Carl von Ossietzky Universität Oldenburg

Optimisation of the System Design and Operation of Distributed Generation Considering Competing Stakeholder Interests

von der Fakultät für Mathematik und Naturwissenschaften
der Carl von Ossietzky Universität Oldenburg
zur Erlangung des Grades und Titels

Doktor der Ingenieurwissenschaften (Dr.-Ing.)

angenommene Dissertation von

Herrn Lucas Schmeling M.Sc.

geboren am 09.10.1992 in Osnabrück

Erster Gutachter:	Prof. Dr. Carsten Agert
Zweiter Gutachter:	Prof. Dr.-Ing. Axel Hahn
Weitere Mitglieder der Prüfungskomission:	Prof. Dr. Alexander Hartmann Prof. Dr. Bernd Siebenhüner
Tag der Disputation:	03.04.2025

Zusammenfassung

Der mit der Energiewende einhergehende Wandel zu einer dezentralen, auf erneuerbaren Energien basierenden Energieversorgung stellt viele Energieverbraucher, vom Einfamilienhaus, über Quartiere bis hin zu Industrieunternhemen vor die Frage, wie ihr zukünftiges Energiesystem zu gestalten ist. Die Methoden, wie klassische Versorgungssysteme in ihrer Dimensionierung und Betriebsweise ausgelegt wurden sind nicht mehr zeitgemäß und müssen durch moderne, simulationsbasierte Planungstools ersetzt werden. Durch hybride Energiesysteme werden zukünftig eine Vielzahl unterschiedlicher Einzeltechnologien intelligent und individuell miteinander verknüpft, um für jeden Anwendungsfall eine sichere, bezahlbare und klimafreundliche Versorgung sicherzustellen. Dabei stehen Entscheidungen im Mittelpunkt, die nicht nur einzelne Akteure betreffen, sondern es sind zumeist eine Vielzahl an Stakeholdern von der Wahl des Versorgungssystems betroffen. Diese müssen somit in die Transformation aktiv eingebunden und ihre Interessen berücksichtigt werden.

Im Rahmen der vorliegenden Dissertation werden unterschiedliche Ansätze präsentiert und demonstriert, wie dies konkret gelingen kann. Nach einem kurzen Abriss über den aktuellen Stand der Wissenschaft zu diesen Themen wird zunächst der gesamte Planungsprozess, von der Definition der Ziele bis zum Betrieb der Anlagen exemplarisch für das Quartier Helleheide vorgestellt, um die verschiedenen Aspekte der Energiesystemauslegung besser zu strukturieren. Basierend darauf wird ein erstes konkretes Planungswerkzeug an dem in Bezug auf die Stakeholderbeteiligung noch relativ einfachen Fall einer Molkerei demonstriert, für die ein wasserstoffbasierter Stromspeicher nebst anderen Erzeugungs- und Speicheranlagen ausgelegt wird. Der Stakeholderaspekt wird anschließend wiederum am Quartier Helleheide genauer beleuchtet, indem ein technologisch und simulativ sehr umfassendes Energiesystemmodell aufgestellt und für dieses konkrete Fallbeispiel optimiert wird. Abschluss findet die Arbeit in der Untersuchung eines Mehrfamilienhauses, für das mit einer Multiple-Criteria Decision Analysis (MCDA)-Methodik optimierte Dämmdicken und Energiesysteme aus Sicht der beteiligten Stakeholder ausgewählt werden.

Auf diese Weise kann gezeigt werden, dass simulationsbasierte Bewertungs- und Optimierungsansätze für hybride Energiesysteme dazu geeignet sind selbst komplexe Energiesysteme optimiert auszulegen. Dabei erlauben die gezeigten Ansätze es die Interessen relevanter Stakeholder in den Entschiedungsprozess einfließen zu lassen und sinnvolle und vor allem objektive Kompromisse zu schaffen. Damit kann eine sowohl technisch effizient als auch durch die Stakeholder akzeptierte Energiesystemauslegung erreicht werden.

Summary

As the energy transition results in a distributed energy supply based on renewable energy, many energy consumers, from single-family homes and districts to industrial companies, are faced with the question of how their future energy system should be designed. The methods used to dimension and operate conventional supply systems are no longer up to date and need to be replaced by modern, simulation-based planning tools. In the future, hybrid energy systems will intelligently and individually link a large number of different individual technologies to ensure a secure, affordable, and climate-friendly supply for every application. In doing so, decisions will not only affect individuals, but in most cases a large number of stakeholders will be affected by the choice of supply system. These stakeholders must therefore be actively involved in the transformation and their interests taken into account.

This dissertation presents various approaches and demonstrates how this can be achieved in practice. After a brief outline of the current state of science on these topics, the overall planning process, from the definition of objectives to the operation of the systems, is presented using the Helleheide district as an example in order to better structure the various aspects of energy system design. Based on this, an initial planning tool is demonstrated using the relatively simple case study of a dairy, for which a hydrogen-based electricity storage system is being designed along with other generation and storage facilities. The stakeholder aspect is then examined in more detail in the Helleheide district again by setting up a technologically and computationally extensive energy system model and optimising it for this specific case study. The work concludes with the investigation of a multi-family house, for which optimised insulation thicknesses and energy systems are selected from the perspective of the stakeholders involved using a Multiple-Criteria Decision Analysis (MCDA) methodology.

In this way, simulation-based evaluation and optimisation approaches for hybrid energy systems can be shown to be suitable for optimally designing even complex energy systems. The approaches shown allow the interests of relevant stakeholders to be incorporated into the decision-making process and to create viable and, above all, objective compromises. This makes it possible to achieve an energy system design that is both technically efficient and accepted by stakeholders.

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List of Abbreviations

AHP Air-source Heat Pump

CapEx Capital Expenditures

CHP Combined Heat and Power

DHW Domestic Hot Water

EA Evolutionary Algorithm

ELY Electrolyzer

EUC Energy Utility Company

FC Fuel Cell

GHP Ground-source Heat Pump

GWP Global Warming Potential

HES Hybrid Energy System

HP Heat Pump

HS Hydrogen Storage

IEA International Energy Agency

IRR Internal Rate of Return

KPI Key Performance Indicator

LCA Life Cycle Assessment

LCC Life Cycle Cost

LCOE Levelised Cost Of Energy

LP Linear Programming

MCDA Multiple-Criteria Decision Analysis

MCS Monte Carlo simulation

MILP Mixed Integer Linear Programming

MINLP Mixed Integer Nonlinear Programming

MO Multi-objective Optimisation

MOEA/D Multi-Objective Evolutionary Algorithm with Decomposition

NG Natural Gas

NLP Nonlinear Programming

NPV Net Present Value

OpEx Operational Expenditures

PEM Proton Exchange Membrane

PP Payback Periode

PtGtP Power-to-Gas-to-Power

PtH Power-to-Heat

PV Photovoltaic

R/P Reserves-to-Production

SA Simulated Annealing

SOC State of Charge

ST Solar Thermal

TES Thermal Energy Storage

TOPSIS Technique for Order Preference by Similarity to Ideal Solution

1 | Introduction

> **Probleme kann man niemals mit derselben Denkweise lösen, durch die sie entstanden sind.**
>
> (Problems can never be solved with the same mindset that created them.)
>
> - Albert Einstein -

With these words, one of the world's most famous scientists sums up one of the central dilemmas of our time. Climate change demands the greatest and fastest transformation efforts from us, and yet in many areas, we cling to conventional thinking and old practices. This is immanent in the way that we have thought about the energy transition for years. Many particularly popular to populist publications are of the opinion that a rapid shift away from burning fossil fuels was technically and economically impossible [1]. That wind and solar power are too unstable for a secure supply [2]. That there are too many valuable raw materials in battery storage systems [3]. That we are bringing Europe to a blackout [4].

Of course, wind and solar behave differently from fossil fuel power plants. Of course, the energy transition means the heavy use of financial and raw material resources. Our society has increasingly faced these hurdles in recent years. And while some are trying to solve these problems with old ways of thinking, namely by burning fossil fuels, using nuclear energy, or fundamentally denying climate change, a large part of society has set out to actively combat climate change and change our energy systems [5]. We all use energy in our immediate environment every day, sometimes more consciously when we turn on the heating thermostat, sometimes more unconsciously when we buy food that costs a lot of energy to produce. All of this energy will have to be sourced differently in the foreseeable future. It is therefore up to each of us to become aware of the opportunities and challenges and to make the right strategic decisions about the energy transition in our own little cosmos.

A key concept is that of technological openness (dt: Technologieoffenheit). To effectively and proactively steer the transformation, it is crucial to thoroughly and impartially understand the available technical options during the planning stage and to choose the optimal technology at that moment through a fair and unbiased technological comparison [6]. In parts of the media and politics, this term is increasingly being used to hinder transformation by artificially keeping known and established technologies alive through subjective perception [7]. This makes it all the more important to base transformation planning on new and innovative planning tools that, through objectivity, make it possible to draw fair technology comparisons and, on this basis, to make good and, above all, sustainable decisions.

But this requires precisely the change in mindset that Einstein demands. This already begins with the planning of the transition and the question of which energy sources we will use to supply ourselves with energy in the future. Traditional planning tools are no longer suitable for successfully positioning and keeping pace in an ever-changing world [8]. New approaches and new ways of thinking need to be established [9]. At its core, this is the aim and motivation of this thesis.

This thesis therefore aims to develop and demonstrate planning tools that make it possible to better organise this transformation and find answers to such key strategic questions. This is less about international or national strategies, but the decision in every company, neighbourhood, or household. The use of digital tools is central to this. Traditional planning tools based on experience, standards, and rule-of-thumbs cannot keep up with the multitude of technical possibilities and their rapid changes. Digital planning tools are the only way to make the strategic planning problem tangible during this phase of rapid change and successfully develop solutions in a wide range of different cases [9]. Of course, standardized solution concepts will be found in the long term and simplified planning tools will be re-established, but the path to these and the necessary experience can be significantly shaped and supported by these digital tools.

But we must not forget that the choice of our future energy supply cannot be planned and evaluated by just one individual, but that everyone can and must play a role in shaping it. Consequently, a wide variety of perspectives and aspects must be integrated into the planning process to not jeopardise the acceptance of this extremely important project in any way. The stakeholder dialogue and inclusion of their interests must thus become a central element of modern planning tools [10].

The planning tools developed as part of this thesis therefore aim to find optimal, technology-neutral energy solution concepts for future use cases in the housing sector and industry and to involve as many stakeholders and their interests as possible. In Chapter 2, the topic of distributed energy supply and the planning and optimisation approaches currently discussed in the scientific literature are examined in more detail. Chapter 3 then explains the publications presented in the following Chapters 4 to 7, which were published as part of the thesis and deal with various approaches and issues relating to modern and cutting-edge planning tools from different perspectives. Chapter 8 summaries the findings of the work and gives an outlook on further development steps.

2 | Optimising Distributed Generation: Motivation and State-of-the-Art

Energy supply is changing. This is driven by several factors: On the one hand, the main energy resources currently used (coal, gas, oil, nuclear energy) are finite. In 2004, the first year of the systematic survey, 93.8 % of gross final energy consumption in Germany originated from non-renewable sources [11]. Although it can be assumed that proven fossil reserves will last for several decades (relevant here is the Reserves-to-Production (R/P) ratio, which relates the current annual consumption divided by proven reserves, which is 48.8 for natural gas and 139 for coal [12]) alternative energy sources must be made available in the long term.

However, climate change requires a much faster phase-out of fossil energy carriers for energy supply. Due to the emission of climate-damaging gases (mainly CO_2, but also N_2O, CH_4 as well as many others) released during combustion, the earth's atmosphere is warming up in a hazardous manner, which leads to a threat to the entire earths ecosystem. During the last approx. 150 years, the atmosphere has warmed by about 1.09 °C, resulting in more severe weather extremes, rising sea levels, and many other impacts. According to the IPCC, humans are responsible for approximately 1.07 °C of this increase, with the use of fossil fuels to generate energy being one of the main factors influencing this [13]. Preventing climate-damaging emissions therefore is unavoidable in the short term in order not to endanger the stability of the ecosystem and thus the prosperity of us all.

A radical restructuring of the energy supply is therefore indispensable and already underway in many places. The first countries, such as Germany and Denmark, began to initiate this change in the 1980s and 1990s in light of the oil crises and beginning social awareness of climate change. With the Kyoto Protocol of 1997 at the latest, a large part of the global community has committed itself to the fight against climate change and has begun to reduce climate-damaging emissions, particularly in the energy supply sector. Germany, once a pioneer of the energy transition, now has a share of renewable energy in its electricity mix of more than 50 % [14] and plans to increase this to 89 % by 2035 [15]. The expansion of wind and solar power and the ramp-up of the hydrogen economy over the next few years will be decisive in this respect. Internationally, the International Energy Agency (IEA) assumes that generation capacities will increase by approximately 250 % from 2023 to 2028, with 95 % of this being in the wind and solar sector. The largest market for renewable energy is now China, which will build 60 % of these capacities according to the IEA forecast [16].

In addition to conserving fossil resources and mitigating climate change, there are other aspects and positive effects that are driving this development.

A concept that is gaining importance in the context of the European energy crisis due to the Ukraine war is resilience [17]. The IEA specifies the term in relation to energy systems as follows:

> "The capacity of the energy system and its components to cope with a hazardous event or trend, to respond in ways that maintain its essential functions, identity and structure, as well as its capacity for adaptation, learning, and transformation." [18]

This term recognises that energy systems are increasingly being threatened in their stability by external events, which in its consequence could be endangering our current energy-hungry society [19, 20]. Traditionally, events such as the failure of technical systems (e.g. [21]) or the effects of natural disasters (e.g. [22, 23]) are considered in this context. However, resilience can equally be understood from the perspective of economic systems [19]. This would mean, for example, that an energy system remains affordable and financially viable even if energy prices change, as was recently the case with the war of aggression in Ukraine [17]. To achieve this, it is necessary, among other things, to diversify the location and technology of energy generation [24] as well as the active participants in the market [25].

All these aspects lead to a steady decentralisation and decarbonisation of energy supply. Fossil fuels are increasingly being replaced by renewable and emission-free alternatives such as wind and solar energy. The share of renewable electricity in total electricity consumption in Germany is at 46.0 % by today (2022) [26] and, according to plans of the current German government, is to rise to 80 % by 2030 and will be almost completely renewable by 2035 [27].

However, since these renewable environmental energy resources are not available centrally, but occur everywhere, the conversion to useful energy has to be decentralised, which in turn contributes to increasing the resilience of the system. The literature refers to this as distributed generation.

2.1 | The Concept of Distributed Generation

In the literature, the term distributed generation is commonly used and can be defined as follows:

> "Distributed generation is an electric power source connected directly to the distribution network or on the customer site of the meter." [28]

This contrasts with the centralised generation of recent decades, which fed directly into the higher-level transmission grid in the form of large power plants. By focussing on feed-in at distribution grid level or even generation directly behind the customer meter, the integration of renewable energies addressed in the previous section can take place in a targeted and comprehensive manner.

Distributed generation can refer to both renewable and fossil energy generation. With regard to renewable energies such as hydropower, wind, Photovoltaic (PV) and biomass, it enables scaled deployment, as the generation potential here is spatially distributed. For example, PV systems are built on individual roofs or fields and thus supply local consumers directly with electricity with only the surpluses being made available to the national energy market via the local distribution grid. In the case of energy generation from fossil resources, the distributed and thus smaller generation capacities mean that the heat generated during combustion can be used more easily. The waste heat emitted by the engine of a usually natural gas-fired Combined Heat and Power (CHP) is used, for example, to supply a local industrial plant or a neighbourhood via a district heating network [29]. This leads to an efficient and close to full utilization of the energy content of this fuel, which is otherwise limited due to Carnot efficiency when the heat isn't used but only the electricity. Of course, larger amounts of climate-damaging gases are still emitted here, but the specific emissions per unit of electricity are lower because some of the emissions can be added to the otherwise unused heat.

In addition, electric transmission losses can be minimised and complex expansion of transnational electricity grids can be reduced [30]. But there are also changes on the economic and social level: It becomes possible for private individuals and smaller companies to generate electricity themselves to some extent and thus become less dependent. Whereas a centralised energy supply is largely monopolistic [31], decentralisation leads to greater participation of civil society in the energy transition [32, 33]. Previously passive electricity consumers are to be transformed into active prosumers [34], thereby making a significant contribution to climate protection, resilience, and independence.

It is important to distinguish between distributed generation and the concept of self-sufficiency, i.e. the sole and isolated supply by such systems. Although theoretically possible, this is not very effective for reasons of resilience, efficiency and cost, since an intelligent interconnection of distributed energy generators can stabilise and complement each other [35].

Usually, distributed generation refers only to the generation of electricity. If other forms of final energy are involved, the term sector coupling is commonly used [36]. Ausfelder *et al.* define the term as the:

> "Integrated optimisation of the whole energy system merging the power, mobility and heat sector. " [37]

Sector coupling solves several inherent problems of the transformation to a distributed energy system [36]. On the one hand, renewable energies are very volatile, i.e. their availability varies greatly both within the day as well as seasonally. The solution here is strategic overbuilding, that is, the construction of more renewable generation capacity than is needed at certain times to close the supply gaps as best as possible [38]. These energy quantities would then remain unused. On the other hand, the heat and mobility sectors in particular are difficult to decarbonise for various reasons. By shifting overproduced energy quantities to these sectors, a significant degree of flexibility can be gained, as these sectors offer an inherent storage capacity and these sectors can also be decarbonised [39]. The electricity is either used directly in e-mobility and heat pumps or stored temporarily in the form of hydrogen and then later converted back into electricity or used in fuel cells for mobility or heating. Distributed generation therefore tends to be especially effective when different forms of final energy are needed on site which can be generated efficiently and directly with a joint energy concept [36].

This extension of the distributed generation concept leads to further important implications. Due to the meteorological volatility of the supply of environmental energy, the continuous availability of final energy can no longer be guaranteed [31, 40]. It is therefore no longer sufficient to provide only individual energy sources for the final energy requirements, but it is mandatory to combine them. Especially the integration of the electricity and heat sectors in the context of sector coupling leads to high temporal dependencies, which make it necessary to form energy generating and storing combinations. The literature refers to such systems as Hybrid Energy System (HES):

> “[HES] refers to an application in which multiple energy conversion devices are used together to supply an energy requirement. These systems are [...] normally include at least one renewable energy source in the configuration. Hybrid systems are used as an alternative to more conventional systems, which are typically based on a single fossil fuel source” [41].

In particular, these HES help to create the aforementioned resilience of energy systems, as they offer both technically and economically viable alternatives for energy supply at all times [42]. If, for example, a system can use both electricity and natural gas, or perhaps hydrogen in the future, for its supply, the cheaper medium can be used during operation, and the system can switch between them depending on the market situation. In an emergency, e.g. if the power grid fails, it becomes possible to fall back on the energy source that is still available as a backup.

In summary, distributed generation can and should therefore be understood as a concept of spatial coupling between energy generation by different complementing technologies and consumption of various energy forms that enables renewable energy to be utilised efficiently on a large scale. Individual energy concepts for buildings or neighbourhoods are therefore predestined for distributed generation, as roof areas, and thus solar radiation energy, as well as environmental heat, are available as resources that can be used to cover the local demand for electricity, heat and mobility [43]. This could include commercial units or flats, while a mixture of both would lead to even better diversification and efficiency [44]. However, both the available resources and the demands of these buildings are very varied, making it difficult to make basic recommendations for the use of distributed renewable energy systems [45].

It is therefore all the more important to plan sector coupled distributed energy supply systems in a smart and effective manner in order to maximise the benefits for the consumers to be supplied and for the energy system as a whole. While the goal of this transformation is clear and straightforward, the practical implementation in individual cases is anything but trivial [46]. Two dimensions need to be optimised when using distributed energy systems, which will be explained in more detail below: On the one hand, the design, i.e., the combination and sizing of the energy technologies to be used, and on the other hand, the operation of these systems, i.e., the continuous operational planning in day-to-day business.

2.1.1 | Optimal Design of Distributed Energy Supply Solutions

Today, a large part of households, but also business and industry, use an energy supply based on electricity from the grid and heat supply via a fossil fuel-fired boiler. Such systems are rather easy to size: For electricity connections, there are usually empirical values and otherwise the possibility of approximating the power of the individual consumers to be supplied and a simultaneity factor [47]. For heat supply, there are industry standards such as DIN EN 12831 [48], which allow to calculate the heating load of buildings based on its architecture, insulation and type of heat distribution. Together with the demand for Domestic Hot Water (DHW) determined e.g. by DIN 4708 [49] and estimates for process heat, this then results in a maximum heating demand that the boiler should at least provide. However, the systems are often oversized in order to avoid any risk of a supply failure. This leads to inefficiencies in the system, which can be avoided if a suitable system is installed by calculating the required supply capacity with greater precision [50, 51].

