a very interesting optimization possibility. Especially if more uncertainties are to be considered, or resources are to be reserved for real-time operation, decisions must be made about the level of safety buffers. The need for optimization arises as usual with such buffers, as higher levels makes the plan more robust, but cause costs (in this case, opportunity costs, due to the lack of capacity that can be used for internal energy exchange). In return, the lower bound of the buffers ('Minimum Charge' in **4.7**) provides access to reserves for energy supply and the upper bound ('Free Capacity') provides the possibility to store additional energy. In this thesis, the available capacity is already given in the data and it is assumed that each participant makes this decision in coordination with the VEU. This is primarily because, despite existing financial benefits, participants may question participation if it involves disproportionate effort or inconvenience. Personal safety buffers for ESS owners are therefore useful anyway. The effort to model the safety buffer and to adjust their levels on this planning level already can, in principle, be justified and be the target of additional research. Under certain circumstances, the safety buffers can also be flexibly controlled in terms of time, so that a VEU uses a more robust planning in certain periods, depending on the data situation, while allowing more available capacity when there are fewer uncertainties.

Another interesting aspect is to take a closer look at the initial state of charge. In the model, its consideration is first of all necessary for the formulation to be valid. In the case studies, however, it is always assumed that for all ESS $k \in K$ there is no initial charge status, so $ic_k = 0$. This is necessary to ensure that initially stored energy quantities are not used and lead to distorted results when measuring the economic impact of storage processes. Realistically, and with use of the model in a rolling planning approach, initial charge levels are inevitable. This means that the cost of the initial stored energy must either be simply ignored or integrated in some way to properly assess the economic impact of storage processes. For this, no change to the model is necessary for the optimization itself, but the costs must be taken into account when interpreting the results (VEU savings).

In measuring the economic value added by the use of EVs, different states of charge when switching between off-grid and on-grid times, such as the initial state of charge, may sometimes be important considerations. A trip to work with a discharged EV, is a good example for such a case. It is possible for the owner to charge such a EV at work for low-cost or free and make this energy available for the VEU later. This is practically equivalent to an external purchase at LEMs for the stationary ESS and offers optimization opportunities. At this point, the formulation needs price information of the charging process to measure the economic value of the consumption of such external charging and it must also be possible to measure how such externally induced charging is used exactly. Especially with the example of charging during working hours and the subsequent use of this amount of energy for own or even VEU consumption, further tax and legal questions are unavoidable. This thesis does not discuss these questions, since it is not within the scope how this monetary advantage should be treated subsequently.

In summary, many aspects can be easily integrated via the data generation or can be inquired in case of potential application within the provisioning process between the VEU and their participants. However, there are also opportunities for deepening the economic analysis and improvement of the developed tools. More complex formulation, though, can be avoided in many cases by focusing only on realistic practical application. The further possible deviation from the previous planning has to be controlled in the detailed planning anyway in case of doubt or can lead directly to adjustments in the planning if announced ahead of time. Altogether, it remains more realistic that a participant provides only that which is tolerable and monetarily meaningful. Here, under certain circumstances, an additional compensation for the pure provision of the ESS for collective storage processes would still have to be discussed, but this can already be taken into account via the distribution procedure of Chapter 4.1.3. An involvement of the respective ESS or EV owner can be taken into account directly in the distribution, or indirectly accounted for via the share of the VEU.

4.3.3. EV Case Studies

When considered in detail, EVs as a load shifting option are a special case, but do not integrate a divergent new central function for the system. They only offer both load shifting approaches already discussed at the same time. Hence, this is also true if a similar shift in demand as in DSM devices were to be integrated. The effects of various parameters on the operation of the ESS is discussed in Chapter 4.1 and therefore does not provide new research opportunities for further studies. On the other hand, the presented implementation of EVs provides an extension of the central function of ESSs in general by two new aspects – the minimum state of charge, and scheduled changes for the state of charge. While these opportunities are not essential for stationary ESSs, they are equally applicable. The focus of this case study is therefore limited on how the system handles these two new aspects. The data set for the seasons spring and summer are therefore once again continued and the case study from Chapter 4.2.2 is used as a basis. Ten EVs are added in each case, which are assigned an available storage capacity that is equally distributed between 12 and 24 kW. This is significantly less than the EV commonly installed in ESSs can provide but follows the assumption that users will want to maintain a sufficient safety buffer in EV. The storage rate is constant at 2.5 kW in each period, which is within the capabilities of a fast charging station that can be installed for ordinary households. All EVs start the optimization already with 50% of available capacity as initial state of charge, although they need to reach this value for each off-grid switch and again at the end of the planning horizon. For this small case study, only trips to work are integrated, which then lead to off-grid states between 8 a.m. and 6 p.m. Whether a daily trip occurs is randomly selected. A uniformly distributed change of the state of charge between 200 and 500 W is also considered for each on-grid switch.

The model is implemented as *model-full.py* with optional fixed schedule and price deviations. Model and data generation (*profiles.py*) are implemented in Python 3.7[17] and CPLEX 12.10 is used to solve the optimization problem.

	Spring All	Spring DSM/ESS	Summer All	Summer DSM/ESS
Savings	265.58 €	243.84 €	311.29 €	291.94 €
ELA Share	105.75 €	106.21 €	132.39 €	133.30 €
ESS Share	112.33 €	89.32 €	126.09 €	105.87 €
OC Share	47.50 €	48.31 €	52.81 €	52.77 €
EV Share	34.76 €	0 €	40.22 €	0 €
ELA	555.50 kWh	556.34 kWh	702.02 kWh	703.68 kWh
ESP Sale	446.04 kWh	582.67 kWh	493.41 kWh	622.01 kWh
Charge Amount	673.99 kWh	532.27 kWh	815.43 kWh	685.43 kWh

Table **4.7**. Seasonal Results with EV

Table **4.7** first briefly illustrates the results for the two seasons analyzed. For both seasons, the results with all load-shifting options are available in the first and third columns respectively, while the results without EVs can be found in the columns two and four for comparison. Unlike the case study in Chapter 4.1.2, both seasons can benefit from the capacity increase brought about by EVs to roughly the same extent. Spring may show slightly stronger savings increases in this regard (row 'Savings'). What both seasons have in common is the fact that the absolute share of savings from self-consumption (row 'OC Share') and from ELA (row 'ELA Share') are quite stable, with a slightly decreasing tendency. Therefore, the total increase in savings is based on the storage processes (row 'ESS Share'), in which those of EVs are also integrated. However, the share of EVs is also provided separately (row 'EV Share') and, with about 31% of the total ESS savings (in spring and summer), thus offers a strong extension of the possibilities. This is further illustrated by the energy amounts, which show a decreasing dependence on ESPs (row 'ESP Sale') and a strong increase in storage processes (row 'Charge Amount'). However, the slight decrease in ELA (row 'ELA') again indicates a small substitution by the storage processes.

Considering the detailed results, it then becomes apparent that the scheduled changes to the state of charge on return to the on-grid state mean that negative savings are even possible for some EVs. In this case, the consumption of the EV causes that the owner has to compensate this via the community. This indicates that there is still a need for a way to specifically offset this consumption through the ESP. This conclusion is further supported by the fact that the data set for the fall cannot be solved at all with these parameter values. There is not enough internal supply to meet the additional

[17] http://www.python.org

demand of the EV and at the same time meet the respective minimum levels at the state of charge in the planning horizon. This raises a fundamental consideration as to whether external charging of the storage facilities should be possible. However, it must be assumed that the participant who simply has the best tariff values with the ESP will then fill the storage facilities. It is therefore questionable whether this will be a realistic option or whether external charging can only be done via external markets. However, since the external connections of the VEU is not a central investigation object of this thesis, this aspect is not discussed further at this point. How the optimization reacts to the mentioned minimum levels for the state of charge, however, shows that a statement formulated in Chapter 4.1.3 is correct. The required charging processes to reach these minimum states follow a greedy linear structure. This also applies reciprocally to the discharges resulting from the provided initial state of charge levels. These independent storage processes are characterized by the fact that no mutual storage process exists in the planning horizon. This leads to a situation where the independent discharges, due to an initial state of charge, are basically established from the most effective storage to the demander with the highest tariff value at its ESP. The discharging then takes place in descending order (respectively for the efficiency of the ESS and the tariff value of the consumers) until the initial state of charge of the ESS has been discharged or is otherwise required. In contrast, for independent charging operations to ensure the minimum level, the supplier with the lowest tariff value will fill the most ineffective storage first. In principle, this effect was to be expected, but nevertheless an interesting aspect that may be helpful for the development of an alternative algorithm.

4.4. Flexibility Discussion

The case studies show that flexibility are a very profitable option for the internal planning of the VEU. It is therefore always recommended to use the shown opportunities, if possible. The special importance of the suppliers in this system is also underlined once again by the analysis of the flexibility options. However, this is mainly due to the fact that the participants in a VEU automatically provide a constant demand over the entire planning horizon. It is therefore more a matter of making the best possible use of the available energy supply since it is usually only available temporarily. This is indicated in turn by the significantly higher importance of supply-based load shifting given by the use of ESSs. The savings increase is higher than with demand-based load shifting, but also gives the VEU many more possibilities to react to seasonal influences and market situations. Which available capacities a VEU can use for the optimization of supply-based load shifting is given in this thesis by the parameter cap_k for every ESS and not an optimization issue. However, this thesis already shows that decisions on potential safety buffers will be necessary in such a system and will extend the spectrum of optimization problems.

Additionally, the added value of demand-based load shifting is similarly highlighted in the case studies. The savings increase is valuable to consider and also provides new opportunities to ensure better use of ELAs in particular. Prioritizing the direct internal energy exchange through ELAs is obviously desirable due to the efficiency loss of ESS storage processes. The capacity of the ESSs otherwise can then be used simultaneously, so that in total, more energy can be kept local. Another interesting aspect that first emerged with the implementation of DSM devices is the practical implementation and interaction with users in such a system. The usability of individual ESS by the VEU can be defined once and does not necessarily need to be modified thereafter. Jobs for DSM devices, on the other hand, must always be actively reported to provide the possibility for optimization. It therefore makes sense not only to accept the jobs for optimization, but to actively engage with the user if they could realize further savings by changing their behavior. In the perception of this thesis, this is also the case for comfort-based devices. It is better to leave the choice to the user and to actively obtain the agreement whether he accepts a deviation from his actual will and/or comfort exactly in this moment. To force an alternative central decision here on the basis of abstract comfort values is even rather counterproductive, if thereby a disadvantage results for the user. The implementations provided can already be used for interactive exchange with the users and thus avoid such problems. The exception to this approach, however, is of course the integration of DR approaches, since the behavior is to be explicitly directed by pricing methods here.

Finally, the next step that must follow is to take advantage of external opportunities in local markets, as highlighted by the flexibility options. The focus on the local level will still be given, because participation in top-level markets is not feasible anyway, due to the small number of participants in a VEU. However, the more important aspect for the VEU in the future will be to be able to differentiate itself from the retail trade at such local power markets (LEMs and LFMs). Eventually, active prosumers or consumers who take the effort to trade directly in such LEMs can realize higher aggregate benefits. The VEU, on the other hand, allows that the effort of the individual is low and the savings due to local energy exchange can even be presented transparently. In addition, the market power of the VEU through aggregated supply and demand can strongly influence exactly these local markets and their pricing, depending on the strength of the remaining market participants. At present, no concrete conclusion can be made about the influence of cooperations that participate in local power markets as there is still a lack of definition of how they will operate. So these questions will become more and more concrete as realization becomes imminent. However, research to this point shows a tendency that auction-based market types like those in current electricity markets are likely. This further substantiates the need for a VEU to have a solid internal optimization as a starting point for their interaction with local power markets. Price limits can thus be easily identified and a sequential bidding decision made. Alternatively, if a simultaneous solution approach is used, the internal planning will be incorrect in case the bid is not accepted and must subsequently be corrected later. A sequential approach based on internal planning, as this thesis recommends, is even more appropriate in this case. The exception is DSM devices where a simultaneous approach is in principle more attractive since demand shifting could then be undertaken in such a way that the best external supply is available at the same time. The optimal solution offered by the model of this thesis also gives the possibility for an alternative approach to be investigated for this purpose. The solution indicates when the system is indifferent due to missing internal possibilities, and the job is scheduled at the beginning of the possible time frame. If there is no other reasonable explanation for this behavior (oversupply, special prices, etc.), an attempt can be made to satisfy this aggregated demand externally for the times or the possible time frames of these DSM jobs. The energy quantities, price limits and time periods of the jobs are accessible and thus an external solution can be generated for this in a subsequent step, without having to rely on simultaneous optimization.

It is furthermore recommendable to look at controllable energy generation by means of small generators or devices for heat production. This would also have the advantage of linking energy management with heat management and thus creating a development toward holistic optimization. However, the core problem of holistic operational planning is that too many systems may be linked together. Although this sometimes increases efficiency due to the resulting synergy effects, it also drastically increases the risks if deviations then occur during real-time operation. At this level of micro planning or real-time control, topics such as safety buffers, which are also addressed in this thesis, must be increasingly integrated. The focus of the available flexibility will therefore inevitably have to be oriented away from the pure economic maximization toward an approach that will also use flexibility more as a safety option. These aspects must then also be considered more strongly in the planning level of this thesis, as the retained energy quantities or capacities become a concrete optimization target for local energy management.

5. Cooperation Management

The virtual economic unit (VEU) as a centrally organized cooperation can evidently improve the economic added value for the community, and thus for the individual participants, by optimizing the internal energy exchange. The next step is to clarify how the savings achieved can be distributed to individual participants in practice. Relevant in this context is the interaction of a proposed distribution and the stability of the cooperation. Theoretically, any distribution of savings is stable, as long as no participant is negatively affected by his participation. However, this already derives from the model since energy quantities are alternatively simply settled via the energy service provider (ESP) as before. The energy quantities of the internal energy exchange, on the other hand, are settled via the VEU. The consumer is charged for his demanded quantity of energy by the community which then uses these funds to pay the suppliers of these quantities of energy. In this case it is even possible that the VEU keeps all the savings by simply accounting all peer-to-peer (P2P) connections at the ESP tariffs. The participants are thereby not worse off, and in theory this cooperation would thus continue to be stable. However, such behavior is unrealistic and stable sharing can therefore only be achieved if it is fair and does not lead to individual participants questioning the cooperation in VEU. For this reason, the purpose of this chapter is to clarify whether and how a sharing can be found that gives the cooperation this stability it is looking for. It is not intended to provide a complete analysis, but rather to present a first classification of this aspect of the VEU. This includes a discussion of the extent to which classical approaches can be used auspiciously for a VEU in the first step. The relevant research area dealing with such questions is game theory. In Chapter 5.1 the tools for a game-theoretical analysis are therefore explained, so that distributions can be analyzed and evaluated in principle. It will also be critically questioned whether these methods and approaches are usable for the VEU concept and whether alternatives exist in the literature that might fit better. The result will lead to a proposal of methods, which will then be outlined in Chapter 5.2 and verified by a first case study in Chapter 5.3. These methods can then also be the basis for a more detailed analysis, which would, on the other hand, exceed the scope of this thesis. Finally, in Chapter 5.4 the results are discussed and also an outlook on further research possibilities is given.

5.1. Fundamental Considerations

Game theory has a set of analytical tools to help understand phenomena that arise when decision makers interact. The basic assumption underlying the theory is that decision makers pursue well-founded, exogenous objectives (e.g., improving their own economic situation) and act rationally. In addition, the decision makers take into account their own knowledge and/or expectations regarding the behavior of other decision makers, i.e., they think strategically. (see e.g., Osborne and Rubinstein (2006) or Abapour et al. (2020)). Game theory can be used to model selfish behavior in networked systems or markets (here in VEU concept) and to show ways to avoid them. This also applies to the case when the exchange of information and energy between participants is organized by a central entity (in the VEU the central unit operator) (see Khorasany et al. (2018)). Altruistic behavior of actors within a VEU is expected to increase the economic surplus of the individual as well as the community. In addition, joint action can result in stronger negotiating power and thus more advantageous terms towards other individuals. However, this is a separate game to be considered between the VEU and external stakeholders. Thus, it has no direct relation to the savings sharing game discussed here, unless the negotiated terms are the basis for those savings. This is not the case in this thesis and is therefore not considered.

5.1.1. Game Theory Basis

The mathematical and conceptual structure of game theory is based on the classic works of von Neumann and Morgenstern (2007) who's original was published in 1944. Basically, game theory can be divided into two parts, the non-cooperative games and the cooperative games. Although the VEU is conceptually a cooperation, a clear assignment to one of the two subareas of games is not given. The participants in this cooperation work together to realize a collective success, which is also characteristic in these kinds of games, but this success is only created by the cooperation of suppliers and consumers. Such vertical cooperation is not considered in classical game theory, even though it is well known from supply chain management (see i.e., Geunes and Pardalos (2005) or Pöhn and Hommel (2020)). Cooperative game theory traditionally analyzes horizontal cooperations that may arise on the respective side of a market. The respective cooperative games are therefore also examined differently in terms of convexity and superadditivity (benefit/utility - supply cooperation) or concavity and subadditivity (cost - demand cooperation). If, on the other hand, both sides of a market are considered, game theory evaluates this as a non-cooperative game. In this kind of game, the cooperative aspect of a VEU is ignored, since each participant wants to achieve only his own goals without coordinating with the other participants in the game and/or reaching joint agreements. Therefore, both classical game forms are already due to their characteristics not promising to represent a game for hybrid cooperation like the VEU. Nevertheless, it is essential to briefly explain the two basic forms in this section, because there is a hybrid form that better describes the VEU game. These so called biform games use both basic forms in a certain way (see e.g. Brandenburger and Stuart (2007)).