The change from such systems to HES now makes sizing even more complex. For example, the size of a CHPs must be optimally matched to the demand for heat and electricity and combined with a suitable Thermal Energy Storage (TES) that is neither too large to have too many heat losses, nor too small, requiring the CHP to be switched on and off too frequently [52]. If not only a CHP is to be used, but perhaps also combined with a PV and a battery storage, it becomes obvious that the dependencies can hardly be handled with gut feeling and rules of thumb.

Mathematically, the sizing of an energy system is a classical optimisation problem: An objective function $\vec{f}(\vec{x})$, which e.g. calculates the economic efficiency of the energy supply, is minimised or maximised by varying the sizes $\vec{x} = (x_1, ..., x_m)$ of the m possible system components [53]. This makes it possible to solve the problem computer-aided by modelling the energy system with variable technology sizes, simulating it over a representative time period, and then evaluating it using an objective function. A distinction must be made between problems that optimise only one objective function (single-objective optimisation, $f(\vec{x}) \in \mathbb{R}$) and those with several objective functions (multi-objective optimisation, $\vec{f}(\vec{x}) \in \mathbb{R}^n$ with n different objectives). The latter are, of course, much more complex to solve, as there are usually no clearly optimal solutions, but only compromises referred to as pareto-optimal [54].

Table 2.1 gives an overview of the method classes postulated in the literature with an estimate of the advantages and disadvantages, as well as examples of publications using them. In addition, there are a large number of meta-studies that deal with the comparison of these methods from a number of different perspectives (e.g. [55, 56]). In this thesis, two of these methods are used for different case studies.

In summary, an analysis of the literature shows that a lot of classical and heuristic methods were used in the earlier literature, but today almost exclusively metaheuristics can be found. There is an

Tabelle 2.1: Review of common strategies to optimise the sizing of HES. In addition, there are other approaches, variations and types; only the most relevant in the current literature are mentioned here

Class	Algorithm	Description	Advantages	Disadvantages	Literature
Rule of Thumb		The size of the individual components are chosen based on experience. This does not require any dedicated simulation or investigation, but only the practical experience of a large number of realised projects. For individual components there are rough rules of thumb and standards, all others are adapted according to individual experience.	• The usual procedure today for the design of simple systems • No complex calculations necessary	• Requires years of practical experience • Changes in (e.g. legal) framework conditions changes optimal solutions • Only applicable for highly standardised projects like residential or office buildings • Mostly purely technical view	[57, 58]
Brute Force		Different, discrete system sizes are defined for each technology. All possible combinations of these technologies are then simulated and evaluated, irrespective of their practicality.	• Algorithm is extremely simple • The search area is investigated extensively, there are clear statements on global optima	• Computational effort increases exponentially with degrees of freedom • Very high computational effort for unreasonable solutions • Optima can easily be missed if they are between combinations	Chapters 5 and 7 [59, 60]
Classical Optimisation	Linear Programming (LP)	The energy system is modelled using linear equations and inequalities and optimised according to a likewise linear objective function using common solvers like CBC or Gurobi.	• Very time- and resource-efficient optimisation • Complex energy systems can be modelled • Variety of commercial and free solvers available	• Linearisation leads to inaccuracies in many cases • Objective function must not have any discontinuities • High mathematical modelling effort	[61, 62]
	Nonlinear Programming (NLP)	These classical optimisation algorithms can be used to solve problems that are non-linear, discontinuous and undifferentiable. By solving the objective function discretely and following the gradient, the optimiser finds patterns leading iteratively to the optimum.	• Complex objective functions and system behaviour can be modelled	• More computational expensive than LP • Only mono-objective optimisation • Frequently find local instead of global optima	[63, 64]
Heuristic	Local Search	Starting from an initial starting point in the search space, the environment is examined for better solutions until no further improvement can be achieved.	• Flexible and efficient solvers • Scalable for large and complex problems	• No guarantee to find global optimum • Sensitive to initial guess	[65, 66]
Metaheuristic	Particle Swarm	The search space is evaluated at various points corresponding to particles. These particles then move toward the current best particle in analogy to various natural phenomena such as fireflies or whales.	• Search space is evaluated very widely and thoroughly • Approach is easy to understand and follow	• Choice of many different implementations and inspirations with mixed quality • Many ways to (mis)configure the optimiser	[67, 68]
	Genetic Algorithm	This refers to algorithms that are based on the processes of natural selection and genetics. A population of possible solutions is evolved over several generations until an optimum is reached.	• Capable to find global optimum • Easy to adapt to different problems • Computation can be easily paralelised	• Computationally expensive with slow convergence • Sensitive to optimiser parameters like selection and mutation process	Chapters 4 and 6 [69, 70]
	Simulated Annealing (SA)	SA takes its inspiration from annealing processes in metallurgy and lets a population explore the search space intensively at the beginning before reducing the temperature (movement speed) until the global optimum is found,	• Avoid local optima • Flexible and easy to implement	• Requires careful parameter tuning • Computationally expensive	[71, 72]
Commercial Software	HOMER	HOMER is an American software developed for the simulation of microgrids. It includes a commercial algorithm for optimal sizing using classical optimization approaches, which is not specified in detail.	• Very easy to use even for inexperienced users • Tested on a large number of projects • Variety of supported technologies and auxiliary functions such as load profile generators	• No insight into how the algorithms work • Hardly any possibilities to extend the functionality individually	[73, 74]
Hybrid Methods		Combinations of the above-mentioned approaches can be found in many cases. Usually, a rough design with little modelling effort and an efficient algorithm is performed, followed by a more detailed design with more complex methods but smaller search space.	• Optimal use of computing resources • Higher probability to find the global optimum	• Needs individual design and testing for each problem • Solvers must be built or interconnected individually	[75]

almost endless number of publications that examine a wide variety of technologies, case studies and algorithms, whereby the focus in the scientific discourse is usually on the enhancement of optimisation algorithms by means of rather rudimentary and unrealistic case studies. Even after intensive study of the subject, it is difficult to find generally valid statements on how to approach such problems. There appear to be few if any particularly mature and robust approaches that would make it possible to optimise realistic cases with the aim of supporting investment decisions in real projects.

This can also be seen, for example, in the many definitions of optimality, i.e. the goal of optimisation ($\vec{f}$). The literature contains a wide variety of approaches, depending on the boundary conditions, the stakeholders involved, and the research question. A review of the current literature on this topic can be found in Table 2.2. In the scope of this thesis, depending on the research question, various optimality definitions are used as well.

Tabelle 2.2: Overview of the common optimisation objectives in the optimal sizing of HES.

Category	Target	Explanation	Examples
Economic	Life Cycle Cost (LCC)	The investment costs and the operating costs over the life of the plant are summed up.	[76, 77]
	Payback Periode (PP)	The time at which a certain investment becomes worthwhile.	[78]
	Levelised Cost Of Energy (LCOE)	The mean cost per kWh of energy produced incl. CAPEX and OPEX.	[79, 80]
	Net Present Value (NPV)	The summed yearly cash flow incl. discounting.	[81, 82]
	Internal Rate of Return (IRR)	The calculatory interest rate an investment yields.	[79, 80]
Technical	Loss of power supply probability	Proportion of the year in which there is a blackout.	[83]
	Self sufficiency	Percentage to which the site is not reliant on external energy.	[84, 85]
	Own consumption	Share of locally generated energy that is used in site.	[86]
	System efficiency	Minimising losses in the energy supply.	[87]
	Resilience	Capability of the system to deal with hazardous events.	[88]
	Power quality	Harmonics, flicker or voltage distortions in the system.	[89]
Ecologic	CO_2 emissions	Emission of carbon dioxide.	[90, 91]
	CO_2 eq emissions	Emission of carbon dioxide and other climate-damaging gases.	[92, 93]
	Share of renewable energy	Percentage in which renewable energies are used during operation.	[94]
	Life Cycle Assessment (LCA)	Considering all environmental impacts of an HES.	[95]

In the literature review, it is immanent that mainly multi-objective approaches that optimise different aspects simultaneously are in use. Roughly speaking, there are three types of approaches:

1. Optimisation of several economic key figures e.g. NPV, IRR and PP (e.g. [96])
2. Optimisation of the lowest total system costs while minimising CO_2-emissions (e.g. [97])
3. Optimisation from a holistic point of view, combining rather simple economic, ecologic and technical indicators (e.g. [84])

What is often missing is an even more holistic view on the optimisation of distributed energy supply that goes beyond investment-theoretical economic, abbreviated ecological and highly complex technical indicators. It is often very simplistically assumed that decisions would be made purely on the basis of such model-based indicators. The roadway from such calculations to real-life decisions is hardly considered in the studies available.

2.1.2 | Optimal Operation of Distributed Energy Supply Solutions

In addition to the correct sizing of an HES, it is equally essential to evaluate and optimise the efficiency of the operated system, i.e., how individual technologies are used at the right times to optimise the overall performance of the system. In the case of the classical systems mentioned earlier, this decision was obsolete; for each form of useful energy, there was exactly only one way to serve it. HES breaks away from this dependency and offers different possibilities to meet energy needs at any time, even across sectors [41].

A good example is a grid-connected combination of CHP and Heat Pump (HP) for heat supply. To achieve economic optimality, it is important to use electricity for the HP when it can be purchased cheaply and to use the CHP when it can sell electricity expensively [98]. This becomes even more interesting when PV is added or there is an additional demand for electricity to be met.

Flexibility is of particular value in this context [99, 100]. Renewable energies are usually completely inflexible in their generation and can only provide energy when, for example, the sun shines or the wind blows sufficiently. Additionally, the requirement for energy tends to be relatively inelastic. For instance, private individuals do not generally factor in solar power generation when scheduling household tasks like laundry, and similarly, the industry does not typically incorporate it when planning its operational processes. In order to ensure a balance between generation and consumption, it is essential to include flexible sources and sinks in the system [101]. This can be, for example, the public grid, but also storage systems or technologies such as CHP or HP combined with TES or batteries.

Coordinating the interaction between flexible and inflexible sources and sinks, as well as storage systems, and generating optimal system behaviour is usually a control system problem [102]. This system needs clear control strategies, which need to be optimised as well. It is already clear from the above example that this is far from being just a technical issue, but that external factors such as market prices or meteorological conditions also play a decisive role in the operation of HES. The complexity of this optimisation increases strongly with the growing number of technologies (= degrees of freedom) and the variability of the boundary conditions.

Mathematically, this is again an optimisation problem in which an objective function $g(\vec{y})$ is minimised or maximised. This objective function is the sum over the objective function of all points in time t of the period under consideration $\mathbb{T}$: $g(\vec{y}) = \sum_{t=0}^{T} g_t(\vec{y}_t)$. The decision vector $\vec{y}$ varies greatly depending on the specific problems and primarily includes the operating modes, i.e. the current energy production or consumption of the controllable system components. In addition, there are a number of constraints that define, for example, the balance between generation and consumption, the minimum and maximum storage levels, or the permissibility of certain power ramps. Here, too, a wide variety of different target definitions serve as objective functions, with costs [103], emissions [104] or technical functions such as regulating distribution voltages [105] being optimised most often.

Research has found approaches to define operation control strategies for a wide variety of systems and applications [106]. These are summarised in great detail in Table 2.3. In this thesis, two different approaches are used.

Tabelle 2.3: Review of common algorithms to optimise the operation of HES.

Category	Algorithm	Explanation	Examples
Classical Approaches	Rules-of-Thumb	Estimation of the system behaviour based on empirical values	Chapter 7 and [107]
	Rule-based Control	Control based on fixed, not dynamically adaptable rules.	[108]
	PID-Control	Application of a classic control theory Proportional-Integral-Derivative-controller.	[109]
Classical Optimisation	Linear Programming (LP)	Simple approach assuming linearity of the operating states.	[110]
	Mixed Integer Linear Programming (MILP)	Extension of the LP approach to include discrete variables.	Chapters 5 and 6 and [111]
Metaheuristic	Particle Swarm Optimiser	Use of nature analogies, such as the behaviour of fish or birds.	[112]
	Genetic Algorithm	Application of inheritance and mutation behaviour of biological systems.	[113]
AI-based	Deep Reinforcement Learning	A system that learns optimal strategies through interaction with its environment.	[114]

When dealing with this type of optimisation problem, a clear distinction has to be made between approaches for operation and approaches for planning the operation of distributed energy systems. By far the most frequently used algorithm for planning is MILP. It allows a large number of decision variables, i.e. operating states of different technologies over long periods of time, to be optimised efficiently, quickly and reliably. In operation, on the other hand, where it is more important to model the system behaviour more realistically, i.e. non-linearly, approaches such as PID controllers or model predictive control, a hybrid approach based on classical control strategy and MILP, can be found. In the end, the advantages and disadvantages of each approach must be compared and weighed up for which application purpose an algorithm is being sought. This is especially true when, as in the following publications, algorithms for optimising design and operation are to be combined intelligently and holistically. The approaches found in the literature and the planning tools developed as part of the thesis are summarised in the respective publications.

2.2 | Competing Stakeholder Interests in Energy Supply

Previous literature on the optimisation of distributed generation assumes in many places that the objective function of the optimisations are universal, in other words almost God-given (e.g. [77, 83]). However, it should be noted that such projects always involve a wide variety of people and organisations [115]. These are summarised under the term stakeholder, which McGrath and Whitty [116] define as follows:

> "An entity with a stake (interest) in the subject activity."

This subject activity is usually a project, such as the construction and operation of a distributed energy supply. The interests of the stakeholders involved in such projects can be highly diverse and depends strongly on the perspective and the degree of involvement in the overall project. It is in the nature of each stakeholder to try to influence the project in their own interest to maximise their benefits. While it is immanent in free-market economies that economic efficiency is one of the top maxims, it will make a big difference which stakeholder is asked for their individual definition of optimality [117].

Here, residential buildings are a good example of clashing stakeholder interests [118–120]. The actual users of this energy system are the residents. If it were solely in their interests, the energy system would have minimal investment and operating costs, whereby no precedence is given here. The building owner, if not identical with the resident, has an interest in passing on as many of the costs as possible to the residents or even selling energy at a profit. The electricity grid operator, on the other hand, would achieve its maximum return if the grid connection had to be as large as possible, the manufacturers of energy technology systems want to sell as many systems as possible, and the energy suppliers want as much energy as possible to be consumed. In addition, as already shown, not only economic factors play a role. For example, some stakeholders such as the residents may value climate-friendliness or low noise emissions, the grid operator is interested in a grid-friendly behaviour of the neighbourhood and the city administration is interested in a highly attractive and innovative concept.

This makes it clear how conflicting the stakeholder interests are when it comes to such an everyday and common system as the energy supply of a building. There is hardly a common objective, but each stakeholder has a different definition of optimality to the others, which in turn would result in a completely different choice of energy supply concept. In the end, however, clear decisions must be made. Not every stakeholder will be able to assert his or her interests to perfection. Compromises must be made in optimising both the design and the operation.

2.2.1 | Stakeholder Management

To deal with the stakeholders and how they influence a project, both academia and industry have developed approaches and methods to be able to successfully conduct projects of this type and support decision making. In general, the term stakeholder management is used [121].

In all cases, the process begins with the identification followed by the mapping of stakeholders. The relevant stakeholders are often identified in brainstorming sessions, through interviews with other stakeholders and experts or by looking at other similar projects that have already been implemented [121].

The identified stakeholders can then be classified using various methods and their influence on the project can be categorised. A classic approach to this is, for example, a power-interest matrix, where, as the name suggests, each identified stakeholder is arranged in a matrix based on their power and interests [122]. Stakeholders with a high level of power and interest should then be managed very closely, whereas stakeholders with little power and influence should only be given minimal consideration. The Stakeholder Saliance Model takes a similar approach [123]. It evaluates whether the identified stakeholders are legitimate, have power or are urgent. This results in different categories. Stakeholders with power and legitimacy, for example, are described as dominant, while those with power and urgency are described as dangerous. Modern methods then use the analysis of stakeholders' social networks [124] or use artificial intelligence methods [125].

Once the stakeholders relevant to the project have been successfully identified and categorised, the process of actively involving them in the project starts. The aim here is to collect the specific, project-bound requirements and preferences of the stakeholders so that these can be taken into account within the project [126]. The key here is continuous communication in the various project phases and agile, stakeholder-focused project management.

This thesis is less concerned with how to communicate with stakeholders or how to engage them, but rather how the different interests of stakeholders can be incorporated into project planning and how compromises can be found. The probably most common approach to finding a compromise is the Multiple-Criteria Decision Analysis (MCDA) approach, which allows decisions to be made based on different competing evaluation parameters.

2.2.2 | Multi-Criteria Decision Analysis

The MCDA is a tool of decision theory, a scientific discipline that uses mathematical and statistical methods to solve decision problems, usually in an economic context. According to Arrow [127] a decision problem can be roughly divided into four parts:

1. Definition of the objective function
2. Definition of the alternatives
3. Modelling the alternatives and evaluating their objectives
4. Choosing between the alternatives

At first glance, many decisions in the business context seem trivial, as they seem to be answered on the basis of simple economic considerations, such as investment theory. For example, the objective function would be the NPV of an investment, the model would be a classic cash flow model and the alternative to be selected would be that of the highest NPV.

On closer inspection, however, decisions are much more complex and depend on many more objectives than a single economic indicator. Even in conventional investment theory, there are many other important indicators in addition to NPV like IRR or PP etc. for selecting an investment alternative. In the rarest of cases, therefore, only one objective function matters, but there are almost always several influencing quantities. The problem is that these usually cannot be easily compared. Mathematically, it is not straightforward to compare the years of PP with the percentage of IRR or the money of NPV.

This is in fact where MCDA comes in and provides methods for the fourth decision step according to Arrow [127] to combine incomparable objective functions into an objective ranking of alternatives [128]. However, this requires a few additional steps. After defining the objective functions, a weighting of the objectives must be determined to describe the measure of influence of the single objective on the final decision. After calculating the various objectives for each alternative, a further step is required to combine the different objectives into an overall score of the alternative. This then results in a clear and comprehensible rating of the various alternatives based on this score.

An overview of common MCDA methods and their application in distributed energy systems can be found in Chapter 7.

Stakeholders can be involved in the process on two different levels: Either by each stakeholder defining their own objectives and then finding a compromise on their weighting, or by already defining the objectives in a compromise process [129]. Both have advantages and disadvantages. While the separate definition of objectives leads to the most accurate possible representation of stakeholder wishes, the smaller number of objectives in the joint definition can lead to fewer conflicts in the interpretation of the results. For this reason, both methods are being tested in Chapters 6 and 7 as part of this thesis.

The main objective, however, is to construct a simplified and more unbiased understanding of the differing stakeholder viewpoints regarding the decision issue in question, like selecting an energy supply system. It must be clear that methods such as MCDA can only support decisions by creating objectivity. In the end, decisions are invariably made by individuals who rely on both their past experiences and their intuitive judgments. The fundamental aspect of engaging stakeholders in decision-making processes is consistently ensuring the highest level of communication. This fosters active participation of these stakeholders throughout the various stages of the project [130, 131].

3 | Contribution and Outline of the Thesis

As shown in the previous chapter, the optimisation of sizing or operation is a topic that has already been heavily researched and shows in various facets how complex these processes can be even for relatively simple systems. It is noticeable that research to date has focused on special cases such as island microgrids or special industries, and on the other hand often only optimises from a very limited perspective of individual stakeholders. In the context of this work, these aspects should therefore be taken up and methods developed and demonstrated that look at the problems described in a more real-world fashion and at the same time take a broader and more individual view of the stakeholders involved. In summary, the thesis sets out to answer the question:

> How can hybrid energy supply concepts be optimised in their design and operation taking into account the interests of various competing stakeholders? What role can simulation models play in objectifying these decision-making processes?

Outline

The research question is answered using a cumulative dissertation. Four publications are presented, the structure and sequence of which are briefly explained in the following.

Paper 1 First, the procedure for implementing distributed energy systems in complex supply structures is examined. For this purpose, the scientific literature is researched to identify how energy systems are usually developed and designed. In order to meet the specific requirements of the research question, these concepts must be expanded to include the aspect of target setting, taking into account the stakeholders. Using the example of the Helleheide neighbourhood on the former Oldenburg air base, the process is developed and described from targeting through synthesis and design to operation. The focus of this publication is primarily on identifying research gaps in various aspects, which will then be addressed in the subsequent publications of this thesis and beyond (see also the publication list in the Appendix).

Paper 2 In the first paper concerned with building simulation models, a relatively simple case study of a dairy is used, which does not yet have a complex stakeholder structure but a typical energy consumption behaviour of the processing industry. A Hybrid Energy System (HES) is designed and evaluated for an existing energy demand. Innovative plant technology in the form of a Power-to-Gas-to-Power (PtGtP) system is to be used to show how to evaluate even complex and innovative systems. The modelling is done in *oemof.solph*, a powerful modelling and operational optimisation tool, while the sizing optimisation is done with a simplistic brute-force approach. Optimisation is based on economic and ecological aspects from the dairy operator's point of view. This reveals the high modelling and computational effort required to solve such problems, as well as the range of possible solutions, even for a relatively simple case study, and the overall innovative but limited choice of technology.

Paper 3 Building on this, the Helleheide neighbourhood, already known from the first publication, is chosen as a much more complex case study. As described in the first publication, a comprehensive stakeholder participation process has been carried out, which serves to select the optimality definition of the optimisation. In addition, the technology selection is extended to cover virtually all currently established electricity and heat generators and storage systems, which also requires the implementation of a more efficient optimisation algorithm in the form of a multicriteria metaheuristic. In addition, new methods of data analysis and visualisation are being developed and used to support the decision-making process in this case study.

Paper 4 Finally, it is shown how the decision-making process can be executed even more fairly and transparently between the stakeholders. For this purpose, a generic German multi-family house is used as an example to carry out a Multiple-Criteria Decision Analysis (MCDA), which allows the goals of each stakeholder to be initially recorded and a comparison of interests to be carried out only with the fully evaluated energy systems. This should make it possible to justify compromises in the decision-making process in the best possible way and to make them transparent. For this purpose, however, it is necessary to deviate from the previously used very complex modelling of the energy systems and to demonstrate the method using simpler models and engineering standards. In conclusion, this should make it possible, depending on the stakeholder composition and their objectives, to design even complex distributed energy solutions with the size and operation to best suit the stakeholders' interests.

Author contributions

Following the CRediT taxonomy (`https://casrai.org/credit/`), the doctoral candidate made the following contributions to the publications.

Paper 1 [132]

Title:	Development of a Decision-Making Framework for Distributed Energy Systems in a German District
Authors:	Schmeling, L.; Schönfeldt, P.; Klement, P.; Wehkamp, S.; Hanke, B.; Agert, C
Published in:	Energies 2020, 13 (3), 552 (doi:10.3390/en13030552)
Author Contributions:	Conceptualisation and methodology: **L.S.**, P.S., P.K. and B.H.; modelling: P.S. and **L.S.**; software development: **L.S.**, P.S. and S.W.; writing–original draft preparation, **L.S.**; writing–review and editing, S.W., P.K., and P.S.; project-administration, P.K.; supervision, B.H. and C.A.

Paper 2 [133]

Title:	Planning, Optimisation and Evaluation of Small Power-to-Gas-to-Power Systems: Case Study of a German Dairy
Authors:	Schmeling, L.; Buchholz, A.A.I.; Heineke, H.; Klement, P.; Hanke, B.; von Maydell, K.
Published in:	Sustainability 2022, 14 (10), 6050 (doi:10.3390/su14106050)
Author Contributions:	Conceptualisation and methodology, **L.S.**; software, **L.S.** and A.A.I.B.; validation, **L.S.**; formal analysis, A.A.I.B. and **L.S.**; data curation, A.A.I.B. and **L.S.**; writing—original draft preparation, **L.S.** and A.A.I.B.; writing—review and editing, P.K. and B.H.; visualisation, **L.S.**; supervision, H.H., P.K., B.H. and K.v.M.; project administration, **L.S.**, H.H. and P.K.; funding acquisition, H.H., P.K., B.H. and K.v.M.

Paper 3 [134]

Title:	A generalised optimal design methodology for distributed energy systems
Authors:	Schmeling, L.; Schönfeldt, P.; Klement, P.; Vorspel, L.; Hanke, B.; von Maydell, K.; Agert, C
Published in:	Renewable Energy 2022, 200 (2), 1223-1229 (doi:10.1016/j.renene.2022.10.029)
Author Contributions:	Conceptualisation: **L.S.**; Methodology: **L.S.**; Software: **L.S.** and P.S.; Data Curation: **L.S.**, P.S. and L.V.; Formal Analysis: **L.S.**; Visualisation: **L.S.**; Writing – Original Draft Preparation: **L.S.**; Writing – Review and Editing: P.S., P.K., L.V. and B.H.; Project Administration: **L.S.** and P.K.; Supervision: B.H., K.v.M. and C.A.

Paper 4 [135]

Title:	Multi-Stakeholder Optimal Energy Supply for Multi-Family Houses under 2021 German Market Conditions
Authors:	Schmeling, L.; Walter, F.; Erfurth, E.; Klement, P.; Hanke, B.; von Maydell, K.; Agert, C.; Siebenhüner, B.
Published in:	Journal of Civil Engineering and Management 2024, 30(6), 481–493. (doi:10.3846/jcem.2024.20924)
Author Contributions:	Conceptualisation and Methodology: **L.S.**; Software: F.W. and **L.S.**; Data Curation: F.W., **L.S.** and T.E.; Formal Analysis: **L.S.** and F.W.; Validation: **L.S.** and T.E.; Visualisation: **L.S.**; Writing – Original Draft Preparation: **L.S.**; Writing – Review and Editing: F.W., P.K., B.H. and B.S.; Project Administration: **L.S.**, T.E. and P.K.; Supervision: T.E., P.K., B.H., K.v.M., C.A. and B.S.

Additional publications in which the candidate was involved are listed in the Appendix.

4 | Development of a Decision-Making Framework for Distributed Energy Systems in a German District

The content of this chapter is identical to the following journal article:

Schmeling, L.; Schönfeldt, P.; Klement, P.; Wehkamp, S.; Hanke, B.; Agert, C. Development of a Decision-Making Framework for Distributed Energy Systems in a German District. Energies 2020, 13, 552, doi:10.3390/en13030552.

Article

Development of a Decision-Making Framework for Distributed Energy Systems in a German District

Lucas Schmeling[1,2,*], Patrik Schönfeldt[2], Peter Klement[2], Steffen Wehkamp[3], Benedikt Hanke[2], Carsten Agert[2]

[1] KEHAG Energiehandel GmbH, Im Technologiepark 4, 26129 Oldenburg, Germany
[2] DLR Institute of Networked Energy Systems, Carl-von-Ossietzky-Str. 15, 26129 Oldenburg, Germany
[3] OFFIS — Institute for Information Technology, Escherweg 2, 26121 Oldenburg, Germany
* Corresponding author: lucas.schmeling@kehag.de / lucas.schmeling@dlr.de; +49 441 36 108 162

Received: 23 December 2019 / Revised: 17 January 2020 / Accepted: 20 January 2020 / Published: 23 January 2020

Abstract: The planning and decision-making for a distributed energy supply concept in complex actor structures like in districts calls for the approach to be highly structured. Here, a strategy with strong use of energetic simulations is developed, the core elements are presented, and research gaps are identified. The exemplary implementation is shown using the case study of a new district on the former Oldenburg airbase in northwestern Germany. The process is divided into four consecutive phases, which are carried out with different stakeholder participation and use of different simulation tools. Based on a common objective, a superstructure of the applicable technologies is developed. Detailed planning is then carried out with the help of a multi-objective optimal sizing algorithm and Monte Carlo based risk assessment. The process ends with the operating phase, which is to guarantee a further optimal and dynamic mode of operation. The main objective of this publication is to present the core elements of the planning processes and decision-making framework based on the case study and to find and identify research gaps that will have to be addressed in the future.

Keywords: energy system planning; energy system simulation; optimal sizing; risk analysis; Monte Carlo Simulation; distributed energy systems; local energy markets

4.1 | Introduction

The planning of a holistic distributed energy supply system is often a lengthy and complex process. In this process, decisions have to be made again and again, which have a significant influence on the result. Especially in projects where involved companies, private persons, and other institutions have different interests and expectations, the planning process often takes years. Such complex actor structures are especially common in the planning of districts where the interests of the public, residents, energy utility companies, real estate developers, and many others come together. For efficiency reasons, however, it seems reasonable to set up a joint supply of electricity, heat, and possibly cooling. This requires joint decision-making that meets the expectations and needs of all stakeholders, which itself calls for transparent, objective, and clearly structured processes that accompany and support the entire path from the preliminary design to the operation of the supply concept. Special energy simulation tools can be used, which in combination with other advanced methodologies can facilitate the joint decision-making. The resulting holistic planning process and decision-making framework shall be developed, described, and implemented in this paper using a district case study. Nevertheless, the resulting framework should be as universally valid and transferable as possible in order to deliver valid results even under different conditions.

The case study of this paper is a district that is to be built on the former Oldenburg airbase in northwestern Germany in the next few years. The district has been designed as a living lab for testing Smart City innovations. Its energy supply concept is being realized within the research project "Energetisches Nachbarschaftsquartier Fliegerhorst Oldenburg" (short *ENaQ*). With the aid of sector coupling, it will be designed to be as climate friendly as possible yet affordable. Furthermore, it is specifically intended to enable energy trading between neighbors.

The aim of this paper is not to examine the planning process down to the last detail but to provide a rough overview of the core elements. Therefore, the paper is structured as follows: First, in Section 4.2 the *ENaQ* case study is presented in more detail. In Section 4.3, based on existing literature, a phase-based planning approach is developed, which is divided into the phases Targeting, Synthesis, Design, and Operation. In the Targeting phase (Section 4.4) all stakeholders agree on a common goal. In the Synthesis phase (Section 4.5) the selection and basic interaction of the technologic components is agreed upon. In the Design phase (Section 4.6) a tool based on the simulation environment *oemof.solph* is presented, which creates a pareto-optimal supply concept by means of optimal sizing and Monte Carlo based risk assessment. In the final Operation phase (Section 4.7) the later system operation is designed and corresponding operation strategies are developed. The paper concludes in Section 4.8 with the identification of research gaps, which are still missing for a complete and successful implementation of the framework and which will be presented in subsequent publications.

In contrast to previous work, a particularly interdisciplinary, application-oriented, and holistic approach is presented here. This approach deals with all phases of planning and operation of supply infrastructure, combines energy technology with energy industry issues, and develops its own tools and methods for this purpose.

4.2 | The Case Study - Energetisches Nachbarschaftsquartier Fliegerhorst Oldenburg

With the participation of a wide variety of stakeholders from industry, research, citizenship, and administration, a new part of town will be built on the former airbase in Oldenburg (northwestern Germany) over the next few years. The redevelopment of the airbase began in 2015 by involving the citizens of the city of Oldenburg in the development of a master plan to convert the site from its former military use to civilian use [136]. In addition to this participatory process, the Smart City Vision of the city was developed in parallel and published in 2017 [137]. It addresses focal points such as Smart Energy, Smart Mobility, or Smart Health that will play an increasingly important role within the city in the future. To test such concepts one of the districts to be built on the former airbase called “Helleheide” has been designed as a living lab. Within the living lab, innovative technologies are to be developed and tested in a practical environment. In this context, the research project “Energetisches Nachbarschaftsquartier Fliegerhorst Oldenburg” (*ENaQ*, `https://www.enaq-fliegerhorst.de/`) has been designated as a living lab for the field of Smart Energy.

Within the framework of this research project, a possibility of district energy supply with a strong focus on digitization, participation, and sector coupling is to be developed. Central objectives are the development of energy exchange among neighbors, market-oriented control of generation and storage facilities, and the testing of innovative energy technologies. The supply concept should be as climate-friendly as possible and thus contribute to the German “Energiewende” by promoting the use of innovative supply concepts in districts. The overall concept developed in this way should then, as far as possible, also be transferable to other German residential areas, which is why another focus is particularly on the development of economically viable business models and universally applicable planning tools.

In the district Helleheide approximately 110 housing units will have to be supplied with electricity and heat, of which about 50% is planned as social housing. The district includes two former military buildings and a large number of different new buildings that are still planned and under construction. The first residents are to move into the new district in 2021. At the current time (December 2019), the planning of the quarter is still in the initial phase. Since May 2019 there has been a legally binding land-use plan, a real estate developer and energy utility company have been found, and there is a rough concept for land use. However, exploratory work for explosive ordnance is still underway on the site and development work has not yet been completed. Much of what is presented below has therefore not yet been planned and tested down to the last detail, as important decisions such as building planning and positioning and the then valid legal framework could not yet be determined. Nevertheless, decisive negotiations are already underway and trend-setting decisions are being made for the energy supply concept.

4.3 | Basic Concept of the Energy System Design Process

Designing an energy system for any kind of demand is in most cases a highly complex process. Often the design process cannot be reduced to a simple decision criterion and decision-maker, but different perspectives and technological alternatives have to be included [138, 139]. This is especially true for district energy supply, where many different stakeholders with many different opinions and goals meet. In addition, there is a multitude of different boundary conditions, which are placed on the energy system from various institutions.

The construction of an energy system is always based on decisions at certain points that have a significant influence on the resulting system. Decision theory is a standard tool in companies in order to be able to make valid decisions and to ensure the long-term success of the system and the company [140, 141]. Applied in various specialized sub-areas like disaster management (cf. e.g., [142, 143]) or medicine (cf. e.g., [144, 145]), decision theory has also been studied in detail in the energy sector. Majidi et al. [146] compare different approaches of decision theory to energy problems, Andreotti et al. [147] use decision theory for the integration of storage systems in distributed supply scenarios, and Yang et al. [148] show how the optimal distributed supply concept should look under uncertainty. However, the focus is often on individual decision-making steps. However, designing an energy supply concept requires a large number of different decisions that are embedded in a holistic planning process.

As a general approach to energy decision making, Multiple-Criteria Decision Analysis (MCDA) is often mentioned [139, 149, 150]. Different decision-makers come together who have different ideas and wishes about a decision that can usually only be made jointly. Various general approaches already exist, such as *PROMETHEE* [151] or *ELECTRE* [152] to solve MCDA problems. These approaches are used in various disciplines, e.g., transport [153, 154] or healthcare [155, 156], in order to make valid and objective decisions despite complex situations. For application in specialist areas such as energy supply, the generic approaches mentioned above must first be individually adapted and extended. This is described, for example, by Özkale et al. [157], who, with the help of *PROMETHEE*, make the choice for renewable energy power plants in Turkey. Kirppu et al. [158] describe the application of an MCDA method for selecting heat generation technologies for a district heating system in Finland. Sahabmanesh and Saboohi [159] use a specially developed approach for multi-criteria evaluation of the sustainability of the energy system of an Iranian city and show that renewable energies offer high advantages in various areas.

Another frequently found approach to energy system planning is the description as a classical mathematical optimization problem, in which decision-making is reduced to an objective function, which is then minimized or maximized by skillful manipulation of certain degrees of freedom by some kind of numerical solver. The literature describes different ways in which such energy system planning approaches can be organized. A large overview can be found, for example, at Zeng et al. [160] or Erdinc and Uzunoglu [161]. Some relevant prior work should be mentioned here.

Often the planning of energy systems is only understood as the optimization of the required plant sizes, which is called optimal sizing. Many of these approaches are very technical and use economy and ecology as objective functions. For example, Gimelli et al. [162] are developing a methodology based on a genetic algorithm for the optimization of combined heat and power (CHP) in Italian hospitals. They optimize both costs and primary energy savings and also take into account the sensitivity of the results to changing conditions. Nimma et al. [163] use a generic case study to demonstrate the optimization of a hybrid supply concept in a micro-grid using a fuel cell. They use an innovative approach based on metaheuristics. Wang et al. [164] develop a planning tool for residential areas with a high share of renewable energies. They reduce the design to a linear system of equations that they then solve using the example of a large Finnish residential area. Buoro et al. [165] choose a similar approach for an industrial area in Italy and Urbanucci et al. [166] for a school building in California.

Specialized simulation tools are often used to map these quite complex processes. Connolly et al. [167] present and compare 37 different planning tools for energy systems, Schmeling et al. [168] develop an evaluation approach based on nine tools and Allegrini et al. [169] show 24 tools for planning neighborhood energy projects.

In addition, more holistic, application-oriented approaches can be found, which often take a phase-based structured approach. Jordanger et al. [170] select four successive phases (problem formulation, data collection, analysis of alternatives, and decision making) and use them to plan investment and operation of the power distribution system. Mirakyan and de Guio [171] show and compare planning processes and tools for the energy systems of entire cities and territories. They also divide the process into four phases (Preparation and Orientation, Detailed Analysis, Prioritization and Decision, Implementation and Monitoring), which are based on Bagheri and Hjorth [172] and identify suitable software tools. A similar, phase-based approach is described by Frangopoulos et al. [173]. They understand the optimization of a supply concept as three consecutive sub-problems or phases: Synthesis, Design and Operation. The planning process presented here follows the phase classification according to Frangopoulos et al. [173] but adds another necessary step before beginning, which is owed to the complex actor structure. In the whole process, a common understanding of optimality is crucial. This can be understood in a technical, economic, and ecologic way, which can lead to fundamentally different results. Phase 0, which can be called targeting, can thus be understood as the creation of a common idea of optimality between all stakeholders. The resulting planning process can be seen in Figure 4.1.

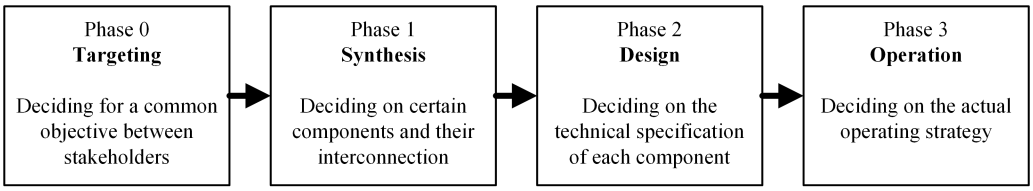


Abbildung 4.1: Presentation of the successive planning processes for designing an energy supply solution in complex actor structures. The phases are run through one after the other with the participation of various stakeholders. Each phase involves important decisions that will have a significant impact on the results of the next phase.

This clearly structured methodology should help to make the planning process as comprehensible as possible for those involved. Each phase has the goal of making certain pathbreaking decisions in order to start the next phase. This ensures transparent and collaborative decision making. However, there is a risk in this approach that the entire planning process may be held up due to delays in the decision-making process of one phase, e.g., due to disagreements between stakeholders. This could be better avoided with a freer, less participatory framework but would then be counteracted by the requirements of involving as many stakeholders as possible and the common pursuit of optimality.

4.4 | Targeting Phase

In order to create a successful energy supply concept for all participants, it is essential for them to agree on a common objective. Involved stakeholders can include a large number of natural and legal persons who are directly or indirectly affected by the energy supply concept. The most important stakeholders for the case study and their possible objectives are summarized in Table 4.1.

Tabelle 4.1: Overview of the main stakeholders for the present case study and qualitative description of their possible objectives. This list does not claim to be exhaustive or transferable to other projects but is merely intended to give an impression of the complexity and multilayeredness of the decision-making processes for district energy supply.

Category	**Stakeholder**	**Possible Objectives**
Privat Persons	Residents of the district	Secure, cheap, and climate-friendly energy supply
	Residents of the surrounding districts	Little nuisance due to energy supply
	Citizens of the town	Showcase project of the city
Legal Person	Energy Utility Company (EUC)	Selling energy with the highest possible profit to the residents
	Distribution System Operator	Reliable supply of the district and use of local flexibilities
	Real Estate Developer	Reliable and inexpensive system to make it as easy as possible to sell/rent apartments
	Plant owner	Produce energy cheaply and sell it with maximum profit to the EUC
	Energy Cooperative	Involving residents in the local energy supply
Politics	City Council Regional politics Federal politics	Showcase project of the “Energiewende” and high transferability
Other	City administration	Attractive neighborhood, high satisfaction of the citizens and thus high profit from tax revenues
	Universities and research institutions	Environment for testing innovations under real conditions (Living Lab)
	Press	Report on exciting and future-oriented projects

The process presented here is explicitly structured in such a way that it is not necessary to agree on a single goal, a combination of different goals is also possible, at least in the first phases by striving for a Pareto optimal system. This makes compromises such as the highest possible individual profitability of individual actors with the most climate-friendly and technically sensible operation possible. The goals created at this point are trendsetting for the further planning process and determine the result decisively.

Three different targets were agreed on in the *ENaQ* project: The district's energy supply should be climate-friendly, supply residents with energy at market prices, and have the highest possible rate of own consumption. The climate friendliness is mainly due to private persons and politics, affordability is a main interest of private persons and the real estate developer, and a high degree of own consumption is in the interest of the distribution system operator, the inhabitants, and the energy utility company. This threefoldness poses certain challenges, as the goals of "climate friendliness" and "affordability" currently often contradict each other under prevailing market conditions and political framework conditions at the district level. The other stakeholders' objectives are also taken into account in the further process and are checked constantly, but they are not the primary objective of the optimization to be carried out.