5.1.2. Cooperative Games

Cooperative game theory analyzes surplus distribution problems in which a grand coalition $\mathcal{S}$ of players $p \in \mathcal{P}$ cooperate to earn a joint reward. The decision problem to maximize this reward for each possible cooperation among these players $\mathcal{S} \subseteq \mathcal{P}$ has already been solved. Consequently, the confronted problem in cooperative games is to find a distribution of the achieved reward that is efficient and ensures stability of the large coalition $\mathcal{S}$. In cooperative game theory, the reward of a formed coalition is represented using a characteristic function $\nu(\emptyset)$.[1]. This function assigns a unique value to each possible coalition and quantifies the optimized added value that can be achieved by the cooperation. The characteristic function $\nu(\mathcal{S}$ of the players $p \in \mathcal{P}$ is then also calculated for all subsets (possible coalitions) $\mathcal{S} \subseteq \mathcal{P}$, so that for each coalition there is a specific value that has the property:

$$\nu\left(\emptyset\right) = 0, \nu\left(\mathcal{S}_1 \cup \mathcal{S}_2\right) \geq \nu\left(\mathcal{S}_1\right) + \nu\left(\mathcal{S}_2\right), \tag{5.1}$$

where $\mathcal{S}_1$ and $\mathcal{S}_2$ are disjoint subsets of $\mathcal{P}$. The cooperative game in the characteristic functional form then consists of the pair $(\mathcal{P}, \nu)$. Initially, the coalition is already stable if the joint reward of the grand coalition is larger than the reward of the individual

[1] The description in the context of this thesis is made from the point of view of a supply coalition. A description from the point of view of a cost coalition is neglected.

coalitions. Various solution concepts and allocation procedures exist for the distribution of the achieved reward in such a cooperative game. The most common concepts are the Shapley value of Shapley (1951) and the core according to Gillies (1959). The *Shapley value* is an allocation by which the value of the grand coalition $\mathcal{S}$ is distributed among the players according to the average marginal contribution each player makes to the coalition game (see e.g. Chis (2018)). Formally, the Shapley value $\pi_p^{\mathcal{S}}$ for player p in coalition $\mathcal{S}$ is calculated as follows for a game $(\mathcal{P}, \nu)$:

$$\pi_p^{\mathcal{S}}(\mathcal{P}, \nu) = \sum_{\mathcal{S} \subseteq \mathcal{P}\{p\}} \frac{(p - |\mathcal{S}|)!(|\mathcal{S}| - 1)!}{p!} \cdot (\nu(\mathcal{S}) - \nu(\mathcal{S}\{p\})) \quad \forall \ p \in \mathcal{P}. \tag{5.2}$$

The other game-theoretic cooperation concept is the *core*, which is in turn a set-theoretic method to assess whether players are willing to form a coalition at certain value distributions in which there is no interest to withdraw. Formally, the core $C(\mathcal{P}, \nu)$ for a game $(\mathcal{P}, \nu)$ consists of allocations $a_p \in \mathbf{a}$ that are efficient and rational, thus possessing the following properties:

$$C(\mathcal{P}, \nu) := \left\{ \mathbf{a} \in \mathbb{R}_+^p \mid \sum_{p \in \mathcal{P}} a_p = \nu(\mathcal{P}) \text{ and } \sum_{p \in \mathcal{S}} a_p \geq \nu(\mathcal{S}) \ \forall \ \mathcal{S} \neq \emptyset \right\}. \tag{5.3}$$

5.1.3. Non-Cooperative Games

These games consider situations in which each player is interested in achieving his own goals without coordinating and/or reaching common agreements with the other participants in the game. In contrast to cooperative games, communication between the players involved is not allowed either. Thus, the game participants try to anticipate the opponent's reaction to their own strategy and then choose the best response/decision to it for themselves. The term non-cooperative means that any cooperation in a non-cooperative game may not be the result of communication or coordination of strategic decisions between players. (see e.g., Abdel-Raouf et al. (2020) orTushar et al. (2018)). This characteristic also prevents an VEU from being classified as a non-cooperative game. In local energy markets (LEMs), on the other hand, participants compete with each other. According to Marzband et al. (2016)), such a structure of the electricity market corresponds to a non-cooperative game with p players, where each player wants to maximize his own advantage first without collusion. This aspect is again interesting for a VEU, because a cooperative distribution of savings must persist eventually in this non-cooperative game. Indeed, two participants should have no incentive to deviate from the central decision of the central unit operator because they can initiate an individual trade that is more advantageous.

The best known solution concept for non-cooperative games is the Nash equilibrium. It describes a condition where the optimal outcome of a game is that no player $p \in \mathcal{P} := \{1, \ldots, P\}$ has an incentive to deviate from his chosen strategy $\mathcal{F}$. In doing so, each player takes into account the choices of the other players when making his own strategy decision. The outcome represents a steady state if it holds for all players that unilateral deviation does not improve their outcome. The best strategy $\mathcal{F}^*_{\mathcal{P}}$ for player p out of the possible strategies $f^*_p \in \mathcal{F}_{\mathcal{P}}$ on all other strategies of the remaining $P-1$ players exists if:

$$\mathcal{F}^*_p = u_p(f^*_1, \ldots, f^*_{p-1}, f^*_p, f^*_{p+1}, \ldots, st^*_P) \geq u_p(f_1, \ldots, f_{p-1}, f_p, f_{p+1}, \ldots, f_P). \tag{5.4}$$

u_p corresponds to the payoff received by player p, for a given strategy combination of all players $p \in \mathcal{P}$. Each player tries to maximize his own payoff. A player chooses f^*_p if this makes his payoff larger or equal compared to other strategy combinations. The selection function is related in meaning to the characteristic function in cooperative game theory. When the number of players is small, the result can also be represented in a matrix.

5.1.4. VEU Savings

The savings $\mathcal{E}$ of the VEU, which is formally the difference of the objective function values with optimized load profiles $ol_{t,n}$ and the predicted load profiles $pl_{t,n}$ of all participants $n \in N$ in all periods $t \in \mathcal{T}$, should be distributed:

$$\mathcal{E} = \sum_{n \in N} \sum_{t \in \mathcal{T}} v_{t,n}(ol_{t,n}) - v_{t,n}(plt, n). \tag{5.5}$$

or alternatively by the summed products of all internally exchanged energy quantities $bal_{t,s,d}$ with their associated savings rate $w_{s,d,t} = dr_{t,d} - sr_{t,s}$:

$$\mathcal{E} = \sum_{s \in S_t} \sum_{d \in D_t} \sum_{t \in \mathcal{T}} w_{t,s,d} \cdot bal_{t,s,d}. \tag{5.6}$$

The savings of a VEU thus corresponds to the characteristic function of a large coalition in cooperative games or the summed payoff functions in non-cooperative games. Allocation occurs by paying the supplier $s \in S_t$ for the amount of energy provided to other participants. Therefore, the price per unit of energy must exceed the tariff value with the supplier's respective ESP ($> sr_{t,s}$). In turn, the VEU will bill the consumers $d \in D_t$ for the purchased energy quantities, with a price lower than their tariff values with the ESPs ($< dr_{t,d}$). Other stakeholders could also be considered in such a distribution, such as grid operators or the VEU itself. The latter will have to retain part of the savings for the management, planning, and execution of the internal energy exchange alone. These stakeholders can be taken into account by subtracting their share from the savings $mathcalE$ as a fixed cost contribution. The focus, however, remains initially on an saving distribution for suppliers $s \in S_t$ and consumers $d \in D_t$ only. Thus, for the VEU, the basis that a distributional match for savings can only exist in periods t if the $\sum_{s \in S_t} \sum_{d \in D_t} bal_{t,s,d} > 0$ holds, since otherwise there is no savings. Furthermore note, that if a share of the savings is to be distributed to the VEU or other stakeholders, this cannot be considered as a part of the game. The contribution of these players, while central to achieving the savings, does not provide energy quantities or otherwise have a direct impact. Rather, the players' shares are non-negotiable fees that are required for the internal energy exchange and thus must be excluded from the game-theoretic calculation for savings distribution between the participants.

5.1.5. VEU Game Specialty

The peculiarity of a VEU-cooperation is, in a modified or theoretical form, already the subject of studies applying classical game theoretic methods to this type of games. In this context, studies show that the application of the Shapley value in a vertical supply chain carries the risk of unstable distributions. Sha and Zheng (2021) show that the conventional computation of a Shapley value in a four-player constellation with producers and consumers is not necessarily in the core, even though the core of the game is non-empty. The authors explain this result by arguing that the influence of individual players on the success of the cooperation is not taken into account sufficiently. However, this is exactly the desirable property of the Shapley value. In vertical cooperations, however, Shapley values are obviously not able to correctly interpret the contribution of individual participants to the success of the coalition and to translate it into a fair distribution.

Yi (2009) criticizes the distribution according to the Shapley value in mixed cooperations but justifies this with the fact that the Shapley approach focuses too much on equality in the distribution of profits. In the authors' studies, this even leads to the fact that individual players are disproportionately favored in the distribution by Shapley. This underlines the interpretation of this thesis that a Shapley approach can no longer correctly interpret or ultimately transform the contribution of individual participants in the case of mixed cooperation. However, since the method itself is designed for horizontal cooperation, these difficulties are not surprising.

Bartholdi and Kemahlioğlu-Ziya (2005) refer to effects that threaten core partitioning as second-order instabilities. Even if individual rationality is respected, this type of instability can arise in Shapley distributions if at least one player can assume that another participant benefits more from the coalition than is appropriate. This player may now demand adjustments to the coalition agreement, e.g., additional payments, which risk individual rationality and thus the stability of the cooperation. Correspondingly, Tushar et al. (2018) show that in this type of game at least one distribution can always be found in the core. Since no one in the VEU, as well as in the studied community of authors, can be worse off in the coalition this finding is not surprising in this respect.

5.1.6. Biform Games

Since classical game approaches are not promising due to their characteristics and the studies, this thesis focuses on an alternative game form. Biform games are a concept for mixed cooperations, which generally builds on the two sections of game theory already presented. The concept, developed by Brandenburger and Stuart (2007) contains a thereby connection of cooperative and non-cooperative solution elements within a game and is analyzed mostly in the context of supply chain management and vertical cooperations there (see e.g., Fiala (2016)). The basic idea is based on a sequential two-phase game, in which first a non-cooperative game is completed and in the second phase a cooperative game. The biform game itself can basically be represented as a decision tree, i.e., the game consists of successive decisions that lead to a new game depending on the players' decisions. In the first phase, players decide independently which strategy to choose. For example, a principled decision would be whether and how to participate in the subsequent cooperative game. This leads to a cooperative game in the second phase, in which both players get the maximum out of their decisions in the first phase together.

Applied to a VEU, the sequence of a biform game can mean that in the first phase each participant decides whether or not to participate in the VEU. The strategic decisions made then lead to a cooperative environment, which is analyzed in the second phase to determine how the total value of the grand coalition is distributed. The unmodified adaptation of this approach is not useful because participation is always beneficial in a VEU and the game of the first phase is thus already decided. The cooperative game is in addition by the central decision of the central unit operator in a certain way also already initiated. The VEU must now actually determine a distribution and each participant of the VEU must decide whether to accept this division. It is therefore more purposeful if both phases of the biform game are swapped and the non-cooperative game only validates whether the distribution determined in the first phase is acceptable to the players. A similar swap of the two phases has also been done by Fuentes González et al. (2020), so that the cooperative phase of the biform game is solved first.

Due to the weaknesses of the classical methods, these are actually unsuitable for the cooperative game. However, there is a solution concept for all games with a non-empty core in which the distribution according to the nucleolus method always leads to a result that lies in the core (see e.g., Xiao and Fang (2022)). Since the core is also a concept for horizontal collaborations, the validity of this otherwise important criterion remains questionable for vertical cooperations. The basic idea of the nucleolus concept is that a distribution is proposed, which is successively improved by the players or a central decision maker. In each iterative step, players will re-evaluate their own advantage and dissatisfaction with the actual proposed distribution. To avoid deviation of individual players in the process, the maximum dissatisfaction of the players is minimized in each step (see e.g., Mueller (2018), Tveita et al. (2018)). The central unit operator of a VEU procedurally takes an intermediate function and minimizes the maximum dissatisfaction of all players considering all possible coalitions and solutions until no further minimization is possible. This procedure theoretically decreases the probability of second-order instability, since there is less or no incentive to deviate due to decreasing dissatisfaction. Conversely, however, a distribution that is found does not guarantee that complete satisfaction will be achieved as a result.

5.2. Methodology

This section is intended to outline three possible distribution forms and thus go beyond the already proposed biform game. The reason for this is that the biform game is also ultimately based on the available classical methods and only attempts to compensate for their inadequate modeling of vertical cooperation by combining them. Therefore, the question arises whether a problem-specific approach is not more appropriate for vertical cooperation. In case a uniformly applicable alternative is preferred, a fair distribution of savings can also be based on a simple but practical feasibility.

5.2.1. Modified Biform Game

In the first phase, the modified biform game proposes to distribute the savings according to a cooperative approach. To construct a nucleolus-aligned procedure for this phase, the maximum dissatisfaction of the players in the coalition $\mathcal{S}$ must be minimized for a proposed distribution $\mathbf{a}$. The coalition excess or dissatisfaction can be expressed by the excess function $e(\mathcal{S}, \mathbf{a})$:

$$e(\mathcal{S}, \mathbf{a}) = \nu(\mathcal{S}) - \sum_{p \in \mathcal{S}} a_p = \nu(\mathcal{S}) - \mathbf{a}(\mathcal{S}). \tag{5.7}$$

so that a distribution ε^* can be found:

$$\varepsilon^* = \min \max_{\{\mathcal{S} \neq \emptyset, \mathcal{S} \subset \mathcal{P}\}} e(\mathcal{S}, \mathbf{a}). \tag{5.8}$$

A negative excess function $e(\mathcal{S}, \mathbf{a})$ represents the additional payoff that the coalition $\mathcal{S}$ receives from the distribution $\mathbf{a}$. The smaller the value, the more satisfied players are with the distribution which conversely means that with larger values they are more dissatisfied with a proposed distribution. To minimize the maximum dissatisfaction, the nucleolus can follow a lexicographic approach. First, the largest dissatisfaction across all coalitions is minimized. Then, among these solutions, the second largest dissatisfaction is minimized, and so on. The computation of the nucleolus can alternatively (see e.g., Owen (2013), Tveita et al. (2018)) be solved optimally with a sequence of linear programs. The linear program to be solved can be described as follows:

$$\min \varepsilon_h. \tag{5.9}$$

$$\sum_{p \in \mathcal{P}} \mathbf{a}_p = \nu(\mathcal{P}). \tag{5.10}$$

$$\sum_{p \in \mathcal{S}} \mathbf{a}_p + \varepsilon_h \geq \nu(\mathcal{S}) \quad \forall\, \mathcal{S} \subset \mathcal{P}, \mathcal{S} \neq \emptyset. \tag{5.11}$$

$$\mathbf{a}_p \in \mathbb{R}, \varepsilon_h \in \mathbb{R} \quad \forall\, p \in \mathcal{P}, h \in H. \tag{5.12}$$

The objective function 5.9 minimizes the dissatisfaction in sequence j. The constraints of the linear program are similar to the stability and efficiency constraints of a core partitioning again. While constraint 5.10 ensures efficiency, 5.11 imposes stability. The intended allocation for coalition $\mathcal{S}$ must be the sum of the dissatisfaction of the current allocation ε_h and be greater than or equal to the achievable saving $\nu(\mathcal{S})$. Otherwise, there is no incentive to form the coalition $\mathcal{S}$. The first sequence $j = 1$ starts with solving the linear program in the basic form. It results in an optimal solution for ε_1 that will equate at least one of the constraints of 5.11. These inequalities are defined as equations for the upcoming sequences and the value for ε_1 is put there instead of the variable ε_h. The constraints are thus fixed, the remaining constraints remain unchanged and a second sequence $j = 2$ is solved with the modified linear program. This procedure is repeated until all constraints are fixed. The solution is then a distribution corresponding to the nucleolus.

In the second phase, the biform game must verify the distribution found through a non-cooperative game and call for a strategic decision from the participants as to whether they accept the distribution of savings. Accordingly, within the community there must be no possibility for them to achieve a division that is better for them. The study of the nucleolus must therefore provide a distribution for each possible cooperation, so that the players can make a rational decision about whether the distribution of the grand coalition is fair. This means that there must be no possibility to realize a better distribution in individual cooperations. For this purpose, the application of a Nash game is suitable, in which all strategy combinations are compared. If the players then choose the strategy that provides for a distribution in the grand coalition, this distribution cannot be improved by a deviation.

5.2.2. Dominated Biform Game

A different idea of the modified biform game for the VEU concept is based on its structural peculiarities and the available information. Both games continue to exist in this case, but the distribution is performed only on the basis of the dominant game. In this case, this is the non-cooperative game, since every cooperative distribution must be examined there at the latest for a possible deviation. The proposed procedure is therefore also inspired by a non-cooperative concept. The Stackelberg model meant here can be solved to find one (or more) Nash equilibria, i.e., strategy configurations where each of the players has chosen an optimal set given the choice of sets of the other players. In principle, there is always a Stackelberg leader who can make a choice first and a Stackelberg follower who can only react to it. The Stackelberg leader uses his prioritization to choose a quantity that gives him an advantage and is tolerated by the Stackelberg follower.

A similar approach is also proposed for a dominated biform game. In contrast to the Stackelberg model, however, the difference between the two sides involved is not the advantage of a preferred decision maker, but that only one side would have the possibility to deviate. Deviation within the coalition can thus be prevented by giving preference to this dominant side. The two market sides of supply and demand are the players in this concept. The amount of energy exchanged internally between these two players must end in equilibrium, which is thus somewhat equivalent to a market clearing volume. Given that the VEU always uses all available energy quantities to the maximum result, there will usually be a concrete bottleneck – either in supply or demand. Thus, the market side with the surplus of energy has participants that are not considered at that moment or only partially, but still have an interest to exchange local energy. The considered participants in the internal energy exchange will accept any *uniformly* applied allocation, since they would otherwise be worse off because of the optimal allocation of the P2P connections. This is also the reason why exceptions to the congestion constellation do not need to be examined separately. This includes when the available supply and demand are already balanced, or both sides are not further allocated because a negative saving would be realized. Accordingly, in this case, there is no possibility to deviate within the cooperation. Consequently, the VEU has to set a uniform price for all P2P connections only for the relevant deviation scenarios which prevents any intervention of the members not considered. The problem structure proves useful in this case as well, since by simply using the scheme of the maximum saving flow algorithm (MSFA), this uniform price can be easily determined. Figure **5.1** shows this on a graph example.