In order to be able to better quantify and compare these rather abstract goals in the further planning process, fixed calculation methodologies for the individual variables were subsequently defined. The S.M.A.R.T. principle of project management is followed, which requires goals to be specific, measurable, assignable, realistic, and time-related [174]. This is easiest for the technical part, which corresponds to the degree of own consumption generally known in distributed generation [175]. The calculation of climate friendliness is highly present in the current political discourse and is quantified by calculating annual CO_2 emissions. To do this, system boundaries are drawn around the district and energy flows into or out of it are recognized. These are then burdened with specific CO_2 emissions. The chosen methodology is inspired by the DIN EN ISO 14064-1 [176]. When external electricity is purchased, this happens dynamically, depending on national generation and consumption in accordance with [177, 178]. Affordable energy for residents at market prices is difficult to quantify because it depends largely on internal company calculations and supply contracts. Here it is assumed that if the total economic costs of the system are minimal, the costs of the financially involved stakeholder must also be minimal. To make this as objective and comparable as possible, the annuity calculation according to VDI 2067 is used [179]. These three quantifiable targets are used below as Key Performance Indicators (KPIs) to assess the energy supply concept.

4.5 | Synthesis Phase

To continue the optimization and decision-making process, the general infrastructure has to be synthesized. By design, this process is completely open to any technology in the first step. However, the choice of technology has to be discussed and thinned out with the involvement of a wide range of stakeholders. This includes many of the stakeholders listed in Table 4.1. The exclusion of certain technologies due to the diverse boundary conditions can be due to a variety of reasons.

Building on this, various scenarios have to be developed as to how the technical components are linked with each other, creating the so-called superstructures.

4.5.1 | Technological Preselection

In the course of the technological preselection process, free brainstorming is required to gather together all conceivable generation, storage, and consumption technologies, as well as all other technologies that come into contact with the energy system. As mentioned above, a large number of different stakeholders, but especially the future residents, the energy utility company, and the real estate developer, should be involved.

The preselection of possible technologies in the *ENaQ* project was carried out with such an open process. The resulting, already clustered table of conceivable technologies can be seen in Table 4.2. This forms the basis for all further planning processes.

Tabelle 4.2: Matrix of all conceivable energy technologies for a distributed energy supply system clustered by their intended purpose. This matrix is the result of a joint brainstorming of the partners involved in the *ENaQ* project. In addition, further technologies would be conceivable, but these were not considered due to their market maturity or other general conditions.

Source	**Distribution**	**Storage**	**Coupling**	**Demand**
Photovoltaic (PV)	District Heating Network	Hydrogen	Heat Pump	Electricity
Combined Heat and Power (CHP)	District Heating Network (low ex)	Battery	Power2Gas	Heat
Fuel Cell	Electricity Grid	Redox Flow Battery	Fuel Cells	Cold
Solar Thermal	Natural Gas Grid	Ice Storage	Power2Heat	E Mobility
Gas Boiler	Hydrogen Grid	Hot Water Storage		Hydrogen
Biomass Boiler		Electric Car		
Geothermal				
Small Wind Turbine				
Power2Heat				
Heat Pump				

The table is the open result of the described joint brainstorming session and does therefore not claim completeness about all distributed energy technologies.

4.5.2 | Boundary Conditions

Boundary conditions can be set by various stakeholders and should be known as early as possible for an efficient planning process. There are many different categories of boundary conditions. The most important ones will be briefly outlined below and supported by examples from the *ENaQ* project:

Technical: The building site is located in a water protection area, making the utilization of any kind of geothermal energy difficult. In addition, the district is planned as a district with as little car traffic as possible. It is, therefore, difficult to justify an energy system that, for example, necessitates the delivery of fuels by trucks. The energy system should also be as unobtrusive as possible in the everyday lives of the residents in terms of noise or exhaust emissions. The type of domestic hot water production and the temperatures of a possible heating network are also part of the technical boundary conditions required here.

Economic: The resulting energy prices have to be customary. For legal reasons, nobody in the district can be forced by law to buy electricity from the local energy supplier. Therefore, there have to be economic incentives to do so. In contrast, the residents are required to cover their heat demand by using the district energy system. Nevertheless, a customary energy price has to be offered to be able to let the apartments. What is more, some of the later residents of the district will receive state support and will therefore have to act very price-consciously in all areas of life. However, regulation of state support also implies biases for their economic optimum. For example, law limits the cold rent, not the sum of rent and heating costs.

Ecologic: The project is committed to establishing a climate-friendly energy supply as far as possible. This should go far beyond the government requirements, e.g., for energetic standards of buildings or renewable energies share of heat supply.

Legal: As mentioned for economic and ecologic boundary conditions, many of the boundary conditions are co-founded by legal requirements. For example, the legislator regulates, among other things, how electricity and heat bills have to look, which taxes and allocations are to be paid on distributed generation and storage, and which energetic building standard is to be observed in a district.

Participation: A distinguishing feature of the *ENaQ* project is the strong involvement of citizens and later residents in decision-making processes. These groups of people also have special needs and ideas about what an energy system can and should achieve, as has already been mentioned several times. For example, there are prejudices against some technologies (e.g., hydrogen or battery storage), there are concerns about data protection, and about the sustainability of the overall system.

4.5.3 | Superstructure Design

After the initially very extensive technology catalog (Table 4.2) could be sufficiently restricted by the boundary conditions, the development of a meta-model or superstructure can be started. The superstructure consists of all technologies still conceivable at that time and their connection, even if these are partly redundant [180]. Due to its technical complexity, the process must be carried out by appropriate experts, since the interrelationships between certain technologies can have decisive effects on the overall system.

At this point, it may be considered to develop different superstructures for fundamentally different technology paths, especially in order to differentiate the different heating and hot water systems. For example, a system based on an electrical, point-of-use hot water supply would possibly look fundamentally different from a centrally fed tankless system. Instead, the process is split in two. In the first step, the heating and hot-water requirements of each individual consumption point and the associated losses of the heating network are calculated and aggregated for the second step. This total heat demand without differentiation of use is then assumed for the superstructure. This approach allows both centralized and distributed hot water generation schemes with just minor modifications. A drawback of considering the losses as part of the demand is that solar thermal generation can only be appropriately modeled at a central position: The decentralized production of heat by solar thermal that feeds at variable temperatures into the grid would alter the flows and thus make the estimation for the losses inappropriate.

In addition to the purely technical linking and interaction of the trades, the interaction with external energy markets must also be decided at this point. For example, for electricity, it can be assumed that the later energy system will purchase the local missing energy quantities on the spot market but more complex market structures such as balancing markets or future flexibility markets can also be served. The same considerations must also be applied to the procurement of natural gas, hydrogen, or biomass.

The exemplary, but very simplified representation of a superstructure for the *ENaQ* system in the form of a directed graph can be seen in Figure 4.2.

The chosen approach has the great advantage that all stakeholders involved can contribute the technologies they favor and that a common vision on energy supply can be developed. Relatively few decisions have to be made that will determine the direction of the energy supply but rather an approach that is open to technologies and manufacturers can be followed. Only in the next phase will concrete technologies be selected. However, this can lead to certain stakeholders feeling betrayed if their preferred technology is not taken into account in the design phase. It is therefore all the more important to make the planning process and the effects of central decisions as transparent as possible.

With the creation and acceptance of the superstructure, the synthesis phase ends.

4.6 | Design Phase

After the end of the actual synthesis phase, the strong involvement of the stakeholders ends for the time being. Now the design phase begins, at the end of which the determination of certain technologies and plant sizes and thus, the actual investment decision by the future plant owners is made. Therefore, the design process is decisively controlled by the decision-maker of the subsequent investment taking into account the interests of other stakeholders.

The process begins with the definition of certain framework parameters, which have to be imprinted into the previously developed superstructure. This includes, for example, the precise grid connection situation, the hourly energy consumption of the consumers, or the exact course of pipes and lines.

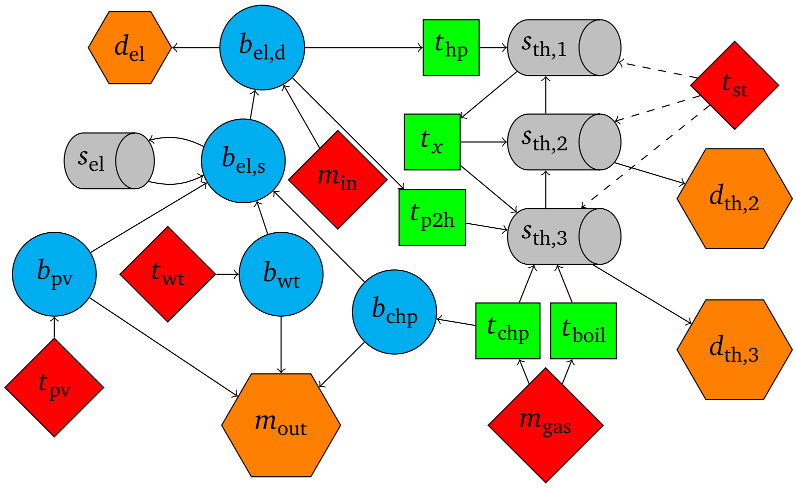


Abbildung 4.2: Depiction of the directed graph meta-model used as base-layout for the integrated energy system. Note that technologies may be optimized out (to have zero size). On display are, among others, energy-generating technologies (e.g., PV t_{pv}, solar thermal t_{st}), energy-converting technologies (e.g., heat pump t_{hp}, CHP t_{chp}), energy-storing technologies (e.g., buffer storage $s_{th,i}$, battery s_{el}), as well as energy sinks (heat demand $d_{th,i}$, electricity demand d_{el}, national energy markets for export m_{out}) and external energy sources (external electricity procurement markets m_{in}, gas markets m_{gas}). The dashed line connecting the solar thermal collector t_{st} and the three thermal storages $s_{th,i}$ indicate that only one of these can be active at a time.

4.6.1 | Load Curves and Other Time Series

In order to be able to make concrete statements about the later operation of the technical facilities, it is necessary to model the temporal course of certain variables more precisely. These include energy generation by volatile energy generation technologies, energy consumption by consumers, price signals from external markets, or meteorological conditions.

To evaluate the energy system over the longest possible time, especially for meteorological data, test reference years are often chosen. These represent the average exemplary course of certain meteorological variables over the course of a year. In *ENaQ*, though, the technical world for which meteorological data are primarily used is explicitly linked with the economic world for which market data, e.g., from the electricity exchange, are used. There are correlations between these two data sources, so that the same data basis must always be used. Unfortunately, this is not possible with test reference years, so that measured meteorological data of a year that is as representative as possible but not too long ago must be used.

At the time of the design phase, the district will not yet be inhabited, which is why assumptions have to be made for the time pattern of the energy consumption of the residents. This is a frequently encountered problem in energy system planning, which is why there are various tools for creating synthetic load profiles [181–183]. *ENaQ* will make use of the LoadProfileGenerator [184] for the generation of electrical and domestic hot water demand curves and a combination of different tools for the generation of heat demand curves.

Apart from the course of these variables over the year, the long-term development must also be taken into account. For example, the energy requirements of the residents may change due to the addition of new family members or more energy-efficient appliances or the meteorological conditions may alter due to climate change. However, these forecasts are associated with a greater degree of uncertainty. In order to compensate for this uncertainty, these are included in a detailed risk analysis at a later stage.

4.6.2 | Energy System Modeling and Simulation

The modeling and simulation of the planned energy supply concepts can make a significant contribution to supporting the decision-making process by making reliable, comprehensible, and transparent statements about compliance with the goals set by the various stakeholders.

The *ENaQ* research project places high and very detailed demands on the functionalities of the energy system modeling and simulation software. The software must be able to map the boundary conditions defined in the synthesis phase (Section 4.5.2) as well as the necessary technical-physical and basic economic assumptions. The simulation of the local energy system has to include the sectors electricity, heat and mobility, as well as possible sector coupling as proposed in the superstructure. The aim of the simulation is to come as close as possible to the initially defined optimality criterion under the defined boundary conditions by clever plant sizing and deployment planning.

There has been a lot of meta-research into which proprietary energy simulation software suits which requirements best [167–169]. It has been found that none of the proprietary simulation environments meet the *ENaQ* requirements sufficiently at this point, since usually the complex actor structure and the interaction of the different technologies cannot be modeled sufficiently. Due to the closed source character of the products and the necessary cooperation with the developers in order to meet the requirements of the project, the use of such a solution must be discouraged at this point. In addition, it was decided not to strive for an own, tailor-made development. This would mean a considerable development effort for the consortium, which would not be in proportion to the planned personnel expenditure. In good circumstances, such an approach could deliver satisfactory results. Still, the development would involve a high risk to the quality of the results, which should therefore be avoided if possible. For this reason, an open-source approach for energy system modeling is favored. Current approaches have therefore been thoroughly analyzed and compared. Among the open-source solutions examined, *solph* [185]—part of the *Open Energy Modelling Framework* (*oemof*) [186]—has proven to be the best suitably highlighted. It is already thoroughly tested and valid (cf. e.g., [187–190]). *oemof* is continuously developed by a large developer community and is relatively easy to use. The mathematical Mixed Integer Linear Programming (MILP) optimization problem created by *oemof* is converted into an LP file, which can then be solved by a numerical solver. *CBC* [191, 192] is used in the project for this purpose.

4.6.3 | Optimal Sizing

After the superstructure has been fed with the necessary boundary conditions and has been modeled using the described energy simulation software, the next step is to dimension the contained technologies. The literature covers a wide range of approaches, from classical standards-based methods (e.g., *f*-chart method for solar thermal energy [193]), to simple brute force approaches (e.g., [194, 195]) to very sophisticated methods (e.g., [196–198]). These differ strongly in the supported technologies, the handling of complex target functions, and the consideration of the boundary conditions. Each approach has its own raison d'être, a universal approach is not to be found due to the massively different case studies [161]. An overview of existing approaches can be found at Twaha and Ramli [199], Prakash and Khatod [200], or Mekontso et al. [201].

The project consortium currently has a ready-made, self-developed solution which, using the simulation software *energyPRO* and a Particle Swarm Optimiser, finds the economic optimum of a CHP/solar thermal combination for industrial applications [65]. This approach will be taken up for the presented case study and extended accordingly. The following approach should be applied:

As described beforehand, the energy system itself is modeled using *oemof*. The model is constructed in such a way that the technology sizes can be adapted from the outside as required. The individual technologies are continuously modeled using large product databases for each technology. The time series calculated by *solph* for a certain sizing are analyzed with the help of post-processing and the relevant KPIs annuity, CO_2 emissions, and own consumption (cf. Section 4.4) are calculated. These values are then transferred to an optimization algorithm, which determines the next sizing constellation to be calculated on the basis of these and previous calculations. In opposition to the existing solution, which could only optimize economic success, a multi-criteria optimization searching for the Pareto frontier based on the KPIs is now carried out. The optimization tool *pygmo/pagmo* [202, 203], especially the "Improved Harmony Search" algorithm [204], is used to solve the resulting Mixed Integer Nonlinear Programming (MINLP) problem in a reasonable amount of time. The schematic approach is shown in Figure 4.3. The results of an exemplary optimization are plotted in a three-dimensional Pareto front in Figure 4.4.

Based on the results, decision makers can define certain scenarios that can be used for further consideration. In the next step, these scenarios have to be evaluated with regard to their inherent risk in order to reach a final investment decision.

The chosen approach has the disadvantage that the computing time for the optimization is extremely high and may take several weeks. Although there are methods to shorten this computing time, e.g., time series aggregation [205], the computing effort remains high. The big advantage, however, is that this approach generates a result that is comprehensible and credible for all those involved, while at the same time being as realistic and technologically open as possible.

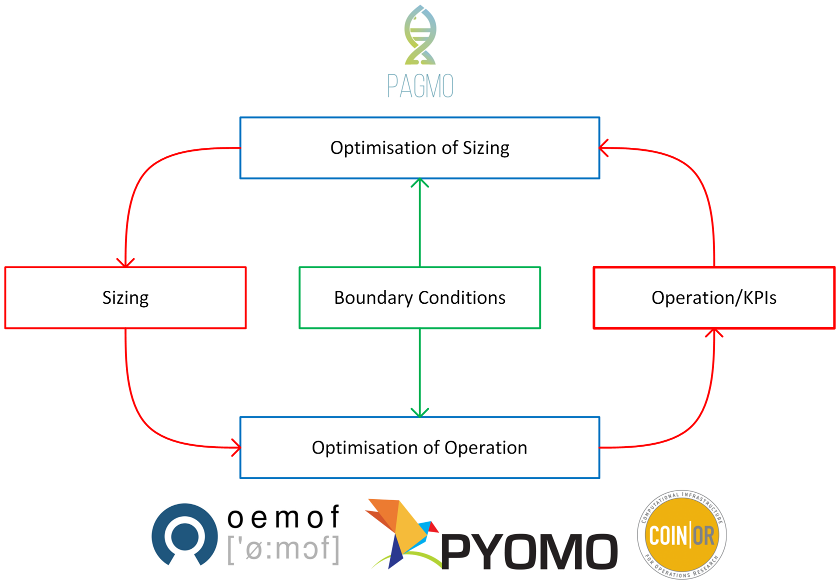


Abbildung 4.3: Flow chart of the energy system optimal sizing loop. The interaction of the various existing software solutions and their interfaces, as well as the necessary consideration of the boundary conditions, is to be seen particularly. All this is implemented in a holistic *Python* based approach.

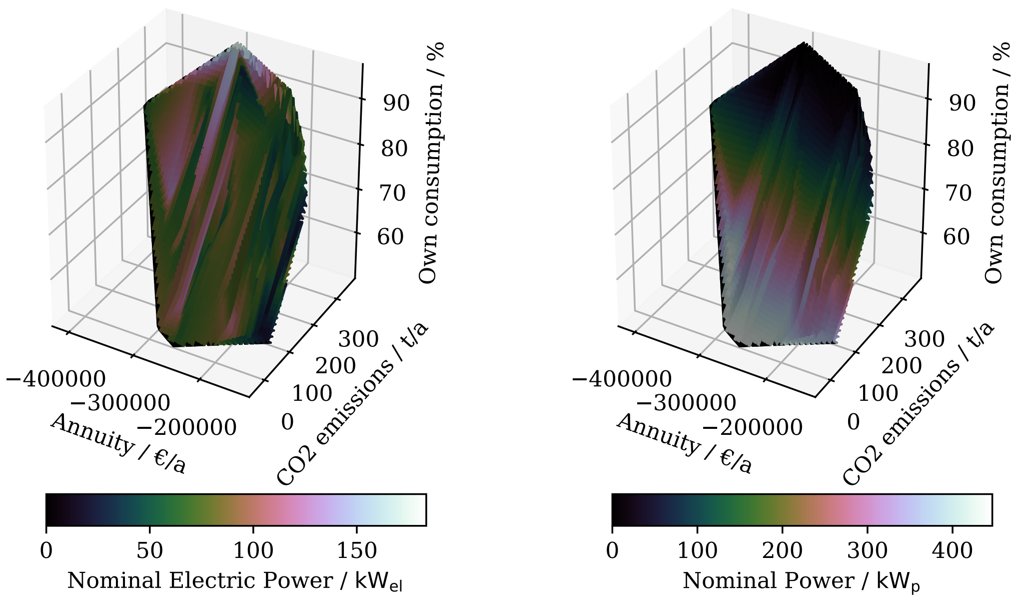
4.6.4 | Risk Analysis

As mentioned several times before, a large number of the variables set in the simulation are subject to a certain uncertainty. This uncertainty is therefore also reflected in the resulting sizing and the KPIs calculated as optimal. In order to make a valid decision for an energy system, this uncertainty must be quantified using some kind of risk analysis. Various approaches can already be found in the scientific literature [162, 206–209].

The project consortium has already gained experience in this area and has a tool that also uses the simulation environment *energyPRO* to carry out a Monte Carlo simulation (MCS) for a rather limited technology selection [65]. The existing procedure has to be heavily modified in order to be suitable for the *ENaQ* project. In the following, the rough procedure of the methodology is presented.

In general, the risk assessment can be divided into four phases [210]:

1. Risk identification
2. Risk analysis
3. Risk management
4. Risk monitoring



(a) CHP (b) PV

Abbildung 4.4: Presentation of exemplary optimal sizing results generated by the described methodology. It shows the Pareto front between the three KPIs (Section 4.4). Color-coded is the corresponding plant size, shown here as an example for combined heat and power (CHP) (**a**) and PV (**b**). Here it is shown for the CHP that a small to medium plant size is almost universally optimal, whereas for PV there is a high dependency on own consumption and CO_2 emissions.

The first step, risk identification, is to identify and describe the individual external risk factors. For the energy sector, universal risk categories can be defined according to [138, 211]:

1. Technical Risk
   a) Topological Risk
   b) Operational Risk
2. Economic Risk
   a) Price Risk
   b) Technical Risk
   c) Financial Risk

The uncertainties identified in the previous planning process of the district energy system must then be described mathematically in the form of probability distributions in order to be used further. There are various approaches and whole textbooks on this process [212].

The subsequent **risk analysis** is carried out with an MCS. In the literature, a variety of alternative approaches, such as sensitivity analyses [213, 214] or SWOT analyses [211, 215], can be found, but here the MCS was chosen because of its high informative value and realistic modeling. A disadvantage is the high computing time and modeling effort. With the help of MCS, the influence of the individual risks is to be summarized and converted into an overall risk on the KPIs. The MCS is based on a scenario approach. Possible variable values are drawn from the probability distributions created in the risk identification using a random number generator and combined with other variables to form a scenario. In this way, thousands of scenarios are created, which are then calculated on an *oemof-solph* basis using the simulation tool presented beforehand combined with the *mcerp* package [216] for MCS. In post-processing, the resulting models are translated into the KPIs already known, which can then be statistically analyzed. The MCS is done in a *Python* based, holistic software solution, as can be seen in Figure 4.5. The exemplary graphical analysis of the distribution function of the economic KPI for different cases can be seen in Figure 4.6.

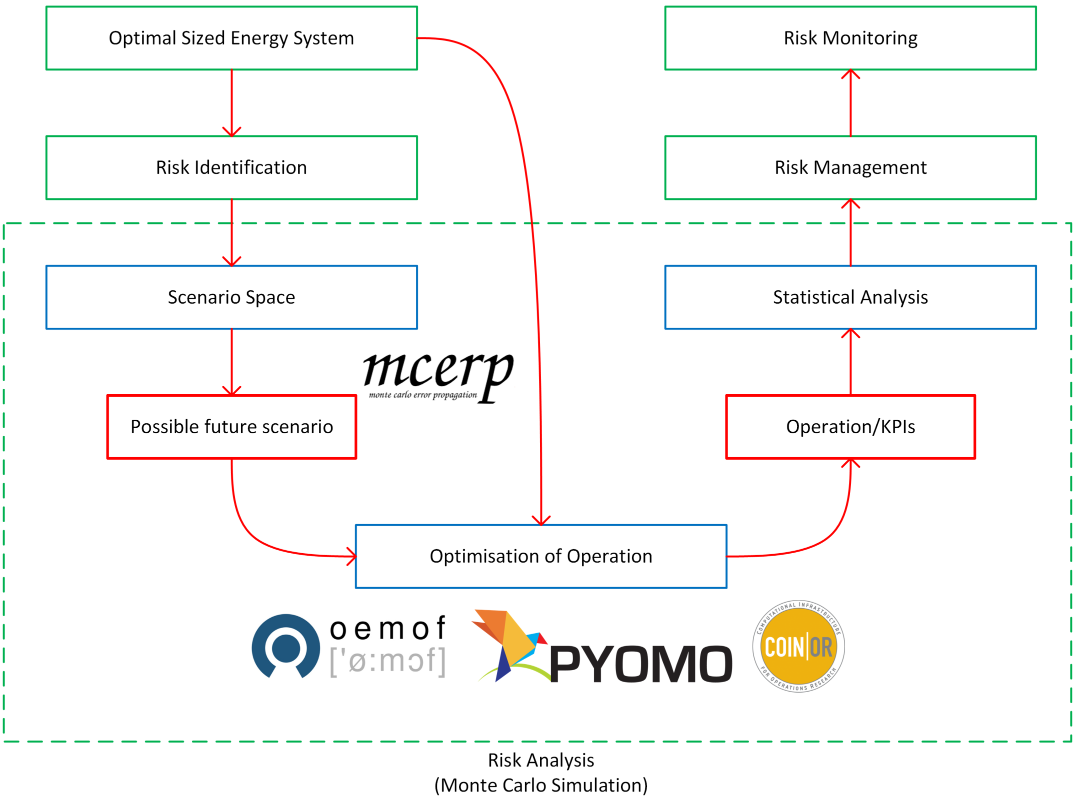


Abbildung 4.5: Flow chart of Monte Carlo based risk analysis of the optimized energy supply scheme. Here, too, the interaction of the selected software solutions is shown in particular, which is also realized in Python.

The overall risk per KPI calculated in this way and in particular the correlation between total risk and individual risk can then be used in the next step, **risk management**, to find out which risk

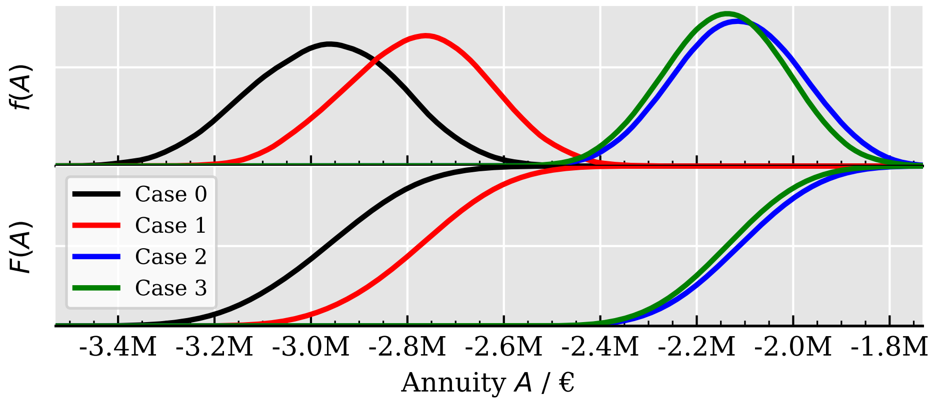


Abbildung 4.6: Presentation of exemplary MCS-based risk analysis results generated by the described methodology. The statistical analysis of the economic KPI as an annuity according to VDI 2067 for four different design alternatives can be seen, which differ both in the average expected result and in their distribution around this point.

factor has the most significant influence on the overall risk. Thishelps to develop countermeasures at an early stage that occur when certain external risk factors change.

The concluding **risk monitoring** determines how the overall system must be monitored in the future based on the previous results. This is essential in order to be able to react as quickly as possible to changing external risk factors and control their impact on the overall system better.

The results of the risk analysis are crucial for further decision making for a certain energy system. Decision-makers will prefer an overall concept that looks good at first glance but is burdened with a high overall risk only in exceptional cases with a lower-risk system.

4.6.5 | Investment Decision and Construction

After the modeling, simulation, and optimization effort, a decision must be made at the end of the design phase as to which energy system is to be implemented. The final decision is mainly made in cooperation between the energy utility company and the real estate developer, taking into account all previously generated results and the interests of all other involved stakeholders. This then leads to an energy supply contract between those two. Especially at this point MCDA (cf. Section 4.4) should be used.

After successful contract negotiations and signing, construction of the supply concept can begin. In addition, approval processes and other bureaucratic efforts still have to be considered at this point, but these were already taken into account as far as possible in the description of the boundary conditions (Section 4.5.2).

This final decision has not yet been taken in the *ENaQ* at this stage and the construction of the supply concept has therefore not yet begun.

4.7 | Operation Phase

After the supply concept has been successfully implemented on-site, the operating phase begins with its own challenges. Only at this point can contact be made with the real residents, since the district usually will only be moved into at this time. This also means that it is only at this point that it is possible to work out with the residents how they envision their optimal energy system. The supply concept must be as flexible as possible in order to respond to certain wishes. This can mean, for example, that the focus between economy and ecology shifts again. In order to respond flexibly to these wishes, a local energy market is planned in *ENaQ*, which will find an optimal operating result for all players on the basis of a market design still to be determined.

4.7.1 | Local Market Design

One of the overriding objectives of the *ENaQ* project is to enable energy trading between residents, e.g., to establish a local energy market. Although the use of a local energy market, e.g., in a residential area, is often described in the scientific community [217–220], real-world implementation under market conditions is difficult. Historically, energy law has been designed for a centralized top-down supply of electricity. Modern approaches, such as energy trading between neighbors, often have difficulties integrating into this existing legal framework. Nevertheless, there are certain legal provisions, at least in the German legal framework, which make neighborhood energy trading possible, at least on a small scale. *ENaQ* tries to make the best possible use of German legislation. The original goal was to establish a direct Peer2Peer energy trading. This is very difficult under current conditions. The decision was therefore made to trade Peer2Peer via an intermediary, the so-called "district aggregator". The district aggregator has the task of setting up energy trading within the district and ensuring that everything runs smoothly. A double-sided auction between producers and consumers (e.g., [221–223]) is currently being considered for optimized energy pricing in the district, but this has to take place completely automatically in the background as far as possible and without direct involvement of the residents. This procedure should ensure an optimal result for all parties involved.

4.7.2 | Operation Strategy

The operating strategy of the technical infrastructure is a direct result of events in the local marketplace. Currently, it is planned to optimize flexible producers and storage facilities in *oemof-solph* as well. The optimized schedules calculated there are then to be sent via a standardized gateway to all controllable plants and run there under certain boundary conditions. Similar approaches already exist at [224–226] but the *ENaQ* idea goes beyond this. *ENaQ* integrates the electricity, heat, and mobility sectors into a common consideration of optimality, takes into account the changing legal and economic boundary conditions, and dynamically adapts to the wishes of the residents. This involves completely new challenges, especially in the real world interaction of the various actors, which will be examined and discussed in more detail within the project and other publications.

4.7.3 | Maintenance

In the ongoing operation of the energy supply concept, maintenance also plays a major role, as it shifts the optimum operating point found in the design phase by making some system components unavailable. However, maintenance is essential to ensure the long-term profitability and secure operation of the supply concept and thus to meet key stakeholder KPIs.

In the literature there is work on how to implement a predictive maintenance strategy based on complex algorithms in order to keep downtime and associated suboptimal system states as short as possible [227, 228]. A similar approach is also envisaged in the *ENaQ* project.

Since topological risk has already been taken into account in the risk assessment of the design phase (Section 4.6.4), it can be assumed for the presented decision-making framework that the effects of maintenance work on the KPIs and thus the satisfaction of the stakeholders should be minimal. During operation, a loss of individual components is immediately logged in the previously discussed operation strategy. Due to the hybrid character of the supply concept, it can still switch to the next best operating condition.

4.8 | Results, Research Gaps, and Future Work

The decision-making framework developed shows how multifaceted and interdisciplinary the planning of distributed supply infrastructure can be. The presented framework has the great advantage that it uses standardized processes and tools, which can thus provide transparent and objective decision-making aids. Although many aspects of the planning and decision making process shown here have already been described and tested in the literature and examined in detail as shown, the interaction of the various aspects poses particular challenges that entail additional research and development work. This is mainly due to the inherent interdisciplinary approach, which combines natural sciences with engineering, social, and economic sciences, and the complex boundary conditions to make the planning process as realistic as possible. In addition, the high computational effort and the complex modeling, which is often based on previous detailed studies, are obstacles in the implementation of such a holistic planning process. In order to develop the decision-making framework in its entirety, a suitable case study is also needed, which can be scientifically accompanied and examined from the first rough concept to the final operational phase. The *ENaQ* project offers the rare opportunity to develop such a framework through the long-term involvement of various partners from research and industry.

The following is a list of further development topics for the successful implementation of the methodology, which, however, does not claim to be exhaustive but will become more concrete in the further course of the project. In the future there will be publications from the consortium on selected topics of this list, but the international scientific community is also called upon to contribute to these problems

- Novel business models for the energy system coordination
- Calculating heat grid behavior from GIS data
- Using the district on national or regional flexibility markets
- Exergetic heat storage modeling
- Modeling of the time-resolved spec. CO_2 emission
- Measurement Concept for distributed generation under German regulation
- Demand Side Management capabilities of districts
- Influence of incentives of the residents (e.g., dynamic pricing)
- Alternative plant deployment planning
- Calculating roof shading from architectural models
- District energy cooperatives
- IoT usage for energy system operation
- ...

4.9 | Conclusions

The conception of a distributed, cross-sector energy supply concept requires a standardized, automated, flexible, and objective planning process, especially in complex actor structures, in order to provide the best possible support to the decision-makers.

Such a planning process, which is to a large extent based on modeling and simulation tools, was presented in this publication in its structure and design. A district planned on the former airbase of Oldenburg was used as a case study, which is to be converted into a living lab in the next few years as part of the "Energetisches Nachbarschaftsquartier Fliegerhorst Oldenburg" (*ENaQ*) research project. This was presented in detail in Section 4.2.

In Section 4.3, the basic planning and decision-making approach was first presented, which is divided into four phases.

The first phase, targeting, in Section 4.4 deals with creating a common understanding of optimality between stakeholders.

In the synthesis phase (Section 4.5), every conceivable technology is collected in an extensive list. This is then shortened, taking into account the various boundary conditions, until a list of conceivable and realistically applicable technologies is obtained. The individual technologies are then combined in a superstructure and the interaction of the supply concept is created.

In the Design phase (Section 4.6) an optimal sizing process based on *oemof.solph* and *pygmo* is used, which optimizes the size of each technology under consideration of the common idea of optimality and the multi-layered boundary conditions. In order to quantify the inherent uncertainty, the design phase is supplemented by a Monte Carlo based risk analysis. At the end there is the finished technology pool, which can then be realized on site.

The planning process ends in Section 4.7 with the operation phase. This is about the specific control of the interaction of technologies and dynamic optimization to achieve the goals set at the very beginning. This also takes place simulation-based and using innovative approaches such as local energy markets.

The planning process presented here has already been designed in its entirety, but there are many partial aspects that have not yet been sufficiently specified, validated, and researched. Some research gaps are therefore briefly listed in Section 4.8.

In conclusion, it can be stated that the planning of a new modern energy supply concept involves a large number of decisions but that these can be made objectively and comprehensibly with a consistent planning process. The involvement of all stakeholders and the extensive use of energy simulation tools is extremely helpful in this context.

Author Contributions: Conceptualisation and methodology: L.S., P.S., P.K. and B.H.; modelling: P.S. and L.S.; software development: L.S., P.S. and S.W.; writing–original draft preparation, L.S.; writing–review and editing, S.W., P.K., and P.S.; project-administration, P.K.; supervision, B.H. and C.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Federal Ministry for Economic Affairs and Energy (BMWi) and the Federal Ministry of Education and Research (BMBF) of Germany in the project ENaQ (project number 03SBE111).

Acknowledgements: The authors thank all the other ENaQ project partners for support, inspiration, and fruitful discussions.

Conflicts of Interest: The authors declare no conflict of interest.

5 | Planning, Optimisation and Evaluation of Small Power-to-Gas-to-Power Systems: Case Study of a German Dairy

The content of this chapter is identical to the following journal article:

Schmeling, L.; Buchholz, A.A.I.; Heineke, H.; Klement, P.; Hanke, B.; von Maydell, K. Planning, Optimisation and Evaluation of Small Power-to-Gas-to-Power Systems: Case Study of a German Dairy. Sustainability 2022, 14, 6050. doi:10.3390/su14106050

Article

Planning, Optimisation and Evaluation of Small Power-to-Gas-to-Power Systems: Case Study of a German Dairy

Lucas Schmeling[1,2,*,†], Alexander August Ionnis Buchholz [3], Hilmer Heineke [3], Peter Klement [2], Benedikt Hanke [2], Karsten von Maydell [2]

[1] KEHAG Energiehandel GmbH, Im Technologiepark 4, 26129 Oldenburg, Germany
[2] DLR Institute of Networked Energy Systems, Carl-von-Ossietzky-Str. 15, 26129 Oldenburg, Germany
[3] New Power Pack GmbH/Kopernikusstraße 23, 49377 Vechta
* Corresponding author: lucas.schmeling@dlr.de; +49 441 99906-536

[†] Current address: Lintas Green Energy GmbH, Alter Stadthafen 3b, 26122 Oldenburg, Germany.

Received: 17 March 2022 / Revised: 1 May 2022 / Accepted: 10 May 2022 / Published: 16 May 2022

Abstract: In the course of the energy transition, distributed, hybrid energy systems, such as the combination of Photovoltaic (PV) and battery storages, is increasingly being used for economic and ecological reasons. However, renewable electricity generation is highly volatile, and storage capacity is usually limited. Nowadays, a new storage component is emerging: the Power-to-Gas-to-Power (PtGtP) technology, which is able to store electricity in the form of hydrogen even over longer periods of time. Although this technology is technically well understood and developed, there are hardly any evaluations and feasibility studies of its widespread integration into current distributed energy systems under realistic legal and economic market conditions. In order to be able to give such an assessment, we develop a methodology and model that optimises the sizing and operation of a PtGtP system as part of a hybrid energy system under current German market conditions. The evaluation is based on a multi-criteria approach optimising for both costs and CO_2 emissions. For this purpose, a brute-force-based optimal design approach is used to determine optimal system sizes, combined with the energy system simulation tool *oemof.solph*. In order to gain further insights into this technology and its future prospects, a sensitivity analysis is carried out. The methodology is used to examine the case study of a German dairy and shows that PtGtP is not yet profitable but promising.

Keywords: hybrid energy system; energy system simulation; hydrogen storage; multi-objective optimisation; Pareto front; sensitivity analysis; optimal dispatch; oemof.solph

5.1 | Introduction

The supply of electricity and heat to businesses is changing. Driven by climate change and the finite nature of fossil resources, the expansion of renewable energy generation is leading to a strong decentralisation of energy production. Companies no longer obtain energy exclusively via national energy grids from large power plants but generate electricity, e.g., with Photovoltaic (PV) systems on their own roofs. In order to be able to optimally cover the demand for energy at any time, different energy generators and storage facilities are combined to form so-called Hybrid Energy System (HES) [41]. These can be defined as systems combining "two or more energy conversion devices (e.g., electricity generators or storage devices), or two or more fuels for the same device, that when integrated, overcome limitations that may be inherent in either" [41].

A classic hybrid system, for example, is the combination of a PV system and battery storage. Here, the limitation due to the volatility of the PV power generation is complemented by the intermediate storage in the battery. Battery storage systems are short-term storage devices that store electricity for only a few hours or days due to their usually low storage capacity and energy density. However, in order to make better use of the locally generated electricity, the surplus summer generation from renewable sources would have to be made usable in late winter via a long-term storage facility.

A promising form of long-term storage for excess local electricity is the Power-to-Gas-to-Power (PtGtP) technology [229, 230], in which electricity is converted into hydrogen via an Electrolyzer (ELY), stored in a Hydrogen Storage (HS) and, if required, converted back into electricity via a Fuel Cell (FC).

In politics, the topic of hydrogen has taken on an important role in the decarbonisation of the economy. In the context of the G20 summit in Japan (2019), the International Energy Agency has published a report to show the current status of hydrogen and provide recommendations and guidelines for its future development [231]. The report notes that clean hydrogen is currently experiencing political and economic momentum, and that the number of strategies and projects around the world is increasing dramatically. The report concludes that the technology needs to be expanded and costs reduced in order for hydrogen to be used on a large scale.

Each country is pursuing different strategies and intermediate steps to achieve long-term decarbonisation. Some countries' strategies, such as those of the EU, are based on the assumption that hydrogen will be produced entirely from renewable energies [232, 233]. In addition, countries such as Germany aim to import renewably-produced hydrogen from countries with more hours of sunshine—for example, Africa—in order to meet future demand [234]. Other countries such as China are equally striving to produce green and blue hydrogen [235, 236].

However, the question must be asked how mature the systems already are for use, what the market chances of such systems look like today, and when a nationwide installation of such systems can be expected. The scientific literature on this is still relatively sparse and has so far focused primarily on the development of the technical components and integration into off-grid systems. For the market ramp-up of PtGtP, there is a lack of detailed analysis of both the valid legal framework and the resulting economic and environmental friendliness. However, this can and must of course be done in close dependence with the technological performance and thus, as a first step, with a realistic techno-economic model of such an HES. In order to address this research gap in more detail and thus provide a better insight into the market ramp-up, we examine the case of a dairy under German conditions that come as close as possible to actual conditions. We initially focus on a small PtGtP system in combination with a common HES. Our intention is to enter the market with a small system as an add-on option to existing systems and thus achieve significant economic and ecological advantages. The main contributions of the publications can therefore be summarised as follows:

- Identification of the relevant current economic and regulatory market conditions in Germany;
- Technical modelling of a PtGtP plant based on data sheets of different manufacturers;
- Linking of all relevant technical components in an established open-source energy system modelling tool (*oemof.solph*);
- Development of a multi-criteria and objective evaluation metric for assessing the use of PtGtP in existing HES;
- Optimal sizing of all relevant technologies for a case study with a brute force approach;
- Analysis of future viability using a sensitivity analysis.

For our study, we proceed as follows: first of all, Section 5.2 presents a detailed literature review of the current state of research on HESs using hydrogen. In Section 5.3, an energy system simulation and optimal sizing framework are presented. This framework is used in Section 5.5 to analyse the case study of a dairy in Oldenburg, Germany, which is briefly introduced in Section 5.4. The results are discussed in Section 5.6, and the next steps are summarised in Section 5.7.

5.2 | Related Work

As outlined above, the integration of hydrogen-based electricity storage in HESs is currently being researched for a variety of reasons. The focus of research has shifted significantly in the last years from mainly technical proof-of-concept studies to economic feasibility and sustainability analyses and finally to analyses of market introduction. We would like to give a brief outline of the relevant literature on this topic in order to be able to frame our research interests.