The graph solution in Figure **5.1** shows a bottleneck on the supply side and thus a surplus of demand. Two consumers can no longer be served internally and would have to continue to purchase this energy via the ESP. The two consumers G and H

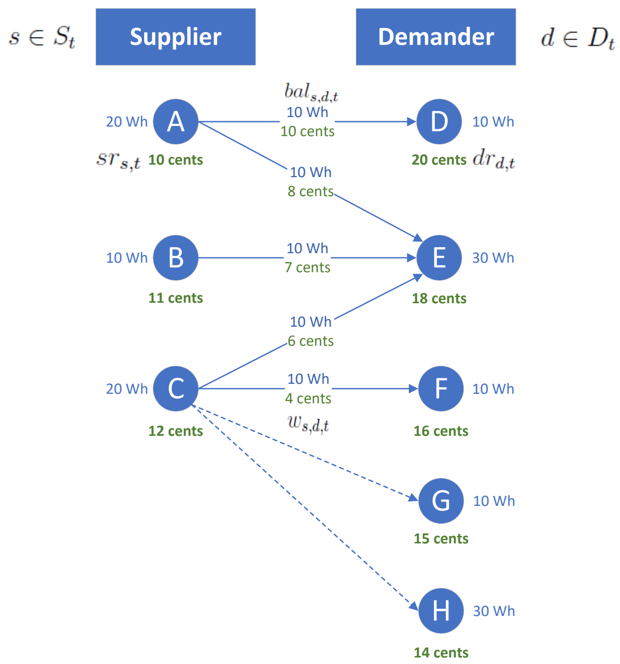


Figure **5.1**. Graph solution of internal energy exchange for potential savings distribution

have no savings at the moment and could offer the suppliers the choice to ignore the central decision of the VEU for a minimal saving. In order for the dominant supply side to ignore this, the unit price for the savings sharing of the P2P connections must prevent this. Formally, this is accomplished by selecting the maximum of the last supplier's rate value $sr_{t,\tilde{s}}$ and the highest rate value $dr_{t,\tilde{d}}$ of the two ignored participants, so that $\max(sr_{t,\tilde{s}}, dr_{t,\tilde{d}})$. Thus, for the figure example, VEU sets a unit price of 15 cents/kWh, which is the tariff value of consumer G. Both demanders then have no way to influence the suppliers without then accepting a higher price compared to their tariff value. Alternatively, the uniform price may favor the dominant side of the market even more if this is desired. The theoretical market clearing price of this solution (16 cents/kWh) is found at the last participant of the inferior market side and also ensures that a deviation is no longer possible in purely mathematical terms. In this case, the last participant involved does not receive any benefit from the internal energy exchange, but is also not in a disadvantageous position. The procedure applies in a mirrored way for the case that the surplus occurs on the other side of the market. For the case that supply and demand quantities are pari, however, the VEU can select an arbitrary uniform price, given that this lies within the interval of the last edge. The result is then stable, since no participant can do better. For the example from Figure

5.1 thus in the interval $[12; 16]$, since the last edge runs between supplier C and demander F. If a uniform price is chosen outside the interval, this would lead to a price that would make one of the participants worse off.

The disadvantage of this form of distribution is that it must be applied very dynamically. The market situation is volatile throughout the planning horizon and the energy quantities change in each period. Affected by these constant changes is thus also the definition of the uniform price for the savings distribution of the P2P connections, which can fluctuate strongly in the periodic intervals. These fluctuating price settings must therefore be explained separately to the participants if a certain transparency is to be ensured. This still leaves a fair procedure, which in the end is reminiscent of the usual auction system. However, due to the exact allocation in the P2P connection, the uniform price can be set as shown in such a way that really all participants can get a fairer share of the savings. The market clearing price would reduce a participant to its tariff value and thus its marginal value before it would be worse off. It must be noted, however, that a dominant biform game can only be applied to the energy load adjustment (ELA), since an exact allocation of the two sides of the market and thus the definition of the periodic uniform price is possible here. For storage processes, allocation is no longer available, as discussed in Chapter 4.1.

5.2.3. Fixed Saving Distribution

This thesis proposes a fixed distribution of savings as the simplest variant to implement in practice for a community such as the VEU. Each participant $n \in N$ thus receives a fixed percentage share of the savings to which he has contributed. The percentage depends on the role of the participant in period t in which the savings occurred, i.e. whether he can be classified as a supplier $s \in S_t$ or consumer $d \in D_t$. The system is comparatively simple and easy to understand for all participants. What an exact distribution looks like can be decided by a VEU itself or can be decided by the participants. A proportion can also be provided directly for the VEU itself. Thus, a possible distribution could provide, for example, that suppliers generally receive 50% of the savings, demanders receive 40%, and the remaining 10% is allocated to the VEU directly. The fixed percentages can be applied to all P2P connections, but can also be used for the storage processes, as detailed in Chapter 4.1.5. Therefore, one advantage is that only one type of distribution needs to be used throughout. The fact that no participant is still worse off due to this distribution also provides stability in the cooperation and takes up the idea from Chapter 3.1.2. The advantage of an exact allocation of the P2P connections in connection with this sharing type is addressed there in the context of the MSFA and the Monge properties.

The disadvantage of a fixed savings distribution is that the price limits of the dominated biform game still exist. So it can happen that there are distributions in which so far unconsidered participants could temporarily or even permanently acquire more savings over a certain period of time. The period-specific decision on the uniform price prevents this in the dominated biform game and can here lead to the named second-order instabilities if participants are permanently not involved. A possible solution in this case can be the share of savings which the VEU receives. A portion of these funds can be used to give each participant VEU a lump-sum payoff, thus reducing dissatisfaction in general. The game theoretic computation itself should not be affected by these stability factors and the distributions should be in the core as long as the distribution of savings is only between participants.

5.3. Case Study

The objective of this study is not a comprehensive analysis of the presented methods, but to offer a first impression on the applicability and how the results can be assessed for further research. For the game-theoretical analysis, the VEU is therefore reduced to two or three participants maximally. This is permissible for interpretation and more useful for presentation. In this limited setting, the non-cooperative Nash game is quick to solve and feasible in a matrix. Constellations in which only one side of the market exists basically do not achieve any savings and can therefore be ignored in general. This leads to the investigation of the following constellations:

- M1 1 supplier, 1 consumer
- M2 2 supplier, 1 consumer (S1, S2, D1)
- M3 1 supplier, 2 consumer (S3, D2, D3)

For simplification, only the basic model with the exclusive use of ELA is applied and thus storage processes are ignored. An initial calculation of the Shapley values for these constellations confirms the results of literature. The result shows that only for *M1* a distribution is found which is always in the core. Since suppliers and demanders contribute the same amount of energy to achieve the savings, the Shapley approach always applies an evenly balanced distribution of the savings. In the constellations *M2* and *M3*, on the other hand, the Shapley approach does not necessarily find a distribution which is in the core. A fair distribution can also not be attested. The approach only considers the amounts of energy that each participant could contribute in order to decide which share of the savings the participant should have. P2P-connections that achieve a high savings margin but exchange lower amounts of energy are then even disproportionately penalized in this case, as shown in Table **5.1**. The first three rows present the results for the *M2* constellation, and the subsequent three rows present the results for the *M3* constellation. The initial data for the original energy quantities (column 'Energy') and for the ESP tariff value of the participant (column 'ESP) tariff') are provided first for both constellations. The results of the optimization for the internally exchanged energy quantities (column 'ELA Energy') and the associated margin between the tariff values (column 'ELA Margin') follow subsequently[2], before the distributions according to Shapley (column 'Shapley') are shown. In both constellations (*M2* and *M3*), the market side representing the bottleneck[3] is given the largest share of the savings. Note that the participant on the other side of the market with which the highest savings margin can be achieved (S2 and D2) is allocated a share of less than 10%. In no constellation can this scaling be justified by the amount of energy exchanged internally alone. The Shapley approach therefore considers the possibility that the respective bottleneck side (D1 and S3) could also exchange the entire amount of energy only with the other participant (S1 or D3). This consideration makes sense, except that the participant that enables a worse margin (S1 and D3) is disproportionately rewarded in this case. The disadvantaged participants (S2 and D2) will not be satisfied with this distribution, given the appropriate transparency, due to their much smaller share of the savings. Incidentally, the Shapley distribution is not in the core in either constellation, which is consistent with what has been proclaimed in the literature. It can be added, however, that the Shapley approach cannot show satisfactory results for mixed coalitions that include more than three participants. An additional analysis of the second phase of the modified biform game can be neglected in this case, since the games are already classified as not stable for the criteria of the cooperative game.

If the nucleolus approach is applied instead, it is shown that a distribution is always found which also lies in the core. However, the proposed distributions do not corre-

[2]The savings margins of the respective single market participants differ, since the margin value can already be seen at the participant of the opposite side, which is involved in the energy exchange.

[3]In both constellations this is the market side with only one participant.

	Energy	ESP Tariff	ELA Energy	ELA Margin	Shapley
S1	2330 Wh	13.50 cents/kWh	288 Wh	21.51 cents/kWh	3,595.76 (37.37%)
S2	139 Wh	10.90 cents/kWh	139 Wh	24.11 cents/kWh	679.01 (7.11%)
D1	427 Wh	35.01 cents/kWh	427 Wh	–	5,271.40 (55.52%)
D2	102 Wh	32.59 cents/kWh	102 Wh	20.79 cents/kWh	432.99 (9.31%)
D3	262 Wh	30.25 cents/kWh	137 Wh	18.45 cents/kWh	1,577.48 (33.94%)
S3	239 Wh	11.80 cents/kWh	239 Wh	–	2,637.76 (56.75%)

Table **5.1**. Shapley Saving Distribution

spond to an overall stable distribution when the results are considered in detail.[4] That the nucleolus does not provide a robust solution for a saving distribution in the VEU is further illustrated by the results in Table **5.2**. The identical arrangement of constellations is analyzed[5] with the repeated information for the amounts of energy exchanged internally (column 'ELA Energy') and for the associated margin between tariff values (column 'ELA Margin'). In *M3*, the distribution of the nucleolus approach (column 'Nucleolus') discriminates customer D2 very clearly, giving a share of 119.34 or 2.57%, and this despite the higher margin of the P2P connection between the two participants involved and the small deviation in the energy quantities exchanged. In the constellation *M2* a distribution arises in which supplier S2 is discriminated and receive only a share of 1.89%. In both constellations, the allocated savings of the respective discriminated participant (S2 and D2) are then so different in comparison to the other participants that this allocation will barely hold. Although the exact distribution that the nucleolus chooses for vertical collaborations cannot be unambiguously reproduced, certain rules and patterns can be identified. This is true in particular, compared to the results of the dominated biform game ('Dominated' column).

	ELA Energy	ELA Marge	Nucleolus	Dominated	Fixed
S1	288 Wh	21.51 cent/kWh	3097.44 (32.45%)	0 (0.00%)	3,716.93 (38.94%)
S2	139 Wh	24.11 cent/kWh	180.70 (1.89%)	361.40 (3.76%)	2,010.77 (21.06%)
D1	427 Wh	–	6,268.03 (65.66%)	8,757.77 (91.74%)	3,818.47 (40.00%)
D2	102 Wh	20.79 cent/kWh	119.34 (2.57%)	238.68 (5.13%)	848.23 (18.25%)
D3	137 Wh	18.45 cent/kWh	1,263.82 (27.19%)	0 (0.00%)	1,011.06 (21.75%)
S3	239 Wh	–	3,265.07 (70.24%)	4,409.55 (94.87%)	2,788.94 (60.00%)

Table **5.2**. Comparative Saving Distributions

[4]It is even evident that by changing the positioning of the constraints in the model, deviating saving distributions are presented as a solution in the nucleolus approach. That several distributions are located in the core and the nucleolus chooses only a certain one of them is understandable. That it can however arbitrarily come to a preference or disadvantage, depending on at which place the constraint is positioned, is not allowed to occur for a stable application of the distribution.

[5]*M2* in the first three rows and *M3* in the subsequent three rows.

The nucleolus method always assigns a larger overall share of the savings to the side representing a bottleneck (in the constellations analyzed, to participants D1 and S3). This preference is due to the fact that the participants on the bottleneck side also have a stronger influence in potential individual cooperations. Thus, they contribute more to the large cooperation for the procedure as a whole and this evaluation of the influence of both sides is even desirable. On the other hand, how the procedure evaluates the influence of the individual participants in the two groups themselves remains elusive. However, a consistent pattern can be identified, as the discriminated participant (S2 and D2) always receives half of what is provided in the dominated biform game. This suggests that there may be a correlation. In the dominated biform game, the savings values of the participants are based on a chosen uniform price which is supposed to prevent participants who are only partially or not taken into account at all from proposing deviating constellations and thus dissolving the grand coalition. Participants S1 and D3 are these potential deviants in the two constellations and also do not receive a share of the savings in the dominated biform game due to the chosen uniform price. The nucleolus method, on the other hand, disproportionately favors the two potential deviants and thus ignores the influence of individual P2P connections on the total savings. In the end, even the actual worst connection between two participants (the last edge in the graphical solution) is awarded the highest share of the total savings, which is also evident in cooperations with more participants. The remaining participants, on the other hand, receive a minimum share that is acceptable for the procedure. The minimum share can be derived from the values of the dominated biform game, as is also the case in the constellations investigated. The disproportionate preference for this connection, which is the worst in terms of margin, does not follow a rational decision especially if the other participants are only granted these minimum amounts. Overall, it can be concluded that although the distributions of the dominated biform game also are in the core, like the distributions of the nucleolus method, both contain clear discriminations of individual participants and therefore do not result in sustainably applicable distributions. Further and more extensive investigations are nevertheless necessary. The discrimination in the dominated biform game is mathematically correct, since deviation is computationally prevented, but in practice the distribution will still cause discontent. Although it must be noted that the preferred side can change constantly with this type of distribution and therefore a possible compensation in the preference can be given over time. However, this would require studies over a longer period of one year in order to make a reliable determination here.

The fixed savings distribution approach (column 'Fixed' with predefined 60% for suppliers and 40% for demanders) offer a very good compromise in this case. The proposed distributions take not only the energy quantities exchanged into account but also the respective saving margins of the P2P connections. It then lacks consideration of the respective market power at a certain point in time and thus ignores temporary influences. How and whether one side is favored can be defined by the VEU and applied constantly. In general, fixed distributions offer more attractive and comprehensible distributions for a cooperation that can be determined by a VEU or selected by a vote. However, a fixed distribution is mathematically challengeable in every period, but only if there are participants that have not been considered so far. This also becomes apparent when the second phase of the biform games is played afterwards. A Nash equilibrium only results if deviating players cannot find a better distribution among themselves when they play in smaller coalitions. Disregarded players can propose coalitions in which they are better off in a fixed allocation and still be able to improve another participant's position. With nucleolus, on the other hand, the arbitrary selection of a split that lies in the nucleolus automatically results in the Nash equilibrium. In the two scenarios studied, the individual coalitions are distributed in such a way that only one player receives all of the coalition's savings, resulting in all players being satisfied with the distribution of the large coalition. The Nash game for nucleolus based distributions thus has no significance because of the nucleolus approach. The dominated biform game also always holds in the Nash game, due to the explicit use of the deviation limits.

5.4. Discussion

Neither the classical game forms nor the biform variants are able to find consistently stable distributions for a VEU, as can be seen from the case study. The dominant biform game at least offers a problem-specific alternative that computationally rules out any deviation. However, it may be doubted whether this approach ensures long-term satisfaction. Although further analysis of the applicability of the core to vertical cooperation games is also appropriate, given the selection of results presented. The most reasonable procedure is a fixed saving distribution, which, however, remains computationally vulnerable. The proposed distribution of this procedure will therefore always depend on the acceptance of the participants and what they consider to be fair. However, this is a question that must be answered using empirical data. Mathematically, the dominant biform game remains the only reasonable game form that can currently be proposed for the savings distribution at the moment. In this case, it is possible to compensate for the purely mathematical weaknesses of the fixed saving distribution with the principles of the dominated biform game. An example is, a fixed saving distribution which nevertheless takes into account the respective market situation and favors the respective bottleneck side. This is in contrast to the market-oriented preference in the dominated biform game, however, to a lesser extent.

An interesting aspect of the dominated biform game when analyzing the entire planning horizon is the constant and, to a certain extent, predictable change of the dominant market side in the course of a day. This is due to the cyclical power production of the photovoltaic (PV) devices. In the beginning, the supply is still very low and will hardly be able to cover an ordinary period demand. The uniform prices in these periods will then favor the supply side. This changes with the increased supply due to the increasing productivity of the PV devices, where the uniform price will then align with the demand side. As energy production decreases, this will then reverse again. For most of the productive phase of the suppliers, the uniform price will thus favor the demand side and provide small savings for suppliers. The dominated biform game thus follows the laws of the market economy, but the approach could understandably also lead suppliers to then seek alternative trading opportunities. The VEU would rather be a submarket then a cooperation and since all participants are still independent, it would be conceivable that they let only parts of their supply or also their demand settle by the VEU. For example, it would be possible for participants to trade residual quantities directly at a LEM or through aggregators if the distribution of the VEU is disadvantageous for them. Alternatively, participants could make strategic decisions and try to strengthen their side of the market in the long run by acquiring new customers or suppliers or by switching sides themselves. Overall, it is likely to be inconvenient to always explain the volatile uniform price throughout the day based on the temporary market composition in the case of transparent settlement vis-à-vis the participants.

The relationship between the price limits in the dominated biform game and how they are taken into account by nucleolus is also an interesting finding. It shows that the nucleolus also takes these price limits into account in order to find a computationally acceptable distribution. In contrast to the dominated biform game, however, the nucleolus exploits the price boundary to such an extent that it not only favors the superior side of the market, but also arbitrarily discriminates between participants within the inferior side of the market. This can be seen in the sometimes drastic discrimination of participants who receive an absolutely minimal saving, so that a deviation is mathematically just prevented. If there are two participants on the inferior side of the market, only one of the participants is discriminated in this way. The other participant then receives a disproportionate share of the savings. Therefore, although the nucleolus finds a computationally stable allocation, which is also in the core, it cannot be used practically. The second-order instability is obvious and a cooperation could only justify such values if it is not transparent to the participants.

6. Conclusion

The climate and resource-related challenges to the energy systems in the coming decades will have a strong influence on the future energy supply. Therefore new solutions and approaches are needed on how our energy systems can be designed and improved. However, it is not only the large scale that will be important, but also changes and adjustments on the individual level. The handling of energy on a personal level and a stronger interaction between individuals will be necessary in order to ensure a more efficient use of energy. Altogether, the more efficient use of energy by individuals can provide a great solution, which is why local energy management and active end users will be crucial elements for a decentralized, smart and interconnected energy world. This thesis also provides a useful element for this environment and a basis for further development of cooperation in such an environment. The development of improved planning and decision support systems for energy cooperatives and energy communities will make more efficient energy use at the local level in the context of the energy transition a little easier to realize. Although this thesis can present some progress on an operational planning level and improve economic decision-making processes, there are of course more elements to be developed and discussed. The coming decade will still hold difficult challenges, especially for the control mechanisms in real-time operation, in order to implement this decentralized, smart and interconnected energy world in a practical or functional form. However, the better and more precise the planning at upstream levels is, as in this thesis, the easier it will be to guarantee a stable and secure energy supply for real-time operation systems.

This thesis concludes with this chapter and in Chapter 6.1 first answers the questions raised at the beginning of the thesis and states how the targeted contributions can be assessed. In Chapter 6.2 follows a selection and discussion of interesting findings of this thesis. What implications this has for future research and what further research goals are to be worked out is elaborated in Chapter 6.3, in addition to the recommendations already made in the course of the thesis.

6.1. Problem Progression and Contributions

The key question to be addressed in this thesis and formulated in Chapter 1.1 is:

> *How can a cooperation of local actors effectively and efficiently coordinate their internal energy exchanges to add economic value ?*

With the virtual economic unit (VEU) this thesis presents a basic concept how independent local actors can act as a cooperation in a future decentralized organized energy system. With the provided mathematical models and algorithms, the internal energy exchange between the participants can be designed in such a way that a system-optimal economic added value is given for this cooperation. The model is modular and is further developed in the course of the thesis and thus also provides the basis for potential extensions of the systems considered so far (energy storage system (ESS), demand side management (DSM) and electric vehicle (EV)) or the integration of further systems/approaches such as controllable energy generators (such as micro combined heat and power) or demand response (DR) approaches. The economic analysis with each iterative step shows how the internal energy exchange generates this added value for the community. The results show interesting influences (e.g., seasonal or parameter dependent), which can be individually evaluated with the provided models and thus can also be used as strategic decision support.

A comprehensive answer to this question also involves addressing the sub-problems identified earlier:

- *How exactly should a framework for cooperation and its operational planning be structured ?*

  With the VEU, this thesis offers a framework for cooperation in local energy management that allows collaboration to occur among still independent participants. Since consumers and prosumers are likely to become more active in the future, they will inevitably be able to conclude several contracts for their individual energy exchange. However, this also means that they will be able to diversify their energy exchange over an undetermined number of service providers and, in the conception of this thesis, a basic type service operator must also be given. This, so far, common energy exchange through an energy service provider (ESP) is not always sufficiently considered in previous literature or not given the importance that is necessary. The alternative prices of the ESP are substantial for the operational planning of internal energy flows, especially if really resilient cost rates are missing. A decisive advantage of the presented modeling is thus the explicit renunciation of the otherwise common cost definition in this research area. The allocation of strategic costs (such as acquisition, etc.) to the operational costs to be optimized is, as is known in the research area of production planning, not expedient and must therefore be avoided. The results of this thesis and the provided modeling are therefore also applicable for further or downstream planning processes and offer relevant decision support for operational planning.

Furthermore, a framework should support modular diversity and be able to decide specifically on the analysis of individual systems. This thesis therefore offers an approach developed from scratch, whose iterative examination also enables a targeted analysis of the individual systems and their contribution or influence for the success of the VEU.

- *What economic influence does flexibility solutions have on the internal exchange of energy in cooperation ?*

  The impact of ESSs has been shown to be of key importance to a VEU. The provision of energy supply in time periods in which it is otherwise mandatory to use a ESP has a significant influence on the economic added value of the internal energy exchange. For a VEU, this flexibility option can thus even be considered essential, even if the efficiency loss of an ESS ensures that direct energy exchange through energy load adjustment (ELA) is usually prioritized. ESSs are, however, quite capable, above a certain threshold on individual connections, of providing more economically lucrative options. It is this capability that makes these systems so valuable to a VEU in a direct matter. This does not take into account the indirect benefits that these systems can have when considered as safety buffers to make real-time operations more robust.

  The application of DSM is comparatively less influential than the application of ESSs in the conducted studies, but nevertheless in general it provides additional economic benefits for a VEU and its participants. Steering the energy demand into time periods in which satisfaction can be more easily realized increases the possibilities of better distributing the energy consumption and thus makes sense if more dynamic pricing is used in the ESP. DSM also benefits from combined use with a ESS and demonstrates very well how different flexibility options can complement each other in this context.

  By the controversial integration of EVs, this thesis shows that it will be crucial how these devices can be planned and considered in the future. The chosen, rather restrained approach already shows the economic potential of EV-optimization with a marginal increase of model complexity. The problem is thereby focused on the core, and potentially most promising aspect, the use as a temporarily deployable ESS. Adding more complexity by incorporating flexibilized periods of use only makes sense if those participants who provide their EVs to the VEU are able and willing to do so. Overall, flexibility is a valuable factor for the VEU because, on the one hand, concrete economic advantages can be generated and, in addition, seasonal or general temporary fluctuations can be better responded to.

- *Are there methods for the participants to distribute the monetary benefits of the cooperation reasonably among each other afterwards ?*

  The VEU is a vertical or hybrid cooperation in which both sides of the market are covered and this type of cooperation is sufficiently known in theory, but a concrete generally applicable procedure for the distribution of success in such type of cooperation is not yet realized. This thesis indicates the disadvantages of the success distribution of classical procedures for small examples already. As an alternative, a problem-specific approach is proposed, which determines a uniform price for each individual energy exchange in a certain time period and thus makes deviating within the cooperation computationally impossible. In general, this approach is an improvement on the distributions of the standard methods, even though it is not a practicable distribution method for the success of VEU. Discrimination of one side of the market will inevitably lead to discussions and thus deviations of participants may occur. The simple, but reasonable alternative provides a fixed distribution of the success which the VEU determines, or for a greater acceptance among the participants can also be determined by vote.

The main contributions of this thesis are:

- A basic framework for a cooperative agreement of participants in a local area of the energy grid (Chapter 2)
  - Classification in the current state of research on local energy markets and cooperations
  - Potential definition of this local area for participation in the VEU
  - Participants are still independent actors and are able to manage their personal energy exchange or parts of it also through other contracts or partners
- A modular and extensible mathematical model provided for the operational op-

timization of internal energy exchange in the VEU
  - The structure of the model starts with a rudimentary basic approach (Chapter 3)
  - Iterative development of the model to include specific flexibility solutions (Chapter 4) like ESS and DSM
  - Holistic approach is provided that can be modified and extended
  - Extensive tool for economic analysis and operational planning
- Comprehensive economic analysis of all incremental modeling steps
  - Insights of how particular parameterizations affect the system now under consideration
  - Focus on practically applicable modeling, predominantly based on a linear program
  - In addition, the analysis of the economic results is also used to show and evaluate alternative solution methods
  - A holistic economic view of the potential success of a VEU and how this success is composed, which influences prevail and therefore can be used concretely also for strategic decisions is created
- Initial game-theoretic analysis on the success distribution within vertical/hybrid cooperations (Chapter 5)
  - The model optimizes the economic success of the entire cooperation, which is to be distributed among the individual participants
  - Delineation and examination of possible distribution methods for this particular form of cooperation
  - First analysis of selected standard game-theoretical methods and new problem-specific approaches

6.2. Summary and Implications

A key insight from the case studies presented is that in local environments such as a local energy market (LEM), energy community (EC) or the VEU, energy supply takes on a more dominant role than before. The overall energy system will be still demand-driven (as described in Chapter A.1) with a constantly existing but volatile energy demand that has to be finally satisfied. However, the individual local and regional energy markets will not operate autonomously, but in conjunction through and with higher grid and energy market levels. The concept of microgrids discussed and studied in the literature proposes autonomous operation, but even there, connection options to the existing grid infrastructure are considered. At these higher levels, energy demand will continue to determine the energy trading quantity to a certain extent. The price of energy is therefore determined by the resources or energy supply required to provide this trading quantity. This condition does not apply to local energy environments, because the energy supply is limited and therefore cannot automatically cover the entire energy demand. The local energy supply therefore exists apart from autonomous environments as before as a supporting energy supply, but is utilized more effectively through local market and community solutions. This again underlines the importance of the basic contracts with the ESP highlighted in this thesis, which guarantee the required basic service. It also highlights that the terms of these contracts are the most important operational optimization criterion for local environments. The cost allocation by means of full cost accounting, which is often used in publications, provides distorted results, since these values assign a different weighting to assets and participants. However, this alteration is based on cost values that do not have an operational character, since photovoltaic (PV) for example has no variable production costs. Strategic investment costs or maintenance, on the other hand, are fixed costs that cannot be optimized and are not expedient for operational planning.

Since energy supply is no longer adjusted to demand, it can be observed in the VEU case studies that a constant and changing imbalance between supply and demand prevails over time. Due to the volatility in PV energy generation, this behavior is understandable. On the other hand, it is also desirable as a basis for analysis since such configurations for the actors is realistic in future local environments. The divergent role of energy supply is highlighted in a particular way by this scenario and there are then two alternating temporary states of this supply, which either represent a bottleneck or result in a surplus. If the internal energy exchange of a VEU is limited to period-specific ELA (the baseline studies from Chapter 3) this imbalance is more pronounced comprehensively. The primary aim of the flexibility options is therefore to make better use of the excess supply in each case. In the case of supply-based load shifting, this is hardly surprising, since it is the purpose of this option. However, demand-based load shifting is also primarily driven by supply, as the optimized DSM schedules attempt to shift demand in a way that prioritizes the use of ELA. It is thus evident that energy supply and demand are balanced differently than before, which also increases the need for these flexibility solutions in order to keep the maximum quantity of energy local. What influence ESSs can have especially in this context becomes clear by the case studies. Despite efficiency losses in storage processes, the savings potential cannot be neglected and exceeds the possibilities of ELAs, since the energy exchange by means of ESSs is no longer time-bound. On the other hand, if the demand is also flexible, the importance of time-bound energy exchange by means of ELAs increases again, since the demand can come to the supply. In summary, it can be seen that through the multitude of options understandably more savings can be achieved and therefore is to be preferred, if possible. The flexibility option through EVs, on the other hand, is treated very controversially in this thesis and abstains from integrating the otherwise focused partial benefit of demand shifting. The additional capacity or flexibility of EVs, on the other hand, is assigned the more valuable contribution for optimization and the integration of EVs is used to introduce a meaningful extension of ESS parameters and to question the sense of explicitly modeling the shifting of the EV energy demand through status changes (off- and on-grid). A final evaluation cannot be made at this point, but will depend to a certain extent on how the EV fleet available to a VEU is structured. Many second cars with rather flexible use options increase the meaningfulness of postponed status changes. This is countered by a rather rigid use of main cars, whose potential for status change shifts is low and thus the different scenarios can also be compared by solving a less complex model several times.

The VEU and implementations provided can help with rough operational planning and provide data that gives a general projection for the next few days. This data can then be used to ensure more stable real-time operations or even serve as decision support for strategic decisions. The VEU or individual participants, for example, will expect a corresponding return on investments in their assets and therefore need analysis capabilities to estimate this. Which operational influence targeted investments may have can be determined with the provided models and the results for the investments can be derived. If the seasonal effects are taken into account, which are shown and discussed in this thesis, the strategic analyses made are more sustainable. For this, it is necessary to extend the planning horizon considerably, which will be feasible due to the favorable modeling.

In the game-theoretical analysis of this thesis, it is noteworthy that the distribution mechanisms examined almost always lead to discrimination of individual participants. The only exception is the fixed distribution. Individual participants are thereby allocated very small shares, even if their contribution to the savings objectively requires a stronger appreciation. Of course, this also lowers the incentive of these participants to continue to participate in the cooperation or increases their dissatisfaction with the cooperation. The literature calls this second-order instabilities and describes why mathematically or procedurally plausible solutions may still not yield a satisfactory distribution. It is interesting that proven methods such as Shapley or nucleolus offer a distribution that can plausibly estimate the share of the two market sides, but ultimately fail to find a fair distribution within the market side. Possibly, it is a plausible approach to carry out a redistribution within the market sides on the basis of an initial solution by the standard procedure, in order to resolve the injustices there. However, this idea was not explored further within the scope of this thesis, but therefore offers a first perspective on future research possibilities, which will be discussed in more detail in the next section.

6.3. Outlook

With the results presented in this thesis, one key extension can be identified in the first place and that would be the external connections of VEUs as an additional option to increase savings. The advantages of the internal energy exchange between the participants have been outlined, and it is now necessary to clarify how an additive connection can be effectively designed for external purposes. For a sustainable analysis, it is necessary that politics and energy industry concretize the market models for local energy management more than it has been done so far. The rather loose framework conditions and rudimentary declarations of intent known so far are not yet sufficient. The theoretical approaches in literature and started scientific practical projects on local energy markets have so far been very close to the known market structures in the energy environment. As shown in this thesis, a two-step approach can be usefully applied in this case, in which the optimal internal energy exchange between the participants serves as a basis or first step. From this, the necessary information can then be derived to make economically appropriate decisions for the external connections of a VEU. This approach can be built upon should the theoretical development so far ultimately lead to regional or local energy markets operating on an auction basis. Meanwhile, the internal optimization of a local community with given technical possibilities and legal framework, even without concrete market access, is already feasible for participants who already want to become active in this form.

The extension and/or improvement of the optimization methods presented is also a potential research approach for the future. Thereby, a focus on the improvement of the optimization methods is quite conceivable, such as the targeted investigation of heuristics for ESSs and DSM. However, the question arises how purposeful a focused development is, due to the presented effective modeling (linear program) and the available powerful solvers (mixed-integer program). The further development of the integrated EV-planning is an exception here, since this thesis explicitly abstains from a schedule shift of the vehicle status comparable to DSM, but only justifies this theoretically. To conduct a detailed study of whether this potential shift in EV deployment times can develop a significant impact is quite purposeful in this regard. The extension of the presented optimization methods, on the other hand, would be more in line with the actual purpose of the modular structure of this thesis. For example, the integration of controllable energy generation by micro combined heat and power or similar devices should be mentioned here. Such devices are primarily used for efficient heat supply[1], but also provide significant electricity production. The electricity produced simultaneously with the heat can then be used within the VEU, providing a missing controllable operational element. Alternatively, a sequential or decomposed approach can be used to integrate this element, in which heat generation is first determined separately or subsequently based solely on heat demand. Thus, the decision of this subproblem is made based on the primary energy demand alone and not simultaneously, as would be the case if the decision is integrated into the existing model structure. An investigation of the integrated approach in comparison to the two potential sequential options may be an interesting future project.

Another opportunity for further elaboration is provided by the uncertainties for this local energy management of the VEU. While there is still a subsequent operational level of control that ensures real-time operation, efficient and robust operational planning at the upstream planning level reduces necessary corrections in real-time operation. Significant improvements can still be made here, even though relying on widely accepted energy forecasts is understandable and reasonable for the purpose of this thesis. However, subsequent studies, especially with potential data from real-time operation, can improve the forecasting methods used in practice. Alternatively, this could be done by applying simulations, even though this thesis considers an improvement of the forecasts to be more reasonable in principle. Regardless of the chosen procedure to improve the handling of uncertainties, it must be considered that even the best procedures cannot guarantee absolute certainty and that deviations will oc-

[1] The devices have a much better resource utilization rate than ordinary thermal power plants.

cur. As a result, especially when using ESSs so far only the mentioned optimization measures will be necessary. This means the level of safety buffers that should be available to ensure reliability of the operational energy balance in the VEU even without external measures (by the distribution system operator (DSO) or the ESP). This has economic relevance especially when the VEU has a similar responsibility for its energy balance as is the case with a balance responsible party (BRP). At the same time, appropriately held security buffers provide opportunity costs, since the storage capacity or the stored energy quantities cannot be used in a profit-maximizing way. Therefore, it is necessary to find optimal buffers that satisfy the need for security while ensuring maximum utilization. However, the determination of the security buffers is not a one-time decision, since, for example, seasonal effects trigger other demands on the system and therefore a dynamic decision is to be expected. Production planning research can provide insights into the design of such buffers under uncertainty, as this topic is well studied in this area.

It is also evident from the thesis that the identification of a suitable method for the distribution of success within the cooperation is still incomplete. The research also only sparsely deals with such vertical or hybrid cooperations in which the interaction of both market sides achieves success. Horizontal cooperations are more common, which is why the focus of research on this type of cooperation seems understandable. However, the standard methods developed for this purpose are evidently not transferable to vertical cooperations such as VEUs, and even the problem-specific methods presented in this thesis do not provide conclusive distributions that make second-order instabilities unlikely. Fixed distributions that are predetermined or determined by voting are the most promising. However, further research is needed in this area to ideally provide a standard applicable method for vertical cooperations, which is not yet available for the energy sector or elsewhere. On the other hand, this thesis explicitly points out that for external connections the used standard procedures are still effective and reasonable. If the VEU acts externally as a cooperation at a market in order to trade energy supply and/or demand there, the involved participants of the VEU may well divide the resulting benefits by the said procedures. In this case, these participants then form a horizontal cooperation on a certain side of the market and can act accordingly. However, since the VEU acts on a local market, the participants can also simply benefit from the better market price that the VEU negotiates for them. Here there are then several options with proven methods to get a distribution that is stable, which is not yet completed for the distribution of the success with internal connections.