Vosen and Keller [237] mentioned that the hybrid storage options, in which hydrogen and battery storage were used, were already investigated in the 1990s. In their study, they investigated the combination of PV, PtGtP (ELY, metal hydride tank and FC), and battery storage via a possible residential design in Arizona, USA. They utilise an algorithm that is programmed so that, over time, the program learns to use system resources more efficiently by adjusting the energy storage strategy to fluctuations in power generation and demand. They concluded that, using the algorithm, the cost of storing energy for the HES is 48 % of the cost of a hydrogen-only storage option and 9 % of the cost if the storage option were battery only. In addition, this algorithm results in cost savings of 30 % of the storage components compared to a simple state of charge algorithm. They also found that the cost of storage in a DC system is 70 % bis 85 % of the cost of an AC system. The sensitivity study shows that the greatest effects of hybrid system cost reduction are the increase in efficiency of energy conditioning and the reduction in the costs of battery, PV, HS, and energy conditioning. The algorithm uses storage components more efficiently, resulting in lower storage costs.

Bocci et al. [238] also investigated in 2011 an HES for a 100 m^2 two-person residential house in Italy (Rome), in which a combination of PV, solar thermal, and PtGtP (ELY, metal hydride tank and FC) is used. In addition, the house was newly insulated, and all electric appliances were replaced with more energy-efficient equipment. Radiators were replaced with radiant heating systems, and the existing heat pump was replaced with an absorber, as the global efficiency for cooling needs in summer was higher than that of the PV and heat pump combined with solar thermal and an absorber. The study shows that it is possible to reduce the maximum electrical and thermal output as well as the total energy consumption to one third. The hydrogen supply should be a safe and reliable power supply system. While the installation costs are 10 times higher than those for batteries or generators, this system is well suited for long-term storage.

Another algorithm that minimizes the total system costs based on various assumptions is used by Gillessen et al. [239], who conducted a case study for a hybrid ELY/battery system in the range of 0.5–3 MW directly coupled to a large PV power plant without grid connection. They investigated the hydrogen production costs of alkaline ELY with different battery types (lithium-ion, vanadium redox flow, zinc–bromine redox flow). They concluded that batteries can adequately support ELY operation but are associated with higher hydrogen production costs and are not competitive compared to the installation of additional ELY capacity or electricity savings. However, if 100 % renewable energy is desired, the installation of a hybrid battery system with a mixture of different battery types is desirable as it is more cost effective for storage than a solution with only one battery type. The factors that result in this benefit include the ratio of battery capacity to performance and the associated differences in performance and the capacity-specific investment of the different battery types.

Nguyen et al. [240] investigate the energy supply of a wastewater treatment plant. Electricity is generated by PV and wind turbines and may be stored temporarily in a battery storage and PtGtP system if necessary. They use economic, environmental, and reliability indicators for optimisation. They applied the fuzzy-TOPSIS optimisation methodology to six different configurations and found that this storage combination resulted in a satisfactory reliability value with good emissions and costs.

As an alternative to the battery as short-term storage, a supercapacitor can also be used. This is what Luta and Raji [241] investigate using an industrial consumer in South Africa without a grid connection. For this purpose, they use the HOMER PRO software, which allows such systems to be modelled and evaluated easily. The main supplier, with over 98 %, is the PV plant buffered by the supercapacitor, while only 2 % comes from the FC. However, the hydrogen system, especially the storage, accounts for a large part of the costs. Through a sensitivity analysis, they underline the conclusion that it is mainly the cost of the hydrogen system that is problematic.

Further alternative storage technologies for renewable energies are investigated by Yazdani et al. [242]. They are investigating compressed and liquid air as well as hydrogen storage. They use it to store 8 hours of production from a large wind farm and compare the energy used. Here, the hydrogen storage has the highest energy efficiency.

Similar topics on HES with PtGtP can be found in further literature [53, 243–246]. In the past, authors focused heavily on technical feasibility and optimisation. They pursued the operating strategy of covering the demand in a self-sufficient manner. They largely agreed that hydrogen, in combination with other technologies, makes the overall system more energy-efficient and is very well suited as a long-term storage medium. However, it was often pointed out that such systems are currently associated with very high additional costs, which, according to the authors, should change in the near future through market penetration, political will, and technical development.

This paper therefore asks the question whether this point has already been reached under the current German market conditions, or how far away it still is. This question is presented and examined using the example of a dairy, but the approach could also be applied to other nations and industries. Furthermore, the effects on the emissions of this consumer are estimated. The hope is that climate-damaging emissions can be saved through more efficient local energy use. We focus on relatively small PtGtP systems, in which we see several advantages: on the one hand, we think that a small, and thus optimally utilised, system can have the greatest effect and thus convince potential users to install larger systems in the long run. On the other hand, we believe that such systems make sense as add-ons to existing HES in order to make them more flexible. Therefore, the space requirement must be as small as possible (here, no more than a small shipping container). Finally, well-established individual components are already available in this power class, which should reduce costs and improve availability.

5.3 | Methodology

HESs are complex in both planning and operation. Detailed analyses and methodologies are required to achieve an overall system behaviour that is worthwhile for the stakeholders involved [247]. According to Schmeling et al. [132], the general planning process for distributed energy supply solutions is divided into four phases.

The planning process starts with the determination of the objectives to be pursued (**Targeting**). These can be of a technical, economic, or ecological nature and have to be quantifiable and comparable. In the second phase (**Synthesis**), all necessary and conceivable technologies are connected to the consumer in unspecified sizes, resulting in a so-called superstructure. In the third phase (**Design**), different sizes and combinations of technologies are tested in the superstructure in order to minimise or maximise the previously defined objectives. In this process, it is decided which technologies from the superstructure are useful or not. The final step (**Operation**) is to define the operational management of the system actually installed on site and to ensure that the system runs as optimally and reliably as possible.

We focus on the first three phases, as these can give us a realistic assessment of the current market situation. The operational phase can only be evaluated and demonstrated on a real system, which of course requires a successful outcome of the first three phases. The first three phases are explained below.

5.3.1 | Targeting

Optimality is always in the eye of the beholder but must be precisely defined for a successful, objective evaluation of technical systems [132]. The associated decision-making problem often cannot be broken down to a single factor, but there are different perspectives [150]. For HESs in particular, there is usually a conflict of objectives between costs, environmental impact, and technical feasibility, which have to be considered together but are usually impossible to directly compare. This problem can be addressed by carrying out a Multi-objective Optimisation (MO) [240, 248, 249].

In general mathematical terms, the subsequent MO problem can be described as follows [250]:

$$\min\left(F\left(x\right)=\left(f_1\left(x\right),f_2\left(x\right),...f_{\mathrm{N}}\left(x\right)\right):x\in X\right) \tag{5.1}$$

where x describes a possible solution vector of the solution space $X\subset\mathbb{R}^M$ with M different degrees of freedom, which is mapped to N different objectives using function $F:\mathbb{R}^M\mapsto\mathbb{R}^N$ [250]. Whether minimisation or maximisation is carried out is irrelevant, as $\min\left(F\left(x\right)\right)=\max\left(-F\left(x\right)\right)$.

In the end, MO seeks solutions that are in one way or another better than alternative solutions; i.e., it is not possible to improve one objective function without simultaneously worsening another [251]. Such a solution is called Pareto optimal. Mathematically, this means that for a conceivable solution $\hat{x}\in X$, there is no other solution $x\in X$ for which $f(x)\leq f(\hat{x})$ in the case of a minimisation. The totality of all Pareto optimal solutions form the Pareto front, which in its completeness is the optimal solution of the MO. Within the context of the research question, the Pareto front contains all optimally sized energy systems and is thus the basis for the subsequent decision-making process.

As described, the integration of a PtGtP system is expected to have both economic and ecological advantages. Therefore, the following objectives, which are common in the evaluation of HESs, are used for the further investigation: the annuity according to VDI 2067 [179] and the CO_2 emission. These are motivated and specified in more detail below.

5.3.1.1 | Economic Evaluation The goal of companies usually is to generate as much profit as possible at low cost [252]. From a business management point of view, it is important to cover both the company's energy requirements and to achieve this at the lowest possible cost [253].

In order to keep the calculation of the techno-economic evaluation of the supply concepts as simple and comparable as possible, the calculation in this paper is based on the annuity method of the

German engineering standard VDI 2067 [179]; the following formulae are derived straight from this standard. The annuity is a repeated annual payment of equal amount, which is required to pay off a system over an observation period. The period under consideration in this case is set at 20 years, as this corresponds to the expected useful life of the PtGtP system. The expenses are divided into capital-related costs ($A_{\mathrm{N,K}}$), demand-related costs ($A_{\mathrm{N,V}}$), operation-related costs ($A_{\mathrm{N,B}}$), and other costs ($A_{\mathrm{N,S}}$). In addition, the revenues from the sale of energy or from the use of government support measures are added to the calculation and are included in the revenues ($A_{\mathrm{N,E}}$). The annual annuity (A_{N}) is calculated from the difference between the revenues and the sum of all cost categories:

$$A_{\mathrm{N}} = A_{\mathrm{N,E}} - (A_{\mathrm{N,K}} + A_{\mathrm{N,V}} + A_{\mathrm{N,B}} + A_{\mathrm{N,S}}) \tag{5.2}$$

The annuities of the individual cost categories X result from the costs of the first year A_{X1} multiplied by an annuity factor a and a price dynamic cash value factor b_X, which in turn depends on an interest factor q and a price change factor r:

$$\begin{aligned} A_{\mathrm{N},X} &= A_{X1} \cdot a \cdot b_X \\ &= A_{X1} \cdot \frac{q^T \cdot (q-1)}{q^T - 1} \cdot \frac{1 - \left(\frac{r_X}{q}\right)^T}{q - r_X} \end{aligned} \tag{5.3}$$

According to this method, the energy supply solution with the highest annuity should be realised. In the industry, energy is usually considered a necessary part of the production process, which is why it is not explicitly remunerated, unlike in the housing sector. This usually results in negative annuities, the highest of which is then preferred.

5.3.1.2 | Ecological Evaluation In recent years, environmental awareness has become increasingly important for people in Germany [254]. At the same time, the economic valuation of greenhouse gas emission is receiving more attention. CO_2 is mainly produced in the energy production process, which is passed along the supply chain to the final consumer. In order to achieve the climate targets, CO_2 balancing is necessary as it gives consumers or planners of HESs the opportunity to design climate-friendly behaviours [255].

The CO_2 emission of the energy supply solution is calculated using a balancing boundary approach as described by Wehkamp et al. [256]. Boundaries are drawn around the supply object and specific emission intensities (CO_2 emission per kWh) are assigned to energy carriers flowing either into or out of the system, which are in this case Natural Gas (NG) (only in) and electricity (in and out). Solar radiation as the energy carrier of PV is assumed to be emission-free, just like environmental heat. Since it is assumed in the following that hydrogen is neither exported nor imported, it is not to be considered as an energy carrier in this regard. Thus, only the operating phase of the system is considered here; emissions from the construction or demolition of the system are not taken into account. An emission intensity of 202 g CO_2/kWh is applied for NG [257]. For electricity purchase $E_{\text{Elec}}(t)$, which has a time-varying composition of different energy sources with different emission intensities, a flow tracing method is used to calculate hourly emissions $S_{\text{Elec}}(t)$[178, 258]. In turn, CO_2 is credited by feeding electricity $E_{\text{Feed}}(t)$ into the public grid [259]. It is not the average German electricity mix that is displaced, but rather the marginal power plant [260]. The value of the emission is defined as the marginal emission, which when averaged over one year gives the displacement mix. This indicates the amount of CO_2 per unit of energy that does not have to be emitted at another place due to the substitution of the marginal power plant by the grid feed-in by the HES. According to a forecast from 2014, the displacement mix in Germany is expected to be 810 g CO_2/kWh in 2020 [261]. A more accurate and up-to-date value cannot be found here due to the complexity of the European energy market. For this reason, no temporal progression can be assumed here; however, the variability should also be significantly lower here, as the marginal power plants are usually base-load power plants.

Thus, the following formula is used to calculate the annual CO_2 emission C_{Total} of the energy supply solution:

$$
\begin{aligned}
C_{\text{Total}} = \sum_{t=0}^{T} & 202 \frac{g\ CO_2}{kWh} \cdot E_{\text{NG}}(t) + S_{\text{Elec}}(t) \cdot E_{\text{Elec}}(t) \\
& - 810 \frac{g\ CO_2}{kWh} \cdot E_{\text{Feed}}(t)
\end{aligned}
\tag{5.4}
$$

The relevant emission intensities throughout the year are shown in Figure 5.1.

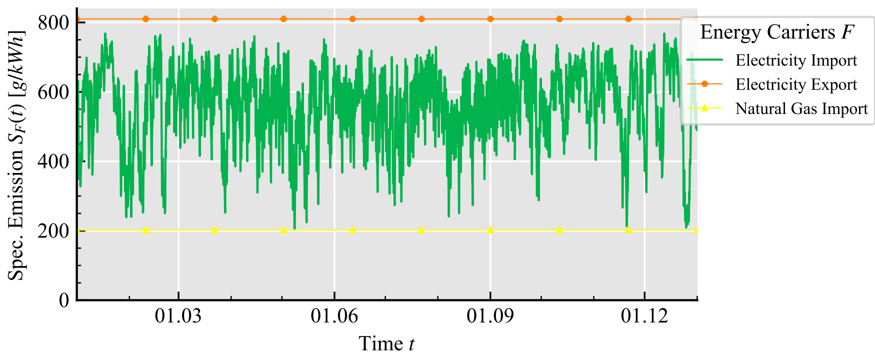


Abbildung 5.1: Time series of relevant emission intensities. All are constant except for electricity imports, which fluctuate due to the changing composition at the national level.

5.3.2 | Synthesis

In the next phase, the superstructures, i.e., the choice of technology and the connections between the technologies, are defined. The superstructure of the energy supply solution to be planned is then divided into different scenarios in order to be able to compare the effects of the innovative PtGtP plants with a state-of-the-art system.

Scenario 1 Figure 5.2 shows an energy supply concept that has been implemented in many industrial projects in Germany in recent years [262, 263]. It therefore serves as a reference for the innovative additional use of PtGtP. The scenario includes a PV system, a battery storage, as well as a condensing boiler and a Combined Heat and Power (CHP) with a mid-term Thermal Energy Storage (TES). Via access to the public electricity and NG grids, the necessary energy resources are available to the consumer. Depending on the market situation, electricity from PV and CHP can be used internally or fed into the grid. In addition, electricity from PV can be temporarily stored in the battery storage. The boiler is primarily used to cover the thermal load peaks that cannot be covered by the CHP. In addition, it serves as a backup should the CHP fail completely. The TES is used exclusively by the CHP. This leads to a decoupling of the electricity and heat generation, so that the CHP can run cost-optimised until the TES is completely filled.

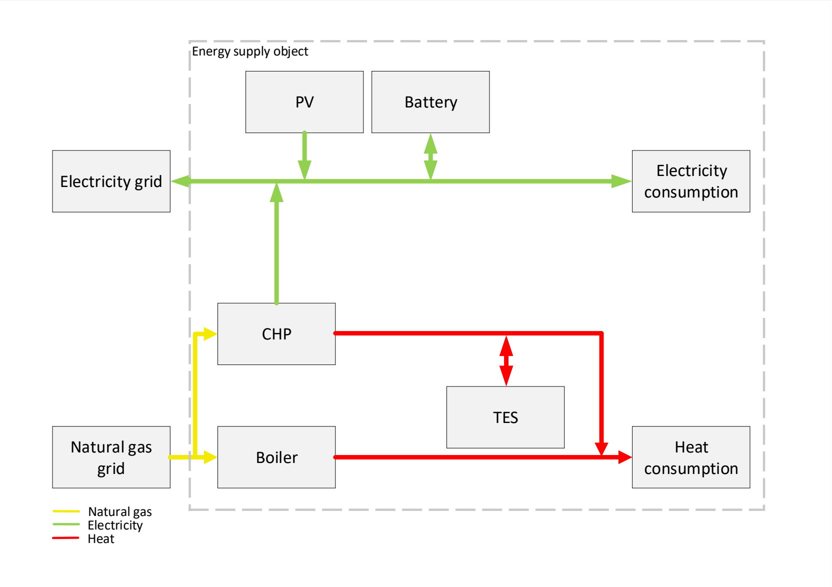


Abbildung 5.2: Scenario 1 with PV, battery, CHP, TES, and boiler. This is a common, distributed supply concept used by companies in Germany today and therefore serves as a reference.

The system is thus a perfect example of an HES. It combines the use of different technologies and energy sources, making it possible to choose the most suitable option at any given time in order to meet the required energy demand in the best possible way.

Scenario 2 In Figure 5.3, the hydrogen path, i.e., an ELY, compressed gas storage as HS and a FC, is added to the energy supply concept of scenario 1. In the model, it is allowed that the ELY can receive electricity from the different power sources. The ELY does not draw electricity from the battery, as German energy law makes it difficult in this configuration (cf. § 61l EEG). The hydrogen generated by the ELY has a pressure of 20 bar. It is fed into the HS tank without further compression and, if necessary, is used to generate electricity via the FC. The waste heat from the ELY and the FC is transferred to the heating system via heat exchangers to increase the overall efficiency and to use the TES to decouple electricity and heat generation. If the heat cannot be consumed, it is released into the air via a recooling system, which is exclusively used by the PtGtP system.

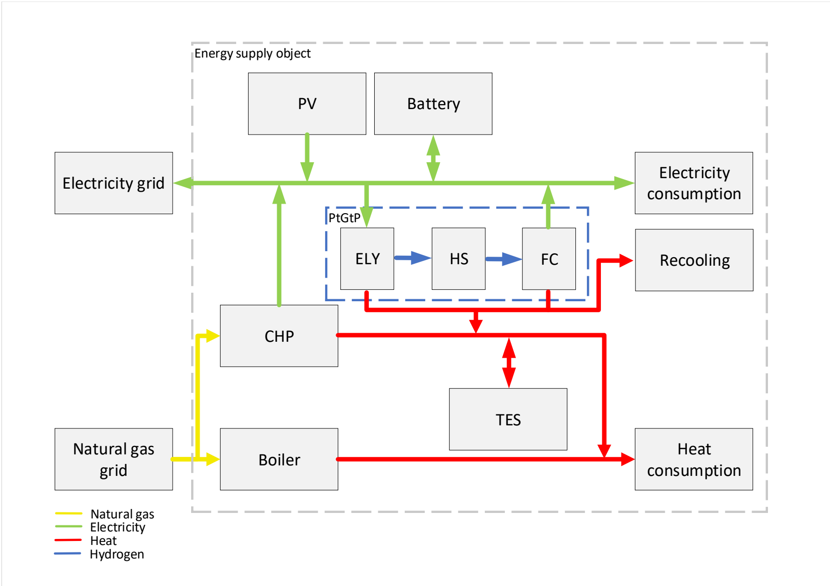


Abbildung 5.3: Scenario 2 additionally with an ELY, HS, and FC (PtGtP). The aim is to investigate whether the addition of the PtGtP plant provides an advantage over scenario 1.

5.3.3 | Design

There are various ways to determine how the optimum system configuration has to be designed for a given superstructure. In engineering, various methods and rules of thumb are known regarding how to successfully design certain systems according to experience. In such complex systems as the one described here, however, there are often no empirical values, and the conventional tools (mostly Microsoft Excel) are not sufficient to conduct reliable analysis. Therefore, it is necessary to find new methods that provide reliable results even in such systems. The process developed for this purpose is based on the modelling of the supply concept in a simulation software, which is then used to evaluate various technology combinations, known as optimal sizing [200]. In this way, the best possible combination and size of the technologies considered can be found that meet the previously defined objectives. The schematic process can be seen in Figure 5.4 and is explained below.

5.3.3.1 | Optimal Sizing In the scientific literature, various optimisation algorithms are used to dimension energy generation and storage technology. A detailed tabular overview of optimal sizing

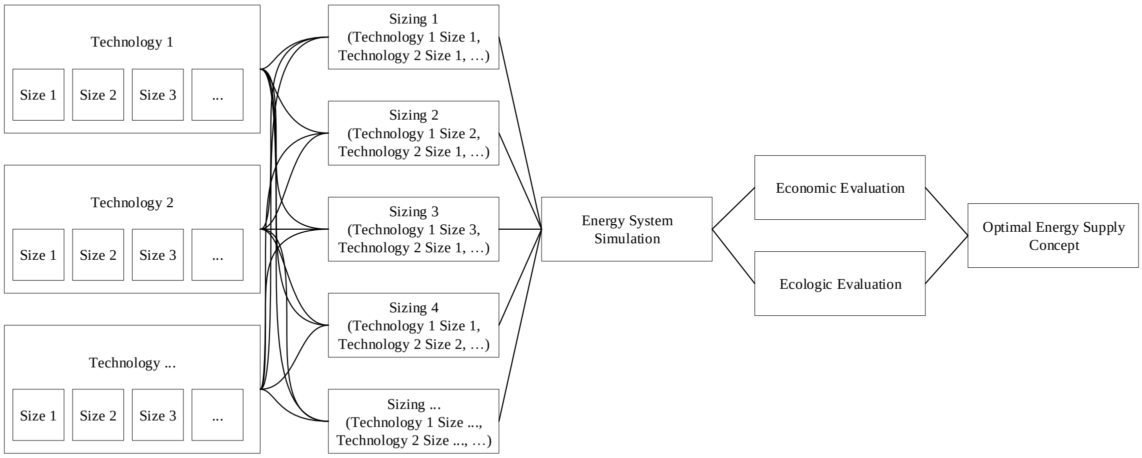


Abbildung 5.4: Procedure for determining the optimum sizes of the system. For this purpose, all possible system combinations are first simulated and then evaluated on the basis of the two objectives in order to be able to compare them holistically.

methodologies of on and off-grid HES can be found at Schmeling et al. [134]. A clear distinction can be made between single objective optimisation algorithms, which can usually be relatively simple, and multiobjective optimisation algorithms, which are more complex in their operation and resource requirements. A distinction can likewise be made between linear optimisers, which are used to solve highly simplified mathematical models, and non-linear optimisers, which can optimise models that are much closer to reality [264]. Because an MO is supposed to be carried out as close to reality as possible, the choice of a suitable approach is rather complex.

In addition, for most of the methods available for solving such problems, all components (degrees of freedom) must be modelled continuously in variable sizes so that it is possible for the optimiser to explore the search space continuously. This in turn proves to be difficult in practice, since no continuous plant sizes with standardised properties can be realised, but each manufacturer offers components in fixed sizes and different properties.

Since we want to be as close as possible to the components that are actually available, a brute force approach is chosen, which does not use intelligent optimisation algorithms to select the sizes but examines all conceivable sizes and combinations, regardless of their feasibility. In this way, the various components can be modelled as closely as possible to the manufacturer's technical specifications, but the computational effort of the simulation is significantly higher. Such an approach is possible here because the choice of technologies and also their size represent a relatively small solution space, which can be solved using modern computer technology and simulation tools.

5.3.3.2 | Energy System Simulation There are several studies concerning simulation software whose main task is to determine the optimal dispatch strategy for the combination of different energy-generating, storing, and consuming devices. Connolly et al. [167] compared 37 programmes in 2010 to investigate the integration of renewable energies into different energy systems. The aim was not to find the perfect software but to get an overview of the software and its individual advantages. Sinha and Chandel [265] examined 19 programmes using a hybrid, distributed energy supply concept. They came to the conclusion that, depending on the software, there are considerable differences in the simulation results. Schmeling et al. [168] developed a comparison methodology of different commercial simulation tools and find in the exemplary application to nine different tools that there are varying recommendations depending on the application case.

The software *oemof.solph* [266] is used for this publication. This open source tool offers the freedom to define new, innovative components, such as the PtGtP system, and to connect them with existing components such as CHP and battery storage. It also offers various options for defining high-resolution input data and analysing the results in detail. It is being continuously developed by a broad community and has already found application in a wide range of research questions (e.g. [267, 268]).

In *oemof.solph*, energy systems are represented as a directed graph, where the vertices represent either components (sources, sinks, technologies) or buses, which manage the resource flows between the components. The edges are directed and represent resource flows between certain components and buses. This graph is then translated to a Mixed Integer Linear Programming (MILP) problem using *pyomo* [269] that can be solved numerically by various solvers [186]. The objective is to minimise the costs caused by energy flows in the system while covering all energy demands. We therefore cannot, as in many other studies, present the operating strategy graphically, as this is calculated and optimised dynamically at each point in time. In this way, it is possible to exchange system components or framework conditions very easily.

Technologies such as transformers have inflows and outflows, e.g., the consumption of gas from a gas bus to a gas turbine, which then feed electrical energy into an electricity bus. Parameters such as efficiency can be used to determine the ratio of inflow and outflow. Sinks only have inflows and can represent consumers, e.g., electricity consumption in households. Sources include wind energy or PV systems, but also raw materials, and only have outflows. A graphical representation of the *oemof.solph* model used for scenario 2 can be found in Figure 5.5.

5.3.3.3 | Modelling the Hydrogen Technologies As mentioned in Section 5.3.3.2, the technologies in *oemof.solph* are modelled as vertices of the energy system graph. This chapter explicitly explains the procedure for modelling the hydrogen technologies, i.e., ELY, HS, and FC. All other components used are established technologies, and their modelling was carried out with usual processes in *oemof.solph* and is therefore not further presented here.

There are different types for both ELY and FC, which offer different advantages and disadvantages depending on the application. For the intended stationary use in industry, Proton Exchange Membrane (PEM) technology is used for both components of the plant. On one hand, the PEM ELY has the advantages of having no danger of oxygen contamination when operating it under low

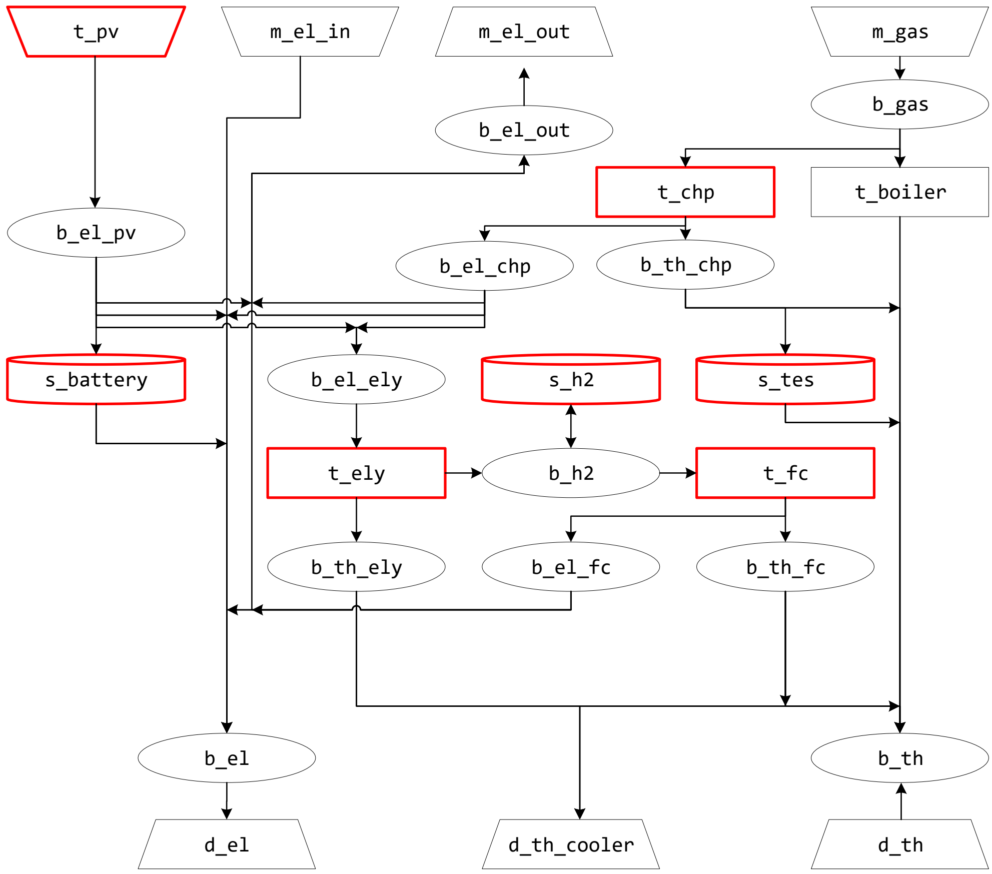


Abbildung 5.5: *oemof.solph* graph to simulate scenario 2, where buses are represented as ovals, sources and sinks as trapezoids, technologies as rectangles , and storage systems as cylinders. The nomenclature distinguishes between conversion technologies (t_), storages (s_), demands (d_), external markets (m_), and the necessary busses (b_). From this type of representation, it is thus easy to see the possibilities and directions of energy flows as well as the positioning of key sources, transformers, and sinks. Components to be optimally sized in the following are marked with a red outline.

partial loads and better management of fluctuating power generation than alkaline ELY. On the other hand, PEM has a significantly higher energy density (i.e., less floor space required and less material used) as well as greater modularity (e.g., with regard to the caustic preparation of the alkaline electrolysis plants). The PEM FC is uncomplicated in terms of its handling and is particularly suitable for a distributed energy supply, since the power output can be controlled with great dynamics [270].

The intended application is in very small performance classes so that the PtGtP system can be optimally integrated in small and medium-sized companies. For ELY, plants up to 5 kW_{el} are used; for FCs, up to 8 kW_{el}. These were obtained from appropriate manufacturers, and the data sheets were analysed accordingly. The data sheets are, of course, based on experiments as well as on the manufacturer's experience and are therefore particularly valuable for the intended examination under realistic conditions. The most relevant parameters are the electrical input and output, the thermal output, as well as the hydrogen production (ELY) and the hydrogen consumption (FC), respectively, both at full load, minimum partial load, and intermediate points. The resulting characteristic curves of hydrogen technologies can be found in Figure 5.6. As a good approximation, a linear behaviour between full load and minimum partial load is assumed. When modelling the two technologies, the *oemof.solph* CHP model (`GenericCHP`) with limited partial load behaviour (`back_pressure=True`) is chosen. Details on the modelling can be found in [271, 272].

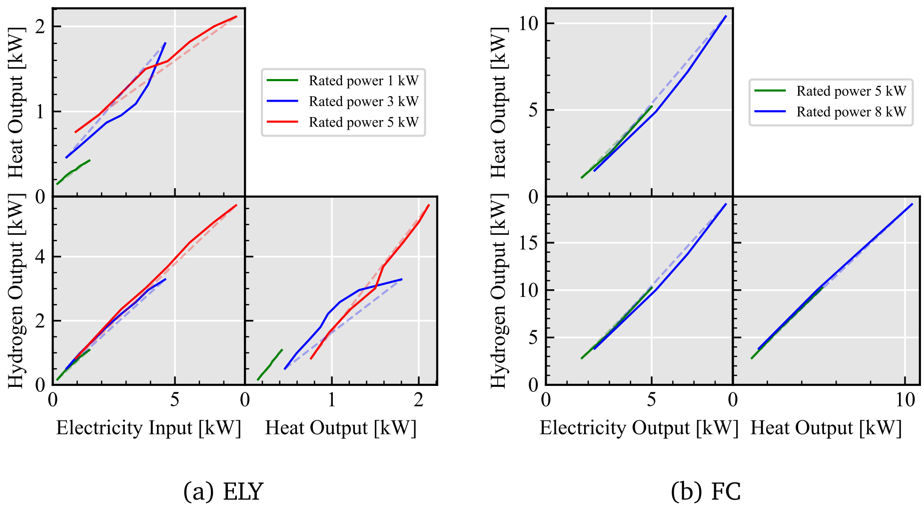


Abbildung 5.6: Characteristic curves of the ELY (**a**) and FC (**b**) based on the manufacturers' data sheets. For reasons of simplification, a linear behaviour between maximum and minimum load is assumed for the simulation, which is shown as dashed lines in the background.

Gas tanks are used as HS which have a storage capacity per tank of 12.6 m^3 each. The HS is modelled in *oemof.solph* as a generic storage (`GenericStorage`). The hydrogen is generated by the ELY, which is fed into the hydrogen storage tank without further pressure increase, and thus without any inflow losses. The FC is operated at the same pressure, which is why there are no outflow losses either. The storage capacity can be calculated by simple physics [273] and results in 670 kWh per tank at the set 20 bar. Compressing the gas would increase the energy content, but it would also significantly increase the electricity demand, which is why we do not consider it here. Instead, several tanks can be placed next to each other and the energy content scaled in this way. According to the manufacturer, the diffusion of the hydrogen through the wall is negligible, meaning that the storage losses can be assumed to be zero.

5.4 | Case Study

In order to be able to make a statement about the usefulness of the use of PtGtP under the current German market conditions, the method described above is used to examine an industrial consumer. The assumptions of the targeting and synthesis phase are adopted, and the optimisation of the design phase is illustrated.

In order to design and optimise this energy system, it is necessary to have detailed information on the energy demand of the energy supply object as well as the prices and remunerations that are applicable under the local energy law for the different energy flows.

5.4.1 | Energy Supply Object

A dairy is used as a case study, for which a location in Oldenburg, north-west Germany, is assumed. It is a medium-sized company that is organised as a cooperative and employs about 40 people. Milk is processed into various products such as butter, cream, and yogurt, for which electricity and heat are required in various places. In addition, several offices are supplied.

Electricity demand profiles are available as quarter-hourly data (599 MWh) and heat demand profiles as hourly data (1 050 MWh) for 2016, which are projected to 2020. The graphic evaluation of the energy demand is shown in Figure 5.7. On the load profile (in the background), it is clearly visible that both electricity and heat are demanded relatively constantly over the year. The load duration curve (in the foreground) represents the power demand in dependence on the utilisation time and is often used for the capacity planning of generation plants. Here, it can be seen that the electricity and heat demand must be provided in a wide range of capacities, whereby the heat demand usually exceeds the electricity demand. Such a configuration is very well suited for hybrid, CHP-based supply concepts.

For the installation of PV, the roof area of a gabled roof with a maximum of 200 m^2 at 30° inclination facing south is available. This corresponds to a maximum installed capacity of approximately 40 kW_p. The other system technologies are installed collectively in a machine room, so no further transmission losses have to be considered. Other electricity generating technologies such as wind power are not an option at this location due to neighbouring buildings. All data for modelling are

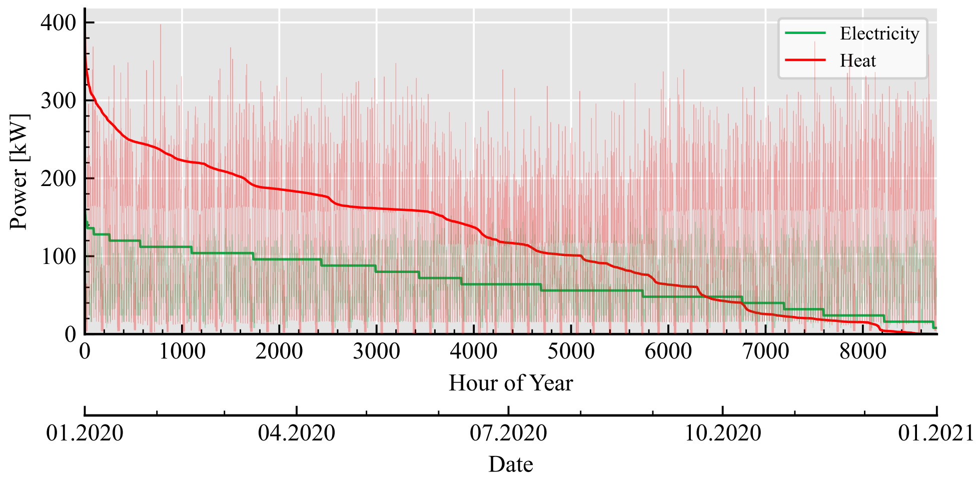


Abbildung 5.7: Energy demand as load curve and load duration curve of the dairy in 2020.

taken from real plant data sheets. However, the exact manufacturers cannot be named for non-disclosure reasons.

On the basis of this information, the maximum sizes of the variable technologies are defined, which can be seen in Table 5.1. For all plants except the PtGtP plant, zero is assumed as the minimum size in both scenarios. For the PtGtP plant in scenario 2, the minimum plant sizes are defined as the smallest possible value, so their presence is forced in order to see the effects of hydrogen integration. As mentioned, the boiler is also used as a backup for the CHP and must therefore be able to serve the maximum thermal load. Its size is therefore not optimised but instead determined based on this load plus a safety margin. On the electricity side, the grid connection is designed for the maximum electrical load with the same argument. This means that, in an emergency, the system can always be supplied with energy in this very stable and safe way and there are no interruptions in production.

Tabelle 5.1: Discrete sizes used in optimisation of the technologies. These correspond to the actual products of selected manufacturers.

Technology	**Performance Spectrum**
Boiler / kW_{th}	500
CHP / kW_{el}	0, 50, 70, 99, 134, 190
PV / kW_p	0, 10, 20, 30, 40
TES / m^3	0, 10, 30, 50
Battery / kWh	0, 30, 70, 131, 233
ELY / kW_{el}	1, 3, 5
HS / kWh	670 , 1 340
FC / kW_{el}	5, 8

This then results in 6 CHP × 5 PV × 4 TES × 5 battery × 3 ELY × 2 HS × 2 FC = 7200 different energy systems using all possible technology combinations in scenario 2, which then have to be simulated and evaluated accordingly. However, there were also some energy systems that could not be calculated because they are not technically possible. For example, a large CHPs must be equipped with a TES. These energy systems are therefore discarded in simulation. The same applies to storage technologies whose producer is missing. Thus, if no CHP and PV is planned, there is also no TES or battery storage needed.

5.4.2 | Energy Prices, Taxes, and Allowances

In order to be able to determine the costs of the energy supply solutions in the simulations, the energy flows between the vertices have been assigned with prices, taxes, and remuneration. These are based on the German legislation and market situation as of 2020. Electricity and NG prices in Germany vary from region to region due to different grid usage fees and concession fees; here, those of Oldenburg are chosen, which are relatively inexpensive compared to the rest of Germany. The procurement of residual electricity is considered to be purchased entirely on the German spot market, the EPEX SPOT, and there are no long-term supply contracts. These variable procurement costs make the HES particularly advantageous, as it can react dynamically to external incentives. NG, on the other hand, is purchased at an annual fixed price, as spot market procurement is very unusual and not easy to implement due to the metering infrastructure. Table 5.2 shows the prices or remuneration of the technologies' links to each other in the supply object.

Tabelle 5.2: Price range of the technology paths in ct/kWh of the dairy as of January 2020. These are given as a price range, since in the course of the simulations, the prices change constantly depending on how, for example, the day-ahead price changes. The technologies on the left are listed as sources, and those on the top as sinks. Fields that are physically impossible are greyed out, and those that are unregulated are highlighted in white and marked with a minus. Connections that are technically possible but are disregarded for this study are marked with an X. Revenues are positive and expenditures negative.

Source \ Sink	Elec. grid	Battery	PtGtP	El. cons.	CHP	Boiler	Th. cons.
Elec. grid		X	−21.43 bis 3.97	−23.48 bis 1.92			
PV	10.06 bis 10.27	0	0	−2.70			
Battery	X		X	−2.70			
PtGtP	−10.49 bis 13.01	X		−2.70			-
NG grid					−5.95 bis −4.59	−5.95 bis −4.59	
CHP	−9.83 bis 21.01		0 bis 4.00	−2.70 bis 1.30			0
Boiler							0

5.5 | Results

In the following, the methodology developed is applied to the case study shown. The dispatch optimisation of the individual plants with *oemof.solph* is first demonstrated, followed by the optimal sizing of the relevant components. In order to verify the assumptions of the model and to be able to make good recommendations for action, a sensitivity analysis is carried out as a final step.

5.5.1 | Optimal Dispatch

The simulation per system configuration is run for one year and then evaluated with the objectives introduced in Section 5.3.1. The schedules are selected in such a way that the costs for the operator are kept to a minimum over the period under consideration.

Figure 5.8 exemplifies the behaviour of the technologies for one week. The entire variety of technological possibilities for energy supply is used, whereby the CHP clearly takes over the main part. During working hours, which have high heat and power requirements, the CHP operates depending on the electricity demand. Surplus heat is stored in the TES. On the electricity side, the CHP is completed by the PV and the battery, meaning that the whole system does not need to draw or feed in electricity at most times. During the night and at weekends, the heat and electricity demand drops and the CHP switches off due to its limited partial load capacity. Thermally, the TES then becomes the main source of heat and, as soon as it is empty in a few hours, so does the boiler. Electrically, these low-demand periods are partly filled by the battery, but there are still times when electricity has to be drawn from the grid. However, due to the chosen optimisation approach, these are usually cheap times on the energy markets, when there is a great deal of renewable energy in the grid. The storage systems, as already mentioned, show steady use. The electricity storage system mainly bridges midday PV surges for the night. The TES shows a similar behaviour for the CHP heat but additionally manages to shift heat from the working week to the weekend due to its larger storage volume. The PtGtP is charged very regularly in this early summer week and increases significantly in filling level over the week. It is fed by both PV and CHP when they need additional flexibility. The system does not play a crucial role but still helps to provide (technical) advantages in the interaction of all technologies.