In addition, there are other aspects that have been addressed only marginally, if at all, in the context of this thesis. Another perspective on the optimization would be the consideration of ecological key indicators in the objective function, such as the predicted CO^2 reduction of the corresponding peer-to-peer (P2P) connection or storage processes. This would result in a multi-objective optimization that considers economic and ecological effects. How, and if, a weighting between the two objectives is made and what effects this would have on the optimized internal energy exchange is a potential study that can broaden the perspective of optimization. On the other hand, it is not advisable to ignore the economic effects altogether, since the acceptance and thus also the success of local energy management will benefit most from monetary incentives. Ecological aspects are increasingly popular in society, but to inspire the population further to actively participate in a diversified energy exchange, monetary benefits will be more convincing. At the same time, there are important areas of research that will have little impact on operational planning itself, but will be essential to the success of VEUs and similar energy communities. These include, above all, data security in an interconnected and decentrally organized energy grid and the general vulnerability of such modern energy infrastructure. Precisely because energy is becoming increasingly important for modern life, the protection of the systems and the data exchanged there is more important than ever. In contrast, the more decentralized organization and interconnected flow of information increases the risks for infrastructure and the requirements within and for the executing systems. In the context of smart grids, these future challenges are currently still under discussion and therefore offer interesting opportunities for interdisciplinary exchange. For the near future, on the other hand, an interdisciplinary exchange will primarily be with the decision-makers for the legal design of local energy communities and local energy markets, in order to create technically feasible and economically sensible framework conditions for local energy management.

A. Energy Background

The commodity ’electricity’ is a fundamental good in modern society, but not easy to manage due to its specific technical characteristics. Compared to normal trade goods, electricity must therefore always be available exactly when it is to be consumed. At the same time, there is a need to always transmit electricity in a stable and constant manner. The possibility of supporting this with a high degree of flexibility (i.e. via storage solutions or more controllable production) is also given in such a system, but entails further (technical) requirements and restrictions. This creates particular challenges for the system structure, possible market designs, the regulatory framework and the different actors within the system. In order to ultimately ensure a consistently reliable power supply and keep the system power flow technically feasible, today’s power grids require large (controllable) generation plants, redundant transmission and distribution grids, as well as various control and monitoring functions. These grown structures and technical necessities are already given and it would not make sense to set up this system from scratch or to abandon the existing infrastructure. It is therefore more reasonable to expand the existing system and to integrate new possibilities into the current grids, especially to avoid unnecessary investment costs. Nevertheless, this means that these circumstances also have a significant influence on the change of perspective that is discussed in this thesis. For an economic view of solutions in local energy management, some basics have to be considered. Section A.1 of this thesis will thus provide the most important information on the traditional structure of electricity systems in this context and why some of the existing services and regulations have to be considered also in new local approaches. Section A.2 then describes how markets for these important systems have been designed so far and why this form of market design is necessary to enable trade in the commodity "electricity".

A.1. Grid Structure

The energy systems installed worldwide are already complex entities with an enormous number of connected users, different installations, various economic actors and a smaller number of system operators. The traditional approach for managing such a complex environment is to focus on covering the sometimes highly volatile demand while maintaining the necessary stable energy flow. For this demand-driven focus to be possible, the system has to actually rely heavily on a few actors in the grid – grid operators for secure transmission and large generators (such as nuclear, coal, gas or hydro power plants). The latter offer a correspondingly large amount of controllable generation capacity that can be called upon when needed and thus allowing for demand-based top-down control of the energy flow. The operation of such powerful generators also entails significant disadvantages. Energy sources such as gas and coal, for example, can only be used very inefficiently on this scale. Hydroelectric power generation, on the other hand, is limited in terms of possible locations and related catchment areas, and nuclear energy is associated with considerable risks.

Nevertheless, it can be stated that this demand-oriented approach greatly simplifies the central coordination of the entire energy flow, since the feed-in only has to be coordinated from the top with involved grid operators via precisely defined interfaces. **A.1** shows how power plants – on the highest grid level – feed with high voltage into the transmission grids. The quantity of energy demanded is distributed (red arrows) with high/medium and low voltage via the distributions grids below to the large number of predominantly passive customers and end consumers. This makes the power flow mainly unidirectional and therefore easy to control. Due to the leading role of the grid operators in such a system, who thus have a natural monopoly, their influence and potential market power is so significant that regulation between the individual actors within a grid is indispensable if the grid is not operated by the state anyway. The same also applies in partial terms to the potential market power of the suppliers, as they can exert active influence in contrast to the normally passive consumers.

In order to ensure the central coordination of the entire energy flow and thus a secure and reliable operation of the energy system by the grid operators, they need flexible and quickly deployable capabilities to be able to intervene. In today's energy system, this required immediate flexibility is provided by so-called auxiliary services. The task of these services is to change the demand for or supply of energy at short notice in such a way that the balance in the system and thus the quality of the energy flow

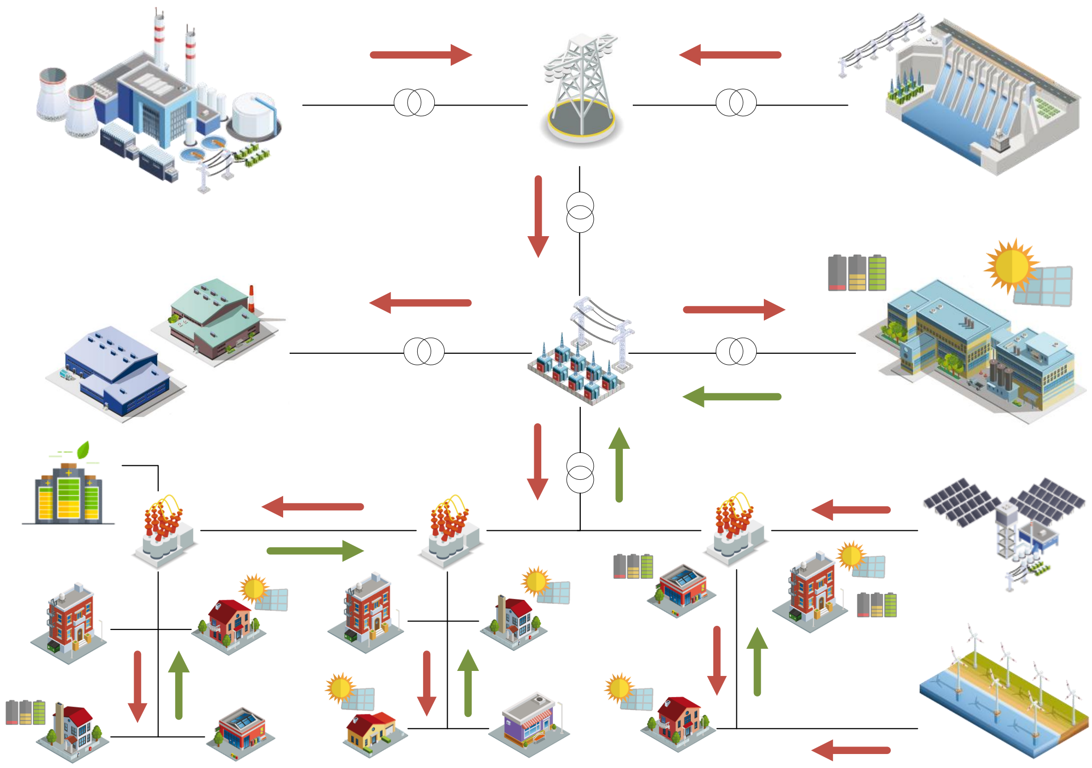


Figure **A.1**. Grid Environment

are maintained within a tolerable range. Therefore, mainly very flexible power plants regulate the frequency of the power flow and provide spinning reserves or merely supply the power to compensate for imbalances within the power system. In addition, a grid operator is able to handle overloading of power lines or transformers, if they have to modify generation schedules of power plants for security reasons. However, these ancillary services are not provided automatically and have to be purchased by a grid operator in special designated markets, so-called *balancing markets*. This highly regulated type of market is discussed in more detail in section A.2. The importance that flexibility has and will continue to have in the energy system is significant, even if only a local perspective will be affected.

A strong and usually very restrictive legal framework is of central importance in an electricity system, in order to define and enforce all principles or rules that the system needs for the necessary functionality. Regulation therefore aims to avoid inefficient behaviour that could occur if the actors in the system were free to interact, as Pérez-Arriaga (2013) describes. This inevitably limits the freedom of actors within the grid and possible energy markets, because monopolies or oligopolies should not be able to determine prices or offer bad services within such a system due to their position. In contrast, regulation is also possible to protect investors from excessive state intervention, where, for example, the setting of utility tariffs limits the return on investment. Regulation becomes particularly important for this thesis when the relationship and responsibility of the actors in the system are clarified. While the grid operators are responsible for the security in the grid and have to create the necessary balance by using auxiliary services, there will be actors who are ultimately responsible for the imbalance that has occurred and have to be charged for it afterwards. The increased use of decentralised approaches for the electricity systems and electricity markets of the future, and the associated more local energy management, means that the more active actors will have to be integrated into the system and coordinated via smart (grid) solutions. The latter will be discussed in Section 2.1.3. The creation of a further developed legal framework that allows for a clearly defined distribution of roles and a clarification of the responsibilities of the individual actors is therefore indispensable.

It is obvious that this traditional structure of the electricity grid was not designed for the future demands on the electricity grids. The already existing supply which is additionally provided on lower grid levels is already a challenge for the central control of the energy flow, so that only parts of it are used at peak times. The planned and inevitable expansion of renewable energy generation in the near future will exacerbate this situation and thus lead to increased supply wedging at these grid levels. The volatile nature of renewable energy generation thus further increases the pressure on the system and the need for flexibility, so that a stable and efficient power supply with a top-down approach and unidirectional power flow can no longer be fully guaranteed. Inevitably, the need for a bidirectional power flow arises, which is nowadays technically possible through tools such as smart meters and the discussed information and communications technologies in smart grid approaches. However, a transition to bidirectional power flows (additional green arrows), as shown in Figure **A.1**, have to be effectively controlled by all grid layers and requires further control elements within the grid. This is mainly referred to as the smart grid, which is intended to make better use of the already increasing degree of digitalisation in the grid, making a decentralised organisation of the grid structure possible in the first place. More detailed information to smart grids is shared in Section 2.1.3 or in e.g. Colak et al. (2016), Ilieva et al. (2016), Menniti et al. (2014).

A.2. Evolution of Power Markets

Traditionally, energy supply has been understood as a fundamental good that must therefore be provided by the state itself or state-owned companies, which is equivalent to a regulated monopoly. There is only one supplier who manages everything himself, from production to transmission and distribution to the end customer. There is no competition at any level, in any way. In order to enforce fair pricing and certain responsibilities (such as security of supply) against the monopolist, appropriate regulation is therefore necessary. Today's modern and increasingly digitalised society depends to an even greater extent on the importance of a stable but also more efficient energy supply. The beginning of deregulation in the 1980s and the associated varying degrees of liberalisation have already dismantled parts of these former monopolistic structures. The goal is to achieve a more efficient use of resources through more competition and at the same time to ensure the necessary security of supply through targeted regulation. Although there are still countries that rely on a monopolistically organised electricity supply, new market forms have developed and prevailed worldwide to trade in the special commodity of electricity. The basic structures are discussed in detail e.g. in Kirschen (2019). The most common forms of market organisation are wholesale markets and retail competition. They are of particular interest for this thesis, as local energy management inevitably has to deal with existing structures and actors, as they will not disappear. In addition, local energy markets will have to take on several tasks and challenges which normally arise in this larger scaled market environment. It is therefore useful to understand what makes these structures special. The two common basic structures are therefore illustrated in Figure **A.2** and will now be briefly explained.

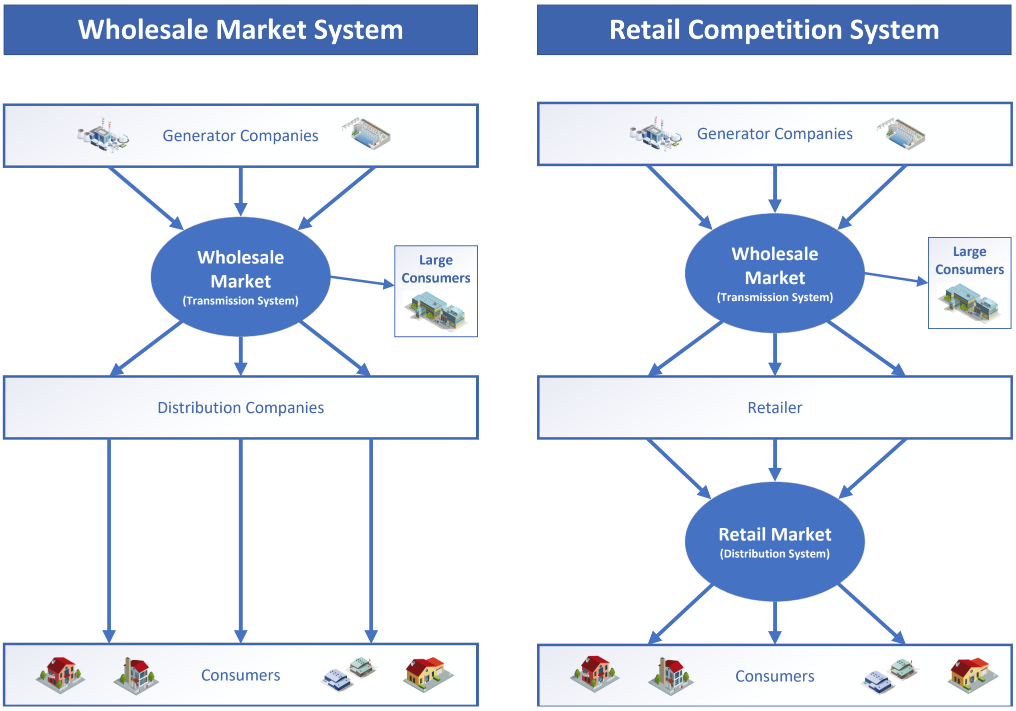


Figure **A.2**. Common Energy Market Structures

Theoretically, there is more competition in a **wholesale market system** (left-hand side of Figure **A.2**) than in a regulated monopoly structure with only one state-owned company. There are several suppliers of energy, so-called generation companies, which place their offers on the wholesale markets. This energy is then in turn purchased by so-called distribution companies, which bundle the demand of consumers in the area assigned to them. As a result, the demand quantities on the wholesale market are correspondingly high and the supply side is met on an equal footing. For ordinary consumers, there is no significant effort or risk involved in the energy supply. If a consumer can guarantee a certain purchase quantity himself, he is in a position to participate directly in the wholesale market. Of course, this also means that a large customer is responsible for its own security of supply. The basic procedure for trading on these markets is either a pool principle, in which supply and demand are cleared in an auction system, or relies on bilateral trading, so-called over-the-counter transactions. The wholesale market price is thus determined by matching supply and demand.

Unlike a regulated monopoly, in a wholesale market there is no central entity solely responsible for the provision of energy, so this responsibility is shared to a certain extent in such a market environment. The main issue here is the responsibility to operate and maintain the grid. However, who provides the services required can be considered separately. While the reliability and operation of the transmission grids as well as the market organisation itself are handled by central entities, the distribution companies are responsible for their own distribution area. They alone have to ensure the security of supply for their customers, but in return they also have a monopoly position for this area. Competition is not foreseen at distribution level and as long as customers do not leave their area, they cannot change their provider. So it is only a partial opening, which is mainly intended to lead to competition between the generation companies. The bundled consumers will still assigned to a monopoly, which must then be regulated accordingly to prevent abuse in pricing.

Probably the most widespread market form in the energy sector is **retail competition** (right-hand side of Figure **A.2**). This form extends the wholesale market concept to include competition at the demand level, in the sense that small and medium-sized end customers are no longer tied to one supplier. End customers are now able to choose between different competing retailers to meet their energy demands. These retailers are referred to as energy service providers (ESPs) in the further process of the thesis. In retail competition, distribution companies no longer have a local monopoly in their area, but can of course act as ESPs in the retail market. In addition, distribution companies are still responsible for operation and maintenance of the distribution grid infrastructure. Distribution companies therefore still have a natural monopoly in this area and ESPs have to pay fees to the respective grid operators, which are necessary for supplying energy to their customers. This can also mean several grid operators and thus also different fees if they are not regulated. Therefore, state authorities usually regulate or restrict the fee design and monitor that the distribution companies distribute the energy properly and without privileges. In this market form, consumers are able to change their ESP depending on their contract situation if they expect better service or a better price elsewhere.

Although the grid fees are passed on to the end customer, retail prices are comparatively more favourable for them than in other market forms due to the competition in the market. The customer is not exposed to a monopoly and is less dependent on state regulation to enforce a fair price development. Retail prices usually also tend to offer a certain degree of certainty and predictability, as long-term contracts with fixed prices are not uncommon. In such a case, the ESP is taking on the price risk, as he has to purchase the energy on the wholesale markets. To take this risk into account and still remain competitive is a key challenge for ESPs. New market concepts in the sense of local energy management must be measured against/compared to this already achievable price level and at the same time offer this level of security for the end consumer. A more active role for consumers must therefore offer appropriate added benefits. The future of ESPs must also be considered, as a not insignificant industry cannot simply be abolished. However, this will be discussed further in Section 2.2.

In addition to these basic market designs, there are two important characteristics in the energy sector by which markets can be distinguished. The market mechanism is the first characteristic and defines how trading is carried out. Therefore, the two common forms of trading are presented below. The second characteristic is the classification of the market into a certain market type. The typification is done in the energy sector by defining the time of trading, i.e. when the trade ultimately takes place and is discussed afterwards.

A.3. Market Mechanism

As Kirschen (2019) explains, there are two possible processes for trading the electricity as a commodity in the energy sector. The simplest variant is bilateral trade, as this only requires two parties. If both parties agree on quantity, price and delivery formalities, they conclude a contract. They are absolutely independent in what exactly they agree on and consider appropriate. This has certain advantages, especially for long-term contracts. For example, to establish a certain degree of planning security and thus reduce uncertainties in price or availability. The disadvantage of bilateral negotiations is the effort that has to be made to deal with only one potential partner. More so, if trying to find the best available offer in the market environment, which would mean negotiating with several parties at once.

For this reason, mediated trading in designated energy markets is more widespread in the energy sector, where trading takes place through intermediation. As shown in e.g. Morey (2001) or Maurer and Barroso (2011), such mediated trade can also end up in a bilateral transaction where an individual price is negotiated between the two actual contracting parties. In the energy markets addressed here, however, trading in electricity as a commodity is predominantly carried out via auctions. The most common variant is a one-sided auction, in which bids can be submitted on a specific offer and a bidder can be awarded the contract for his bid on the basis of certain rules. The bid then determines the price at which the transaction is ultimately settled. In the case of electricity and related electricity products, such as ancillary services, it is generally referred to as a pool-based auction market, where the creation of a pool is the mechanism that balances generation and demand. In these auctions, therefore, it is not an individual price that is determined, but a uniform price that applies to all market participants (buyers and sellers). However, most wholesale electricity markets offer a wide range of trading forms and are not limited to one particular form. Thus, a combination of bilateral mediation and power exchanges or pool-based auctions can be found. From the perspective of the market operator or the central role of the market itself, the focus is on the procurement of electricity. Since demand within the system cannot simply expire or not be met, the market primarily collects the quantity demanded and tries to optimise the procurement costs. At the same time, however, the fulfilment of technical and legal requirements must be ensured, but depending on the market design, this can also be remedied afterwards. In addition, the market participants themselves will place their bids in such a way that they maximise their profit.

According to Morey (2001), the most important component of auctions for energy markets is the traditional concern to prevent collusive, predatory and market entry deterrent behaviour. The primary goal must be to make the process of energy generation predictable so that demand can be met in full and at the lowest possible cost to society as a whole. Attractive prices and high market efficiency also contribute to the achievement of other goals. These include, for example, the development of a transparent and competitive market platform that encourages participation and can thus increase market liquidity. The auction itself is divided into three central phases: Bidding, Clearing and Pricing. The bidding phase is simply about submitting bids according to certain rules (e.g. whether there are several bidding phases, whether prices can be staggered, etc.) and within certain time frames. Each market participant will base its bids on its forecasts for price developments, commodity availability and consumption scenarios. After the bids are final, the market is cleared in the next phase. In energy markets, one-sided and two-sided auctions are held for this purpose. In both, a market clearing price and market clearing volume must be determined, whereby in a one-sided auction only the supply side submits bids and the market clearing volume is ultimately determined by the estimated demand. The market clearing price is then obtained when this supply curve mets this demand. In two-sided auctions, both the supply and demand sides submit their bids and MCV/MCP are classically derived by the crossing point of the two curves. Finally, the pricing or settlement phase takes place, in which the trading prices are finally determined. In the energy sector, there are several types, with pay-as-cleared and pay-as-bid being the most common. Pay-as-cleared is also referred to as uniform pricing or non-discriminatory pricing and ultimately only means that all successful bids are settled at the market clearing price. This may lead to severe problems in a demand-driven market, as the European energy crisis of 2022 has shown. High costs in one type of generation (in this case gas) can cause the overall market price to rise disproportionately. With pay-as-bid, on the other hand, the successful buyer always pays exactly the price he bid, even if the seller he eventually buys from originally offered a lower price. This pricing is therefore also called discriminatory pricing. A detailed description and analysis of auctions and examples of the individual mechanisms can be found in the works of Klemperer (see e.g. Klemperer (1999), Klemperer (2002)).

A.4. Market Types

The market types on an energy market differ in terms of when the traded energy quantities must be settled. The type of market an actor uses therefore depends fundamentally on the point in time for which he wants to trade the energy. It should be noted, however, that not all stakeholders can participate in every market type. In a descending chronological order, now a distinction is made between Future/Forward Markets, Spot Markets (Day-Ahead and Intraday Markets) and Balancing Markets.

The first-mentioned **future or forward markets** represent the longest period for the subsequent delivery of energy. In these more second-tier markets, long-term trading agreements are made that can provide for delivery of the commodity within two days to several years. The long-term commitment secures the conditions and is intended to hedge the risk of rising or falling prices, depending on the expected price development and the own goals. In both types of contract, price and quantity are fixed and delivery is mandatory. There are penalty clauses in the event that one of the contracting parties cannot fulfil the contract or can only fulfil it partially. Forward contracts also specify the physical delivery, whereas future contracts do not have this restriction and are therefore attractive to speculators. In a forward market, the respective participant must therefore be able to demonstrate its own demand or supply in order to trade, whereas in a future market this is not necessary and only access authorisation is required. Speculators buy or sell the required quantities with which they have traded on a future market then on the spot markets and make a profit or loss through the resulting price difference. In addition, these long-term markets also accept well-known special clauses or contract forms such as options (there is only the option to trade a certain quantity at a certain price) and difference (the buyer/seller pays the difference to the then current price on the spot market, thus foregoes the profit from the price difference).

Spot markets are marketplaces for short-term trading of electricity. The time of contract fulfilment is a maximum of one day in the future, which naturally makes the price development much more volatile. Short-term changes in supply or demand as a result of external shocks have a direct influence on prices on these markets. The best-known and widely used **day-ahead market** worldwide is also the market with the greatest influence of all the market types listed here, in terms of volume traded there. At a day-ahead market, energy is traded for the entire next day at certain time slots, usually in packages called programming time units. In European energy markets, a programming time unit usually spans one hour and the auction ends at noon. The price is usually set according to a two-sided market mechanism, but can still change due to technical restrictions, interconnections or more complex problems. For example, individual providers may need to be replaced by others due to network restrictions. By replacing the suppliers, the restrictions can then be complied with, but it of course has a negative effect on the trading price if, for technical reasons, an offer that was previously not taken into account is preferred. In Europe, grid constraints are only considered after the auction and solved by the involved grid operators, whereas in the USA the auctions already take such corresponding limitations into account directly. Once the auction is completed at the day-ahead market, the **intraday market** starts. Note, that a intraday market is a market form that is mainly found in Europe. It allows the market participants of the day-ahead market to adjust any deviations in their day-ahead plan and the influence on their bids on the day-ahead market. This is particularly necessary if their own forecasts (e.g. weather) deviate too much from reality or if unforeseen disturbances occur. Since this type of market only reacts to deviations, the market volume is much smaller than with a day-ahead market. How exactly an intraday market is structured varies between different countries or market zones, but it must cover the day-ahead market time horizon after the auction and represent the period of delivery from one programming time unit to one day. intraday market auctions are also directly supervised by involved grid operators, who can act as a last resort in the next market type if the market participants cannot resolve any deviations themselves.

balancing markets are the shortest possible variant for trading electricity and are thus the last resort for keeping the system in balance. This is also the only task of balancing markets, which is why there is only one type of bidder in this market – grid operators. The services that can be accessed are also highly regulated to prevent abuse of power and ensure security. The grid operator is ultimately responsible for activating appropriate reserves if imbalances occur in the energy systems in real-time operation. This mainly involves the upward or downward regulation of the grid voltage, which can be achieved by increasing or decreasing supply and demand at short term. These so-called auxiliary services are traded on the balancing market and, in the first step, activated or procured there by the grid operators. In the second step, the grid operators will then charge the market participants responsible for the deviation with a corresponding penalty, provided they are considered a balance responsible party and the imbalanced portfolio of supply and demand is assigned to them. This can also be a market or its market operator. However, the market operator is then free to pass on these payments to the parties actually responsible for the deviation. More detailed documentation on the different market types and also detailed information on technical details can be found, for example, in KUL Energy Institute (2015).

A.5. Conclusion

The concise summary of the most important details of the previous structure of the energy systems and the associated energy markets already shows some decisive limitations that cannot be ignored. From an economic perspective alone, a complete reconstruction or new construction of energy systems is unrealistic. It is therefore much more important to clarify what can be integrated into the existing system or how possible extensions must be designed. One possible solution, which has already been discussed, is to adopt a more local perspective in the future and to provide for decentralised control elements at this level. This in turn means that certain tasks and duties which previously had to be considered at higher grid levels are now assigned to this local level. Nevertheless, the influence of higher grid levels remains present and cannot be ignored, which makes additional communication and coordination necessary.

A central task that will have to be solved locally in the future, at least in part, and which also requires locally available resources, is certainly the security aspect of energy systems. This subsequently requires a consistent balance between supply and demand. There will still have to be a grid operator who, in the last instance, will ensure the necessary balance. For this task he needs auxiliary services from local counterparts of the balancing markets. At the local level, comparable auxiliary services for needed flexibility will be different in detail and smaller in scope, but they will undoubtedly be needed. It is also obvious that local energy markets will not replace the existing wholesale markets, but exist as some kind of minor small-scaled markets. Therefore, there may well be players in the system who operate in several markets and also at different levels at the same time. It is not unreasonable to assume that the previously established market types and mechanisms can also be used in the same or at least similar form at the local level.

Another important aspect that will be analysed more intensively in this thesis is the question of who exactly is responsible for the balance beyond the grid operators in a local environment. The more active end-consumers should and perhaps must become in the context of local energy management, the more responsibility they are given. This is a point that is still insufficiently represented in the current debate, because it is first and foremost about empowering the previously passive end-consumers to become more active. These possibilities for participation are therefore extensively discussed and also examined in this thesis. For a more comprehensive view, it is also discussed which degree of participation seems realistic at all, considering which responsibilities, tasks and duties will go along with it.

B. Full Mathematical Model

Legend

- Basis model formulation
- Storage Extension
- DSM Extension
- EV Extension

Note: If the title of the constraint is highlighted, it is added by the dedicated extension.

Maximise VEU balance

$$\max Z = \sum_{n \in N} \sum_{t \in \mathcal{T}} v_{t,n}(ol_{t,n}) - \sum_{n \in N} \sum_{t \in \mathcal{T}} dr_{t,n} \cdot hc_{t,n}. \tag{B.1}$$

Load balance equation

$$\begin{aligned} ol_{t,n} = pl_{t,n} - \sum_{(n,d) \in B_t} bal_{t,n,d} + \sum_{(s,n) \in B_t} bal_{t,s,n} - sl_{t,n} + hc_{t,n} \\ - \sum_{(k,n) \in BCh_t} ch_{t,k,n} + \sum_{(k,n) \in BDc_t} dc_{t,k,n} \cdot \alpha_k \quad \forall\, n \in N, t \in \mathcal{T}. \end{aligned} \tag{B.2}$$

Association limitation

$$\sum_{d \in D_t} bal_{t,s,d} + \sum_{k \in K} ch_{t,k,s} \leq pl_{t,s} \qquad \forall\, s \in S_t, t \in \mathcal{T} \tag{B.3}$$

$$\sum_{s \in S_t} bal_{t,s,d} + \sum_{k \in K} dc_{t,k,d} \cdot \alpha_k \leq -pl_{t,d} + sl_{t,d} \qquad \forall\, d \in D_t, t \in \mathcal{T}. \tag{B.4}$$

Storage balance

$$soc_{t,k} = soc_{t-1,k} + \sum_{s \in S_t} ch_{t,k,s} \cdot \alpha_k - \sum_{d \in D_t} dc_{t,k,d} + stu_{t,k} \quad \forall\, k \in K, t \in \mathcal{T}. \tag{B.5}$$

Storage limitations

$$0 \leq soc_{k,t} \leq cap_k \quad \forall\, k \in K, t \in \mathcal{T} \tag{B.6}$$

$$0 \leq \sum_{s \in S_t} ch_{t,k,s} + \sum_{d \in D_t} dc_{t,k,d} \leq pcap_{t,k} \quad \forall\, k \in K, t \in \mathcal{T} \tag{B.7}$$

$$soc_{t-1,k} \geq mcap_{t,k} \quad \forall\, k \in K, t = 2, \ldots, T+1. \tag{B.8}$$

Storage initialization

$$soc_{k,0} = ic_k \quad \forall\, k \in K \tag{B.9}$$

One job, one start

$$\sum_{t=ST_j}^{ET_j - du_j + 1} x_{j,t} = 1 \quad \forall\, j \in J. \tag{B.10}$$

Prevent double assignments

$$\sum_{j \in J | z_{m,j}=1} \sum_{u=\max(ST_j, t-du_j+1)}^{\min(t, ET_j)} x_{j,u} \leq 1 \quad \forall\, m \in M, t \in \mathcal{T}. \tag{B.11}$$

DSM load determination

$$sl_{t,n} = \sum_{j \in J | y_{n,j}=1} jl_j \cdot \sum_{u=\max(ST_j, t-du_j+1)}^{\min(t, ET_j)} x_{j,u} \quad \forall\, n \in N, t \in \mathcal{T}. \tag{B.12}$$

Supplier load restriction

$$ol_{t,s} \geq 0 \quad \forall\, s \in S_t, t \in \mathcal{T}. \tag{B.13}$$

Sets

T ... set of periods $t \in \mathcal{T} := \{1, \ldots, T\}$
N ... set of participants $n \in N$
K ... set of energy storage systems $k \in K$
J ... set of DSM jobs $j \in J$
M ... set of DSM devices $m \in M$

Parameters

$pl_{t,n} \in \mathbb{R}$ ... predicted energy load of participant n in period t

$sr_{t,n}(pl_{t,n})$ ... supplier rate of participant n in period t for current load

$dr_{t,n}(pl_{t,n})$ ... consumer rate of participant n in period t for current load

$v_{t,n}(pl_{t,n})$ ... variable tariff of participant n in period t, based on current load

$$v_{t,n}(pl_{t,n}) = \begin{cases} sr_{t,n}(pl_{t,n}) \cdot pl_{t,n} \text{ if } pl_{t,n} \geq 0 \\ dr_{t,n}(pl_{t,n}) \cdot pl_{t,n}, \text{ if } pl_{t,n} < 0 \end{cases} \tag{B.14}$$

α_k ... storage process efficiency of energy storage k

ic_k ... initial charge status of energy storage k

cap_k ... capacity of storage k

$pcap_{t,k}$ ... periodic capacity (storage rate) of storage k in period t

$stu_{t,k}$ ... predicted storage deviation for energy storage k in period t

$mcap_{t,k}$ ... planned minimal state of charge for energy storage k in period t

ST_j ... first possible start period of job j

ET_j ... last possible end period of job j

dur_j ... duration of job j

jl_l ... periodic energy load demand of job j

$y_{n,j}$ ... binary parameter, 1 if job j is associated to participant n

$z_{m,j}$ ... binary parameter, 1 if job j is associated to DSM device m

Derived Sets

Association of every participant n, based on their predicted load $pl_{n,t}$ in a period t

S_t ... set of supplying participants $s \in S_t$ in period t

D_t ... set of consuming participants $d \in D_t$ in period t

Due to the bipartite problem structure, the possible pairs can be defined as

B_t ... set of possible bipartite pairs $B_t = (S_t, D_t)$ in period t

Charge only from suppliers, Discharge only to consumers

BCh_t ... set of possible charge pairs $BCh_t = (K, S_t)$ in period t

BDc_t ... set of possible discharge pairs $BDc_t = (K, D_t)$ in period t

Variables

$ol_{t,n}$	... optimized load of participant n in period t
$bal_{t,s,d}$	... load adjustments in period t between supplier s and demander d
$soc_{t,k}$	... state of charge of storage k in period $t = 0, \ldots, T$
$ch_{t,k,s}$	... amount of charge in period t between supplier s and storage k
$dc_{t,k,d}$	... amount of discharge in period t between storage k and demander d
$x_{j,t}$	... binary variable, 1 if job j starts in period t
$hc_{t,n}$	... auxiliary variable, for excess DSM demand of participant n in period t

C. Extended Maximum Saving Flow Algorithm

The maximum saving flow algorithm (MSFA) which is originally presented in Chapter 3.1.2 can be extended based on the findings in Chapter 4.1.3. Note, that the extension cannot find the optimal solution (but feasible) for instances that covers multiple charge cycles, due to the possible occurrence of cross-cycle delayed energy load adjustments (DELAs), as described in Chapter 4.1.4. The procedure follows a sequence that can be divided into three phases.

- Phase I - Use the MSFA to find the optimal energy load adjustments (ELAs), as described in Chapter 3.1.2
- Phase II - Establish optimal DELAs that do not substitute ELAs
- Phase III - Establish optimal DELAs that substitute ELAs (Rejustment)

What now needs to be clarified is how to decide in the two storage-related phases which DELAs will be established and how to identify ELAs to be substituted in phase III.

C.1. Phase II - Delayed Energy Load Adjustments

The whole procedure to determine the DELA basically follows the same greedy-based approach, which is already used for the MSFA. The difference here is that the available energy quantities of all participants in every period are considered and sorted instead of considering each period individually one after the other. The total accessible storage capacity and periodic capacities must also be taken into account. The amount of energy eventually exchanged by the DELA between a supplier $s \in S_t$ and a consumer $d \in D_t$ must therefore take into account that each storage process involved (i.e., the charging as well as the discharging) is feasible. A supplier can only charge as much as it has energy available, and a consumer can only discharge as much as it also demands. The storage involved can also only receive as much energy as its storage rate and total capacity allow.

Initialization

1. Identify each remaining energy supply $ol_{t,n}^{ELA} > 0$ of the solution from phase I
2. Identify each remaining energy demand $ol_{t,n}^{ELA} < 0$ of the solution from phase I
3. Sort the suppliers by their price (ascending) $sr_{s,t}$, then by the remaining quantity (descending) $ol_{t,n}^{ELA}$
4. Sort the consumers by their price (descending) $dr_{d,t}$, then by period (ascending) $t \in \mathcal{T} := \{1, \ldots, T\}$
5. Sort all available energy storage system (ESS) $k \in K$ by their efficiency α_k (descending).

Iterative process

1. Choose the first ESS $k \in K$ in the sorted set
2. Use the first energy supplier in the sorted set
3. Use the first consumer in the sorted set whose demand period follows the supply period
4. Determine the energy quantity of the DELA to be established (in this case from the point of view of the demand side):
   - Possible charge amount of the supplier $(ol_{t,s}^{ELA} \cdot (2 \cdot \alpha_k))$
   - Possible discharge amount of the supplier $(ol_{t,d}^{ELA})$
   - Available periodic capacity at the time of charging $((pcap_{t,k} - soc_{t,k} + soc_{t-1,k}) \cdot (2 \cdot \alpha_k))$
   - Available periodic capacity at the time of discharge $((pcap_{t,k} - soc_{t,k} + soc_{t-1,k}) \cdot \alpha_k)$
   - Maximum available total capacity of the ESS in all storage periods $((cap_k - max(soc_{t,k} \forall t) \cdot \alpha_k)$
5. Choose the minimum from these possible energy amounts
6. The calculation of all possible energy quantities prevents that by the selection of an energy quantity, the DELA becomes invalid.
7. The selected amount of energy already corresponds to the final amount of energy that is received by the consumer.
8. Calculate the amount of energy of the supplier, which is equal to the amount of

energy of the demander $/2 \cdot \alpha_k$

9. Calculate the amount of energy in the storage, which corresponds to the amount of energy of the demand $/\alpha_k$
10. Calculate the savings rate $w_{s,d,t}^{DELA}$ of this DELA
11. Check if the calculated savings rate $w_{s,d,t}^{DELA}$ is better than possible rejustments.
12. If not, abort and go directly to Phase III, or else
13. Update the supply and demand quantity of the involved participants
14. A participant whose energy quantity decreases to 0 by the DELA is removed from the respective sorted list
15. Update the values for the ESS ($soc_{t,k}$ and $pcap_{t,k}$)
16. If the ESS be completely charged by the DELA, remove the ESS from the sorted list
17. Repeat the process until no more DELAs can be established, i.e.
18. Each ESS is completely charged once, or
19. There is no more energy supply or demand available.

C.2. Phase III - Rejustments

Rejustment is the dissolving of an established ELA from the first phase of this algorithm in order to realize a savings-increasing DELA with the released amount of energy. Since only a savings-increasing DELA can be achieved, the application of a rejustment makes sense only after the second phase of the algorithm has been completed. This means that no more DELA can be established or the saving rates of the DELA turn out to be lower than the savings increases possible with rejustments. In either case, at least one available ESS must still have free storage capacity that could not be better used elsewhere. The procedure for the optimal identification and implementation of a rejustment can again be based on a greedy approach. The ELA to be substituted can be determined with the Phase I solution and is the worst established ELA due to the lowest savings rate $\min(w_{s,d,t}^{ELA})$. In principle, it is actually irrelevant which ELA is substituted, but due to the efficiency α_k of an energy storage device, the selection of the worst ELA is mandatory. This is briefly illustrated by a small example and Figure **C.1** shows a graph solution for this with a fictitious withdrawal on the supply side in each case.

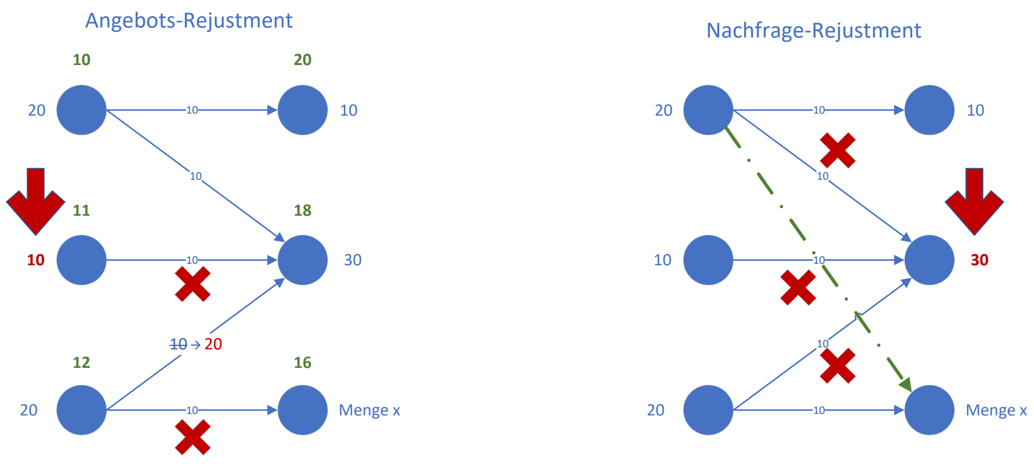


Figure **C.1**. Storage Rejustment Example

An edge of the graph corresponds to a ELA between supplier $s \in S_t$ and demander $d \in D_t$. The edge value is the amount of energy $bal_{t,s,d}$ exchanged between these participants. The blue values next to each node are the original energy quantities demanded or offered $pl_{t,n}$ by the involved participant $n \in N$, while the green values show the associated tariff value of the participant. The total savings achieved by the original solution for this exemplary period t is equal to 350 GE ($\sum_{s \in S_t} \sum_{d \in D_t} bal_{t,s,d} \cdot (dr_{d,t} - sr_{s,t})$). Now, if the supply is taken from node 'B' of this solution, this not only has an immediate impact on edges directly connected to the node, but also on all subsequent edges. Any withdrawal will always be visible on the last edges. The achieved saving of this corrected solution amounts to only 300 GE. However, the savings loss between these two solutions of 50 GE can also be derived without recalculation. The withdrawn quantity of the supplier B of 10 ME must be multiplied for this purpose only by the tariff difference of the withdrawn node and the last influenced nodes on the opposite side. So in this case from node F and thus $10 \cdot (16 - 11) = 50GE$. Alternatively, if the last edge of the solution and thus the connection from C to F is removed directly, the savings loss is initially smaller ($10 \cdot (16 - 12) = 40GE$), although the same amount of energy of 10 ME is removed from the solution.

However, both withdrawals result in the same savings gain when the alternative DELA for the substituted ELA is determined, initially ignoring the efficiency level of the ESS. If the withdrawn quantity of 10 ME is intermediated in a later period by a DELA to demander D, the resulting savings starting from node B ($10 \cdot (20 - 11) = 90GE$) is higher than the resulting savings for a connection starting from node C ($10 \cdot (20 -$

$12) = 80GE)$. Overall, the savings increase for both withdrawals is thus identical and amounts to 40 GE. However, this changes when the efficiency levels of the ESS are taken into account. These affect the savings from the DELA, while the initial savings loss from the dissolution of the ELA, on the other hand, is not affected. In an example with an overall efficiency of the involved ESS to be considered of 90%, the savings of a DELA would be starting from B $((10 \cdot (20 - 11)) \cdot 0.9 = 81GE)$ would still be higher than for a DELA starting from C $((10 \cdot (20 - 12)) \cdot 0.9 = 72GE)$. However, the total savings gain achieved by the rejustment is now lower for the substituted edge of B with $81 - 50 = 31GE$ than for the substituted edge of C with $72 - 40 = 32GE$. Thus it is always better, or at least not worse, to directly substitute the worst edge of all established ELA. Therefore, the selection can again be done by a simple sort that list of all established ELA in ascending order of their savings rate $w^{ELA}_{s,d,t}$. The next edge to be dissolved is thus always uniquely identifiable and the best possible DELA for it can then be established by the procedure from the second phase until all storage capacities are exhausted or no more savings growth can be induced.

Bibliography

(2018). Flexibility in the energy transition: A tool for electricity dsos. Technical report, European DSO Cooperation.

Abapour, S., M. Nazari-Heris, B. Mohammadi-Ivatloo, and M. Tarafdar Hagh (2020). Game theory approaches for the solution of power system problems: A comprehensive review. *Archives of Computational Methods in Engineering 27*(1), 81–103.

Abapour, S., K. Zare, and B. Mohammadi-Ivatloo (2015). Dynamic planning of distributed generation units in active distribution network. *IET Generation, Transmission & Distribution 9*(12), 1455–1463.

Abdel-Raouf, O., M. A., and E. F. (2020). A survey of game theory applications in electrical power micro-grid systems. *International Journal of Computer Applications 177*(37), 25–34.

Abdella, J. and K. Shuaib (2018). Peer to peer distributed energy trading in smart grids: A survey. *Energies 11*(6), 1560.

Abrishambaf, O., F. Lezama, P. Faria, and Z. Vale (2019). Towards transactive energy systems: An analysis on current trends. *Energy Strategy Reviews 26*, 100418.

Al Kawasmi, E., E. Arnautovic, and D. Svetinovic (2015). Bitcoin-based decentralized carbon emissions trading infrastructure model. *Systems Engineering 18*(2), 115–130.

Amin, W., Q. Huang, M. Afzal, A. A. Khan, K. Umer, and S. A. Ahmed (2020). A converging non-cooperative & cooperative game theory approach for stabilizing peer-to-peer electricity trading. *Electric Power Systems Research 183*, 106278.

Ampatzis, M., P. H. Nguyen, and W. Kling (2014). Local electricity market design for the coordination of distributed energy resources at district level. In *IEEE PES Innovative Smart Grid Technologies, Europe*. IEEE.

Azim, M. I., W. Tushar, and T. K. Saha (2021). Cooperative negawatt p2p energy trading for low-voltage distribution networks. *Applied Energy 299*, 117300.

Bacher, P., H. Madsen, and H. A. Nielsen (2009). Online short-term solar power forecasting. *Solar Energy 83*(10), 1772–1783.

Bakker, V., A. Molderink, J. L. Hurink, and G. J. M. Smit (2008). Domestic heat demand prediction using neural networks. In *2008 19th International Conference on Systems Engineering*, pp. 189–194. IEEE.

Barbato, A. and A. Capone (2014). Optimization models and methods for demand-side management of residential users: A survey. *Energies 7*(9), 5787–5824.

Bartholdi, J. J. and E. Kemahlioğlu-Ziya (2005). Using shapley value to allocate savings in a supply chain. In J. Geunes and P. M. Pardalos (Eds.), *Supply chain optimization*, Volume 98 of *Applied Optimization*, pp. 169–208. New York: Springer.

Bayram, I. S., M. Z. Shakir, M. Abdallah, and K. Qaraqe (2014). A survey on energy trading in smart grid. In *2014 IEEE Global Conference on Signal and Information Processing* (*GlobalSIP*). IEEE.

Bazaraa, M. S. (2013). *Linear Programming and Network Flows* (4 ed.). Hoboken: Wiley.

Belvaux, G. and L. A. Wolsey (2000). bc — prod: A specialized branch-and-cut system for lot-sizing problems. *Management Science 46*(5), 724–738.

Bertsch, V., M. Hall, C. Weinhardt, and W. Fichtner (2016). Public acceptance and preferences related to renewable energy and grid expansion policy: Empirical insights for germany. *Energy 114*, 465–477.

Block, C., D. Neumann, and C. Weinhardt (2008). A market mechanism for energy allocation in micro-chp grids. In *Proceedings of the 41st Annual Hawaii International Conference on System Sciences* (*HICSS 2008*). IEEE.

Blouin, M. R. and R. Serrano (2001). A decentralized market with common values uncertainty: Non-steady states. *The Review of Economic Studies 68*(2), 323–346.

Bose, S., E. Kremers, E. M. Mengelkamp, J. Eberbach, and C. Weinhardt (2021). Reinforcement learning in local energy markets. *Energy Informatics 4*(1), 1–21.

Brandenburger, A. and H. Stuart (2007). Biform games. *Management Science 53*(4), 537–549.

Burkard, R. E. (2007). Monge properties, discrete convexity and applications. *European Journal of Operational Research 176*(1), 1–14.

Capper, T., A. Gorbatcheva, M. A. Mustafa, M. Bahloul, J. M. Schwidtal, R. Chitchyan, M. Andoni, V. Robu, M. Montakhabi, I. J. Scott, C. Francis, T. Mbavarira, J. M. Espana, and L. Kiesling (2022). Peer-to-peer, community self-consumption, and transactive energy: A systematic literature review of local energy market models. *Renewable and Sustainable Energy Reviews 162*, 112403.

Carreiro, A. M., H. M. Jorge, and C. H. Antunes (2017). Energy management systems aggregators: A literature survey. *Renewable and Sustainable Energy Reviews 73*, 1160–1172.

Chis, A. (2018). Demand response and energy portfolio optimization for smart grid using machine learning and cooperative game theory. (*Keine Angabe*).

Chronis, A.-G., F. Palaiogiannis, I. Kouveliotis-Lysikatos, P. Kotsampopoulos, and N. Hatziargyriou (2021). Photovoltaics enabling sustainable energy communities: Technological drivers and emerging markets. *Energies 14*(7), 1862.

Clement-Nyns, K., E. Haesen, and J. Driesen (2011). The impact of vehicle-to-grid on the distribution grid. *Electric Power Systems Research 81*(1), 185–192.

Colak, I., S. Sagiroglu, G. Fulli, M. Yesilbudak, and C.-F. Covrig (2016). A survey on the critical issues in smart grid technologies. *Renewable and Sustainable Energy Reviews 54*, 396–405.

Crespo-Vazquez, J. L., A. A. La Sanchez de Nieta, and M. Gibescu (2019). A decision-making framework encouraging local energy exchanges among smart buildings. In *SEST'19*, Piscataway, NJ, pp. 1–6. IEEE.

Cui, S. and J.-W. Xiao (2020). Game-based peer-to-peer energy sharing management for a community of energy buildings. *International Journal of Electrical Power & Energy Systems 123*, 106204.

Cui, T., Y. Wang, S. Nazarian, and M. Pedram (2014). An electricity trade model for microgrid communities in smart grid. In *ISGT 2014*. IEEE.

Densmore, A. and G. Prasad (2015). An energy market for rural, islanded micro-grids. In *2015 International Conference on the Domestic Use of Energy* (*DUE*). IEEE.

Díaz-González, F. (2016). *Energy storage in power systems*. Chichester, West Sussex: John Wiley & Sons Inc.

Ding, Y., L. H. Hansen, P. D. Cajar, P. Brath, H. W. Bindner, C. Zhang, and N. C. Nordentoft (2013). Development of a dso-market on flexibility services. Technical report, Strategic Platform for Innovation and Research in Intelligent Power.

Directorate General for Energy of the European Commission (2019). *Clean energy for all Europeans*. Publications Office of the EU.

Divya, K. C. and J. Østergaard (2009). Battery energy storage technology for power systems—an overview. *Electric Power Systems Research 79*(4), 511–520.

Eseye, A. T., M. Lehtonen, T. Tukia, S. Uimonen, and R. J. Millar (2019). Optimal energy trading for renewable energy integrated building microgrids containing electric vehicles and energy storage batteries. *IEEE Access 7*, 106092–106101.

EURELECTRIC (2014). Flexibility and aggregation: Requirements for their interaction in the market. *EURELECTRIC paper*.

European Parliament and the Council of the EU (2019). Directive (eu) 2019/944 - on common rules for the internal market for electricity and amending directive 2012/27/eu. Technical Report 2019/944.

Faber, I., W. Lane, W. Pak, M. Prakel, C. Rocha, and J. V. Farr (2014). Micro-energy markets: The role of a consumer preference pricing strategy on microgrid energy investment. *Energy 74*, 567–575.

Faia, R., J. Soares, Z. Vale, and J. M. Corchado (2021). An optimization model for energy community costs minimization considering a local electricity market between prosumers and electric vehicles. *Electronics 10*(2), 129.

Fang, X., S. Misra, G. Xue, and D. Yang (2012). Smart grid — the new and improved power grid: A survey. *IEEE Communications Surveys & Tutorials 14*(4), 944–980.

Faqiry, M. N. and S. Das (2019). Distributed bilevel energy allocation mechanism with grid constraints and hidden user information. *IEEE Transactions on Smart Grid 10*(2), 1869–1879.

Farhangi, H. (2010). The path of the smart grid. *IEEE Power and Energy Magazine 8*(1), 18–28.

Ferruzzi, G., G. Cervone, L. Delle Monache, G. Graditi, and F. Jacobone (2016). Optimal bidding in a day-ahead energy market for micro grid under uncertainty in renewable energy production. *Energy 106*, 194–202.

Fiala, P. (2016). Profit allocation games in supply chains. *Central European Journal of Operations Research 24*(2), 267–281.

Fuentes González, F., A. H. van der Weijde, and E. Sauma (2020). The promotion of community energy projects in chile and scotland: An economic approach using biform games. *Energy Economics 86*, 104677.

Fuentes González, F. A. (2019). *Increasing the penetration of renewable energy through community energy projects : an economic approach based on biform games*.

Geunes, J. and P. M. Pardalos (Eds.) (2005). *Supply chain optimization*, Volume 98 of *Applied Optimization*. New York: Springer.

Ghelardoni, L., A. Ghio, and D. Anguita (2013). Energy load forecasting using empirical mode decomposition and support vector regression. *IEEE Transactions on Smart Grid 4*(1), 549–556.

Gillies, D. B. (1959). *Solutions to general non-zero-sum games, in\Contributions to the Theory of Games," Volume 4 (AW Tucker and RD Luce, Eds.)*. Princeton: Princeton University Press.

Good, N. and P. Mancarella (2019). Flexibility in multi-energy communities with electrical and thermal storage: A stochastic, robust approach for multi-service demand response. *IEEE Transactions on Smart Grid 10*(1), 503–513.

Hahn, H., S. Meyer-Nieberg, and S. Pickl (2009). Electric load forecasting methods: Tools for decision making. *European Journal of Operational Research 199*(3), 902–907.

Heidari, A., M. Moradi, A. Aslani, and A. Hajinezhad (2018). Optimization of microgrid electricity market based on multi agent modeling approach. *International Journal of Energy Optimization and Engineering 7*(3), 1–23.

Helber, S. and F. Sahling (2010). A fix-and-optimize approach for the multi-level capacitated lot sizing problem. *International Journal of Production Economics 123*(2), 247–256.

Hildebrandt, B., J. Hurink, and M. Manitz (2024). Local energy management: A base model for the optimization of virtual economic units. *Energy Economics 129*, 107252.

Hoogsteen, G., A. Molderink, J. L. Hurink, and G. J. Smit (2016). Generation of flexible domestic load profiles to evaluate demand side management approaches. In *2016 IEEE International Energy Conference (ENERGYCON)*, pp. 1–6. IEEE.

Horta, J., D. Kofman, D. Menga, and A. Silva (2017). Novel market approach for locally balancing renewable energy production and flexible demand. In *2017 IEEE International Conference on Smart Grid Communications (SmartGridComm)*. IEEE.

Huynh, T., F. Schmidt, S. Thiem, M. Kautz, F. Steinke, and S. Niessen (2022). Local energy markets for thermal-electric energy systems considering energy carrier dependency and energy storage systems. *Smart Energy 6*, 100065.

Hvelplund, F. (2006). Renewable energy and the need for local energy markets. *Energy 31*(13), 2293–2302.

Ilieva, I., B. Bremdal, S. Ødegaard Ottesen, J. Rajasekharan, and P. Olivella-Rosell (2016). Design characteristics of a smart grid dominated local market. In *CIRED Workshop 2016*. Institution of Engineering and Technology.

International Energy Agency (2016). Re-powering markets: Market design and regulation during the transition to low-carbon power systems. Technical report, IEA.

Iria, J., F. Soares, and M. Matos (2018). Optimal supply and demand bidding strategy for an aggregator of small prosumers. *Applied Energy 213*, 658–669.

Jelenkovic, L. and T. Budrovic (2015). Simple day-ahead bidding algorithm for a system with microgrids and a distributor. In *2015 38th International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO)*. IEEE.

Jogunola, O., B. Adebisi, K. van Hoang, Y. Tsado, S. I. Popoola, M. Hammoudeh, and R. Nawaz (2022). Cblstm-ae: A hybrid deep learning framework for predicting energy consumption. *Energies 15*(3), 810.

Jogunola, O., Y. Tsado, B. Adebisi, and M. Hammoudeh (2022). Virtelect: A peer-to-peer trading platform for local energy transactions. *IEEE Internet of Things Journal 9*(8), 6121–6133.

Kabalci, Y. (2016). A survey on smart metering and smart grid communication. *Renewable and Sustainable Energy Reviews 57*, 302–318.

Kamrat, W. (2001). Modeling the structure of local energy markets. *IEEE Computer Applications in Power 14*(2), 30–35.

Keles, D., J. Scelle, F. Paraschiv, and W. Fichtner (2016). Extended forecast methods for day-ahead electricity spot prices applying artificial neural networks. *Applied Energy 162*, 218–230.

Khajeh, H., H. Laaksonen, A. S. Gazafroudi, and M. Shafie-khah (2020). Towards flexibility trading at tso-dso-customer levels: A review. *Energies 13*(1), 165.

Khorasany, M., Y. Mishra, and G. Ledwich (2017). Auction based energy trading in transactive energy market with active participation of prosumers and consumers. In *2017 Australasian Universities Power Engineering Conference (AUPEC)*. IEEE.

Khorasany, M., Y. Mishra, and G. Ledwich (2018). Market framework for local energy trading: a review of potential designs and market clearing approaches. *IET Generation, Transmission & Distribution 12*(22), 5899–5908.

Kirschen, D. S. (2019). *Fundamentals of Power System Economics* (2nd ed. ed.). Newark: John Wiley & Sons Incorporated.

Klemperer, P. (1999). Auction theory: A guide to the literature. *Journal of Economic Surveys 13*(3), 227–286.

Klemperer, P. (2002). What really matters in auction design. *Journal of Economic Perspectives 16*(1), 169–189.

Koirala, B. P., E. Koliou, J. Friege, R. A. Hakvoort, and P. M. Herder (2016). Energetic communities for community energy: A review of key issues and trends shaping integrated community energy systems. *Renewable and Sustainable Energy Reviews 56*, 722–744.

Kounelis, I., G. Steri, R. Giuliani, D. Geneiatakis, R. Neisse, and I. Nai-Fovino (2017). Fostering consumers' energy market through smart contracts. In *2017 International Conference in Energy and Sustainability in Small Developing Economies (ES2DE)*. IEEE.

Kriukov, A., B. Vicol, and M. Gavrilas (2014). Applying a micro-market inside an electric vehicles parking facility. In *2014 49th International Universities Power Engineering Conference (UPEC)*. IEEE.

KUL Energy Institute (2015). *The Current Electricity Market Design in Europe* (4. KUL Energy Inst. ed.).

Kumar, G. V. B., R. K. Sarojini, K. Palanisamy, S. Padmanaban, and J. B. Holm-Nielsen (2019). Large scale renewable energy integration: Issues and solutions. *Energies 12*(10), 1996.

Lamparter, S., S. Becher, and J.-G. Fischer (2010). An agent-based market platform for smart grids. In *Proceedings of the 9th International Conference on Autonomous Agents in Multiagent Systems*, pp. 1689–1696.

Lane, W., W. Pak, M. Prakel, C. Rocha, I. Faber, and J. V. Farr (2013). Costing consumer preferences for a micro energy market. Technical report, United States Military Academy West Point.

Le Cadre, H., G. Leclercq, M. Pavesi, T. Gueuning, A. Ashouri, P. Sels, R. D'hulst, and F. Geth (2019). Network and market models. Technical report.

Lezama, F., J. Soares, P. Hernandez-Leal, M. Kaisers, T. Pinto, and Z. Vale (2019). Local energy markets: Paving the path toward fully transactive energy systems. *IEEE Transactions on Power Systems 34*(5), 4081–4088.

Liu, C., K. T. Chau, D. Wu, and S. Gao (2013). Opportunities and challenges of vehicle-to-home, vehicle-to-vehicle, and vehicle-to-grid technologies. *Proceedings of the IEEE 101*(11), 2409–2427.

Lode, M. L., G. te Boveldt, T. Coosemans, and L. Ramirez Camargo (2022). A transition perspective on energy communities: A systematic literature review and research agenda. *Renewable and Sustainable Energy Reviews 163*, 112479.

Long, C., J. Wu, C. Zhang, L. Thomas, M. Cheng, and N. Jenkins (2017). Peer-to-peer energy trading in a community microgrid. In *2017 IEEE Power & Energy Society General Meeting*. IEEE.

Long, C., Y. Zhou, and J. Wu (2019). A game theoretic approach for peer to peer energy trading. *Energy Procedia 159*, 454–459.

Mannaro, K., A. Pinna, and M. Marchesi (2017). Crypto-trading: Blockchain-oriented energy market. In *2017 AEIT International Annual Conference*. IEEE.

Marzband, M., M. Javadi, J. L. Domínguez-García, and M. Mirhosseini Moghaddam (2016). Non–cooperative game theory based energy management systems for energy district in the retail market considering der uncertainties. *IET Generation, Transmission & Distribution 10*(12), 2999–3009.

Maurer, L. and L. A. Barroso (2011). *Electricity auctions: An overview of efficient practices*. Washington D.C: World Bank.

McAfee, R. P. and J. McMillan (1987). Auctions and bidding. *Journal of Economic Literature 1987*(25), 699–738.

Mengelkamp, E., J. Diesing, and C. Weinhardt (2019). Tracing local energy markets: A literature review. *it - Information Technology 61*(2-3), 101–110.

Mengelkamp, E., J. Gärttner, K. Rock, S. Kessler, L. Orsini, and C. Weinhardt (2018). Designing microgrid energy markets. *Applied Energy 210*, 870–880.

Mengelkamp, E., J. Garttner, and C. Weinhardt (2017). The role of energy storage in local energy markets. In *2017 14th International Conference on the European Energy Market (EEM)*. IEEE.

Mengelkamp, E., B. Notheisen, C. Beer, D. Dauer, and C. Weinhardt (2018). A blockchain-based smart grid: towards sustainable local energy markets. *Computer Science - Research and Development 33*(1-2), 207–214.

Mengelkamp, E., P. Staudt, J. Gärttner, and C. Weinhardt (2017). Trading on local energy markets: A comparison of market designs and bidding strategies. In *2017 14th International Conference on the European Energy Market (EEM)*, pp. 1–6. IEEE.

Menniti, D., A. Pinnarelli, N. Sorrentino, and G. Belli (2014). A local market model involving prosumers taking into account distribution network congestions in smart cities. *International Review of Electrical Engineering (IREE) 9*(5), 976.

Menniti, D., A. Pinnarelli, N. Sorrentino, A. Burgio, and G. Belli (2014). Management of storage systems in local electricity market to avoid renewable power curtailment in distribution network. In *2014 Australasian Universities Power Engineering Conference (AUPEC)*. IEEE.

Menniti, D., N. Sorrentino, A. Pinnarelli, A. Burgio, G. Brusco, and G. Belli (2014). In the future smart cities: Coordination of micro smart grids in a virtual energy district. In *2014 International Symposium on Power Electronics, Electrical Drives, Automation and Motion*. IEEE.

Mihaylov, M., S. Jurado, N. Avellana, K. van Moffaert, I. M. de Abril, and A. Nowe (2014). Nrgcoin: Virtual currency for trading of renewable energy in smart grids. In *11th International Conference on the European Energy Market (EEM14)*. IEEE.

Mohan, V., M. P. R. Suresh, J. G. Singh, W. Ongsakul, and B. K. Kumar (2015). Online optimal power management considering electric vehicles, load curtailment and grid trade in a microgrid energy market. In *2015 IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA)*. IEEE.

Mohd, A., E. Ortjohann, A. Schmelter, N. Hamsic, and D. Morton (2008). Challenges in integrating distributed energy storage systems into future smart grid. In *2008 IEEE International Symposium on Industrial Electronics*, Piscataway, NJ, pp. 1627–1632. IEEE.

Moret, F. and P. Pinson (2019). Energy collectives: A community and fairness based approach to future electricity markets. *IEEE Transactions on Power Systems 34*(5), 3994–4004.

Morey, M. J. (2001). Power market auction design: Rules and lessons in market-based control for the new electricity industry. Technical report.

Moroni, Antoniucci, and Bisello (2019). Local energy communities and distributed generation: Contrasting perspectives, and inevitable policy trade-offs, beyond the apparent global consensus. *Sustainability 11*(12), 3493.

Mueller, D. (2018). The usability and suitability of allocation schemes for corporate cost accounting. In *Game Theory in Management Accounting*, pp. 401–427. Springer, Cham.

Nguyen, T., M. Negnevitsky, and M. de Groot (2011). Pool-based demand response exchange: Concept and modeling. In *2011 IEEE Power and Energy Society General Meeting*. IEEE.

Olivella-Rosell, P., E. Bullich-Massagué, M. Aragüés-Peñalba, A. Sumper, S. Ø. Ottesen, J.-A. Vidal-Clos, and R. Villafáfila-Robles (2018). Optimization problem for meeting distribution system operator requests in local flexibility markets with distributed energy resources. *Applied Energy 210*, 881–895.

Olivella-Rosell, P., P. Lloret-Gallego, Í. Munné-Collado, R. Villafafila-Robles, A. Sumper, S. Ottessen, J. Rajasekharan, and B. Bremdal (2018). Local flexibility market design for aggregators providing multiple flexibility services at distribution network level. *Energies 11*(4), 822.

Osborne, M. J. and A. Rubinstein (2006). *A course in game theory* (12. print ed.). Cambridge, Mass.: MIT Press.

Owen, G. (2013). *Game theory* (Fourth edition ed.). Bingley: Emerald Group Publishing Limited.

Parag, Y. and B. K. Sovacool (2016). Electricity market design for the prosumer era. *Nature Energy 1*(4).

Paschalidis, I. C., B. Li, and M. C. Caramanis (2012). Demand-side management for regulation service provisioning through internal pricing. *IEEE Transactions on Power Systems 27*(3), 1531–1539.

Pavlovic, M., T. Gawron-Deutsch, C. Neureiter, and K. Diwold (2016). Sgam business layer for a local flexibility market. In *CIRED Workshop 2016*. Institution of Engineering and Technology.

Pérez-Arriaga, I. J. (Ed.) (2013). *Regulation of the power sector*. Power systems. London and Heidelberg: Springer.

Pinson, P., T. Baroche, F. Moret, T. Sousa, E. Sorin, and S. You (2017). The emergence of consumer-centric electricity markets. *Distribution & Utilization 34*(12), 27–31.

Pöhn, D. and W. Hommel (2020). Imc: A classification of identity management approaches. In *Proceedings to European Symposium on Research in Computer Security 2020*, pp. 3–20. Springer, Cham.

Rahbari-Asr, N., U. Ojha, Z. Zhang, and M.-Y. Chow (2014). Incremental welfare consensus algorithm for cooperative distributed generation/demand response in smart grid. *IEEE Transactions on Smart Grid 5*(6), 2836–2845.

Ravichandran, S., V. A, K. S. Swarup, H.-S. Rajamani, and P. Pillai (2016). Short term energy forecasting techniques for virtual power plants. In *2016 IEEE 6th International Conference on Power Systems (ICPS)*, pp. 1–6. IEEE.

Roberts, B. P. and C. Sandberg (2011). The role of energy storage in development of smart grids. *Proceedings of the IEEE 99*(6), 1139–1144.

RONT (2011). Detailergebnisse niederspannung.

Rosen, C. and R. Madlener (2013). An auction design for local reserve energy markets. *Decision Support Systems 56*, 168–179.

Saad, W., Zhu Han, H. V. Poor, and T. Basar (2011). A noncooperative game for double auction-based energy trading between phevs and distribution grids. In *2011 IEEE International Conference on Smart Grid Communications (SmartGridComm)*. IEEE.

Safdarian, A., P. H. Divshali, M. Baranauskas, A. Keski-Koukkari, and A. Kulmala (2021). Coalitional game theory based value sharing in energy communities. *IEEE Access 9*, 78266–78275.

Sahling, F., L. Buschkühl, H. Tempelmeier, and S. Helber (2009). Solving a multi-level capacitated lot sizing problem with multi-period setup carry-over via a fix-and-optimize heuristic. *Computers & Operations Research 36*(9), 2546–2553.

Sajn, N. (2016). Electricity 'prosumers'. Technical Report PE 593.518, European Parliamentary Research Service.

Schlereth, C. and B. Skiera (2012). Measurement of consumer preferences for bucket pricing plans with different service attributes. *International Journal of Research in Marketing 29*(2), 167–180.

Sha, J. and S. Zheng (2021). Revenue distribution of hybrid channel supply chain based on modified shapley value with cost. *Discrete Dynamics in Nature and Society 2021*, 1–8.

Shamsi, P., H. Xie, A. Longe, and J.-Y. Joo (2016). Economic dispatch for an agent-based community microgrid. *IEEE Transactions on Smart Grid 7*(5), 2317–2324.

Shapley, L. S. (1951). *Notes on the n-Person Game—II: The Value of an n-Person Game*. RAND Research Memorandum RM 670. Santa Monica, Kalifornien: The RAND Corporation.

Sikdar, S. and K. Rudie (2013). Microgrid level competitive market using dynamic matching. In *2013 IEEE Electrical Power & Energy Conference*. IEEE.

Soares, J., H. Morais, T. Sousa, Z. Vale, and P. Faria (2014). Day-ahead resource scheduling including demand response for electric vehicles. In *2014 IEEE PES General Meeting | Conference & Exposition*. IEEE.

Sousa, T., T. Soares, P. Pinson, F. Moret, T. Baroche, and E. Sorin (2019). Peer-to-peer and community-based markets: A comprehensive review. *Renewable and Sustainable Energy Reviews 104*, 367–378.

Stadtler, H. (2003). Multilevel lot sizing with setup times and multiple constrained resources: Internally rolling schedules with lot-sizing windows. *Operations Research 51*(3), 487–502.

Swan, M. (2015). *Blockchain: Blueprint for a new economy* (1. ed. ed.). Safari Tech Books Online. Beijing: O'Reilly.

Tan, K. M., V. K. Ramachandaramurthy, and J. Y. Yong (2016). Integration of electric vehicles in smart grid: A review on vehicle to grid technologies and optimization techniques. *Renewable and Sustainable Energy Reviews 53*, 720–732.

Torbaghan, S. S., N. Blaauwbroek, P. Nguyen, and M. Gibescu (2016). Local market framework for exploiting flexibility from the end users. In *2016 13th International Conference on the European Energy Market (EEM)*. IEEE.

Tsaousoglou, G., J. S. Giraldo, and N. G. Paterakis (2022). Market mechanisms for local electricity markets: A review of models, solution concepts and algorithmic techniques. *Renewable and Sustainable Energy Reviews 156*, 111890.

Tushar, W., B. Chai, C. Yuen, S. Huang, D. Smith, H. Poor, and a. Yang (2016). Energy storage sharing in smart grid: A modified auction based approach. *IEEE Transactions on Smart Grid* (7-3), 1462–1475.

Tushar, W., T. Saha, C. Yuen, T. Morstyn, M. McCulloch, H. Poor, and a. Wood (2019). A motivational game-theoretic approach for peer-to-peer energy trading in the smart grid. *Applied Energy* (243), 10–20.

Tushar, W., T. K. Saha, C. Yuen, P. Liddell, R. Bean, and H. V. Poor (2018). Peer-to-peer energy trading with sustainable user participation: A game theoretic approach. *IEEE Access 6*, 62932–62943.

Tveita, E., M. Loschenbrand, S. Bjarghov, and H. Farahmand (2018). Comparison of cost allocation strategies among prosumers and consumers in a cooperative game. In *2018 International Conference on Smart Energy Systems and Technologies (SEST) conference proceedings*, Piscataway, NJ, USA, pp. 1–6. IEEE.

USEF Foundation (2015). Usef: The framework explained.

Verschae, R., T. Kato, and T. Matsuyama (2016). Energy management in prosumer communities: A coordinated approach. *Energies 9*(7), 562.

Villar, J., R. Bessa, and M. Matos (2018). Flexibility products and markets: Literature review. *Electric Power Systems Research 154*, 329–340.

von Neumann, J. and O. Morgenstern (2007). *Theory of games and economic behavior* (60. anniversary ed., 4. print., and 1. paperb. print ed.). Princeton Classic Editions Ser. Princeton, NJ: Princeton University Press.

Vytelingum, P., S. Ramchurn, T. Voice, A. Rogers, and N. R. Jennings (2010). Trading agents for the smart electricity grid. In *Proceedings of the 9th International Conference on Autonomous Agents in Multiagent Systems*.

Wanapinit, N. and J. Thomsen (2020). Exploiting renewable energy and flexibility potential via local cooperation. In *2020 17th International Conference on the European Energy Market (EEM)*, Piscataway, NJ, pp. 1–6. IEEE.

Wu, F. F. and P. Varaiya (1999). Coordinated multilateral trades for electric power networks: theory and implementation. *International Journal of Electrical Power & Energy Systems 21*(2), 75–102.

Xiao, H. and Q. Fang (2022). Arboricity games: the core and the nucleolus. *Mathematical Programming*, 1–25.

Xiao, Y., X. Wang, P. Pinson, and X. Wang (2018). A local energy market for electricity and hydrogen. *IEEE Transactions on Power Systems 33*(4), 3898–3908.

Yi, C.-h. (2009). Using modified shapley value to determine revenue allocation within supply chain. In *2009 International Conference on Information Management, Innovation Management and Industrial Engineering*, Piscataway, NJ, pp. 78–80. IEEE.

Yu, A., C. Zhang, and Y.-J. Angela Zhang (2020). Optimal bidding strategy of prosumers in distribution-level energy markets. *IEEE Transactions on Power Systems 35*(3), 1695–1706.

Zhang, Z., R. Li, and F. Li (2020). A novel peer-to-peer local electricity market for joint trading of energy and uncertainty. *IEEE Transactions on Smart Grid 11*(2), 1205–1215.

DOI: 10.17185/duepublico/81732
URN: urn:nbn:de:hbz:465-20240314-111414-1