Figure 5.9 shows the SOCs of electricity, heat, and hydrogen storage systems over the full period of one year for the same exemplary system setup. A clearly different basic behaviour of the various storage systems can be seen here: the battery storage system serves as a short-term storage system and, as already seen in Figure 5.8, is used, for example, to save excess PV electricity during the day into the night hours. In contrast, the thermal storage is used as medium-term storage to absorb excess CHP heat at the weekend or in the night hours and save it for load peaks during production, so that the boiler can be avoided. Hydrogen storage, for its part, fulfills its task as long-term storage and helps to transfer the summer PV surpluses into the winter. The systems thus complement each other and do not compete with each other. What is particularly exciting and promising here is to see that the PtGtP is actually used very regularly. Due to the selected optimal dispatch algorithm,

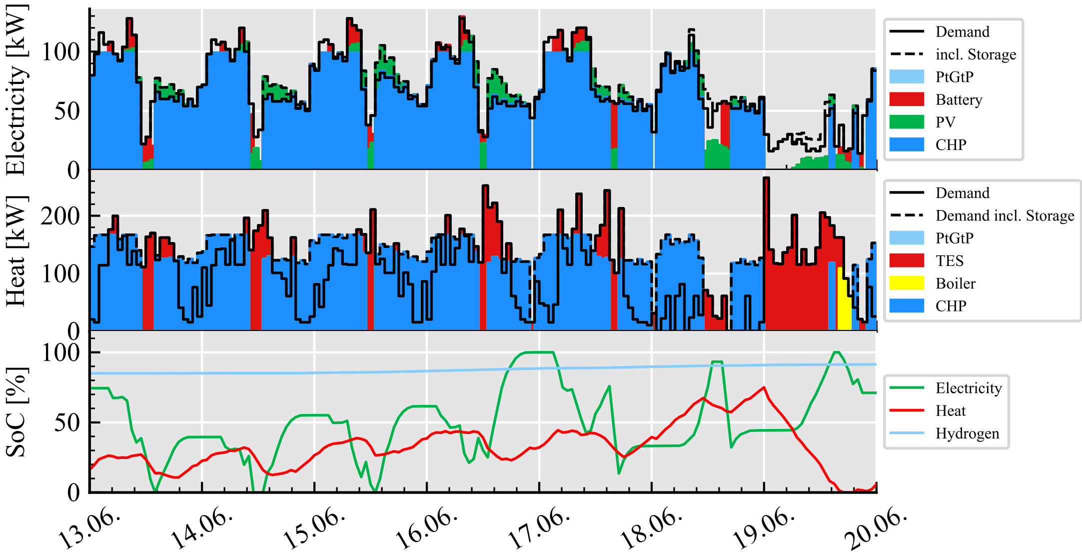


Abbildung 5.8: Exemplary presentation of dispatch optimisation for a one week (Monday–Sunday) timeframe and an exemplary system setup (CHP 99 kW_{el}, PV 40 kW_p, TES 10 m^3, battery 131 kWh, ELY 1 kW_{el}, HS 1 340 kWh, FC 5 kW_{el}). Electricity consumption and production (top), heat consumption and production (middle) and the State of Charge (SOC) of all storages (bottom) are shown.

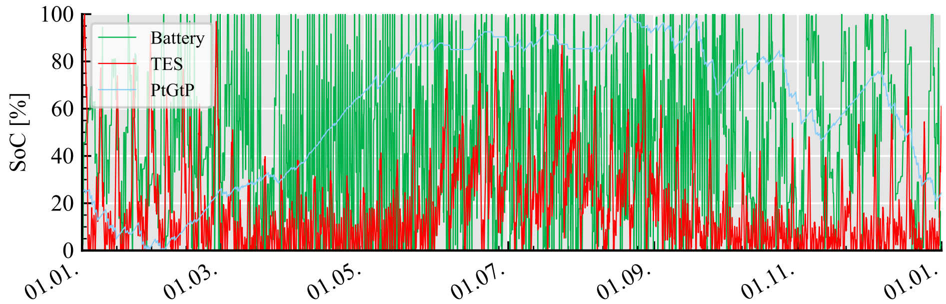


Abbildung 5.9: Visualisation of the SOC as filling level in percent of the storage systems used during the investigated year for the system configuration used in Figure 5.8.

this only happens when its operation represents an actual added economic value during operation. It can therefore already be stated at this point that the hydrogen storage system can achieve cost advantages in operation.

5.5.2 | Multiobjective Optimal Sizing

As described in Section 5.3.3.1, the technology sizes are changed in the course of the optimisation, meaning that different combinations of the technologies are iterated. A maximum computing time of 2.5 h per sizing was set, which was rarely reached. In addition, different sizing calculations were computed in parallel on different CPU threads, which was easily possible due to the chosen brute force approach. The complete optimisation of both scenarios needs about 140 h or 6 days on a modern desktop PC.

The results of this MO can now first be examined as a scatter plot of the two target dimensions and with regard to the influence of the different technology sizes. The Pareto front, which includes all optimal energy system alternatives, is particularly relevant here. The graphical representation for scenario 1 can be found in Figure 5.10, while that for scenario 2 can be seen in Figure 5.11. The technology sizes are shown as colour codes, and for each technology there is a separate diagram. The Pareto front is shown as a red line in each graph. In addition, the Pareto optimal configurations are summarised in Table 5.3 forming a multi criteria decision matrix.

For scenario 1 (Figure 5.10) we see that the CHP has by far the largest impact in both dimensions and that large clusters of these energy systems form. Here, no CHP is the worst choice in economic and environmental terms (upper left corner). By increasing the CHP size, the point cloud moves towards the bottom right. This means that the energy supply concept becomes cheaper and emits less CO_2. After a system size of 99 kW_{el}, this behaviour changes, at least in economic terms. A further improvement in emissions is then only possible with rising costs, and a broad Pareto front forms. A larger PV plant also (almost) always leads to an improvement in both dimensions, even if the effects are significantly smaller here. Here, the tipping point of an overly large system does not seem to be reached due to the limited roof area. The larger the CHP becomes, the more important a larger TES seems to be, which seems logical. Here, bigger seems to be overall better, even if the improvement stagnates at some point. Only four of those systems are actually Pareto optimal. These include systems with large PV installations, large TESs, and no to small batteries. The saving of one tonne of CO_2 costs 732€ /t bis 1 061€ /t, which seems rather high. The German Federal Environment Agency estimates the societal climate costs of a tonne of CO_2 in 2020 at 195€ /t [274]. Implementing the more climate-friendly and thus more expensive solutions therefore does not seem advisable today.

The course of scenario 2 (see Figure 5.11) looks very similar to scenario 1. By adding the hydrogen technologies, the point clouds are correspondingly larger, since the combination possibilities are much more extensive. Nothing changes in the conclusions about the technologies that have already been examined in scenario 1. The graphically visible effects of the PtGtP system are rather small.

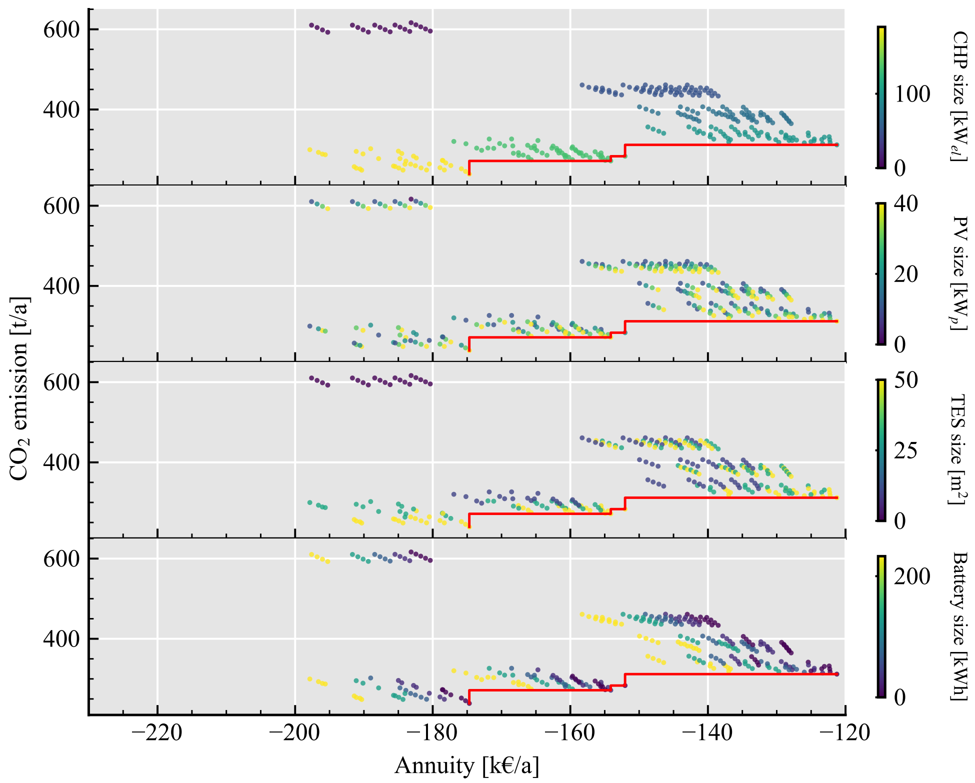


Abbildung 5.10: Illustration of the results of scenario 1 as a scatter diagram. It shows the Pareto front (red) between annuity and CO_2 emission. The colour codes show the dependency on the technology size, and each technology has its own graph.

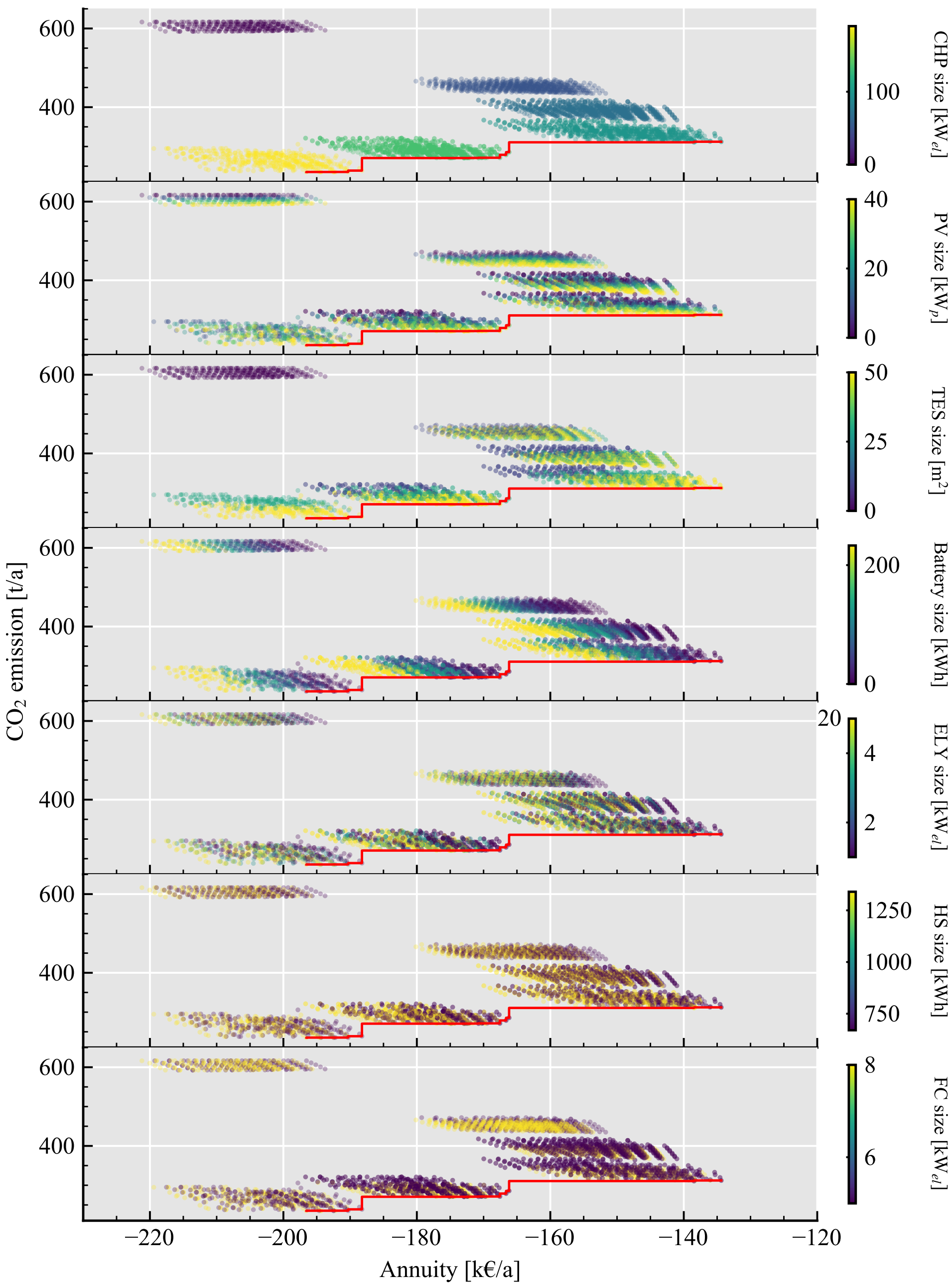


Abbildung 5.11: Illustration of the results of scenario 2 as a scatter diagram. It shows the Pareto front (red) between annuity and CO_2 emission. The colour codes show the dependency on the technology size, and each technology has its own graph.

Tabelle 5.3: Multi-criteria decision matrix of the two scenarios. Shown are the Pareto optimal system configurations sorted by ascending costs and descending emissions.

	CHP	PV	TES	Battery	ELY	HS	FC	Annuity	CO_2 Emission
	kW_{el}	kW_p	m^3	kWh	kW_{el}	kWh	kW_{el}	€ /a	t/a
Scenario 1	99	40	50	0	-	-	-	−121 263	312
	134	20	50	0	-	-	-	−152 043	283
	134	40	50	30	-	-	-	−154 122	272
	190	40	50	0	-	-	-	−174 683	239
Scenario 2	99	40	50	0	1	670	5	−134 384	312
	99	40	50	0	1	1 340	5	−138 463	311
	134	30	30	0	1	670	5	−166 177	286
	134	40	30	0	1	670	5	−166 628	279
	134	40	50	30	1	670	5	−167 556	271
	134	40	50	0	3	670	5	−170 751	271
	134	40	50	0	1	1 340	8	−172 152	271
	190	40	50	0	1	670	5	−188 228	239
	190	40	50	0	3	670	5	−190 295	235
	190	40	50	0	1	670	8	−192 218	235
	190	40	50	0	5	670	5	−192 457	235
	190	40	50	0	5	1 340	8	−196 565	235

As a tendency, it can be noted that the economic efficiency tends to worsen with larger system components, but the emissions hardly change. A closer look at the decision matrix confirms this observation. Adding even a small PtGtP plant to the optimal systems from scenario 1 significantly worsens the annuity, but the emissions remain almost the same. The additional costs for the hydrogen system are approximately 13 000€ /a bis 22 000€ /a, which corresponds to a cost increase of approximately 11 %.

5.5.3 | Sensitivity Analysis

A key challenge for any company is to make decisions in the face of uncertainty, which can turn out to be either an opportunity or a risk for them. An unpredictable future and its consequences are difficult to assess. If decisions are to be made, appropriate methods must be used to determine sound estimates and trade-offs between the effects on the company [210].

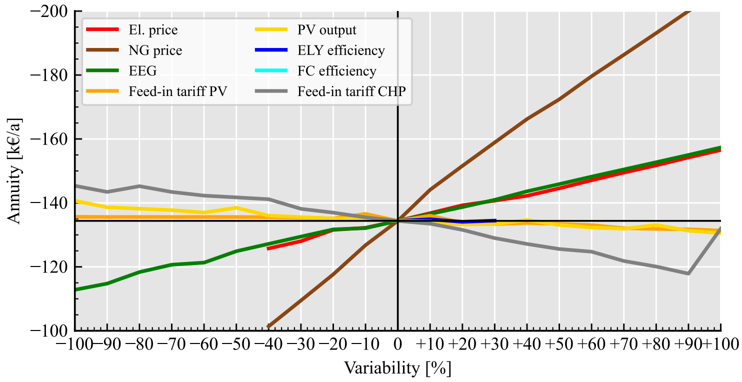
As shown in Section 5.5.2, the installation of a PtGtP system is neither ecologically nor economically advantageous from today's perspective. However, the question arises as to which framework conditions would have to change in order for such a system to become more sensible. In order to gain a better insight into this, a sensitivity analysis is carried out in the following. Sensitivity analysis is a method to quantify the influence of various uncertain parameters on the performance of a complex system [275]. In the literature (cf. [197, 206, 276]), it is used to understand, for example, the impact of changing energy prices on the economic viability of a supply concept and thus to develop appropriate countermeasures and make risk-minimising decisions. Likewise, this method can be used to investigate, as in our case, which parameters would have to change and to what extent in order to make a project successful. For this purpose, one of the uncertain input parameters is varied in several steps, while the others are kept constant. The system results can then be shown as a function of these changes and compared between the parameters.

We have identified the following parameters (in bold) as particularly relevant and uncertain for the success of a PtGtP solution. **Electricity and NG prices** depend not only on very volatile international trading markets but also, and above all, on national legislation and therefore change frequently and with little predictability. This includes not only procurement prices but also subsidies for feeding locally generated electricity into the grid (**PV and CHP feed-in tariff**). In Germany, the **EEG levy**, used to fund renewable energy subsidies, is a matter of great debate. This levy has risen sharply in recent years and is payable, for example, on electricity generated in-house as well. In addition to these more energy-economic factors, this section also looks at advances in energy technology, especially **efficiency improvements in ELY and FC** and changes in **PV electricity production**, as would be possible, for example, by relocating.

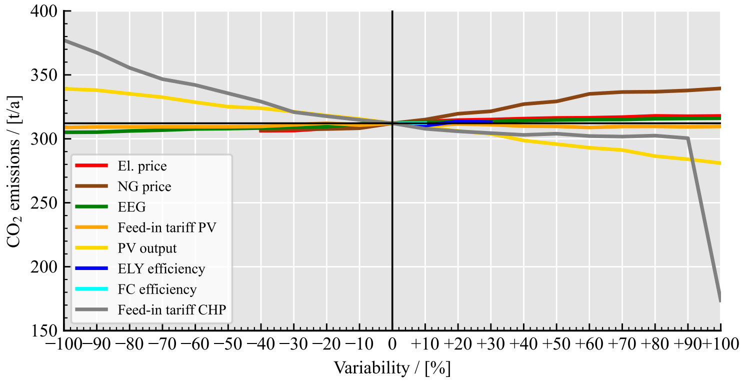
For the sensitivity analysis, the technologies of the most economical solution of scenario 2 are used (CHP 99 kW_{el}, PV 40 kW_p, TES 50 m^3, battery 0 kWh, ELY 1 kW_{el}, HS 670 kWh, FC 5 kW_{el}). The statements for this system should, on the one hand, be the most relevant and, on the other hand, their basic statement should be transferable to all systems. The identified parameters are varied in a range of −100 % to 100 %. Parameters for which this makes no physical or economic sense (e.g., the increase in FC efficiency) are varied correspondingly less. Figure 5.12 shows the results of the sensitivity analysis as an impact on the annuity, the emissions, and the amount of hydrogen produced as a function of the identified parameters.

With regard to the annuity, it can be seen that the most sensitive parameter is the NG price. The increase is relatively constant and primarily affects the operating behaviour of the CHP. At the same time, the boiler is also operated minimally more. If the NG price rises, the annuity increases considerably, and CO_2 emissions rise by around 30 t/a. Hydrogen production is initially reduced when the price of NG rises by 10 % because less CHP electricity flows to the ELY. If the price of NG falls, the annuity decreases significantly, but nothing changes in terms of CO_2 emissions and hydrogen production. This is due to the fact that the operating behaviour of the CHP unit has not changed in terms of NG consumption, and only the reduction in the price of NG makes up this difference in annuity.

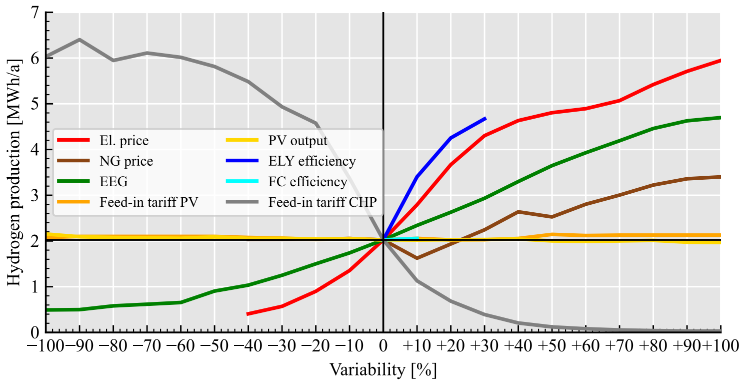
The price curve of electrical energy is significantly flatter than that of NG. As the electricity price increases, the amount of electricity imported slowly decreases, making the dairy more self-sufficient. Therefore, hydrogen production continues to rise as the ELY is supplied with more PV and CHP electricity. If the price of electricity falls, less and less PV and CHP electricity is used for hydrogen production as the costs of purchasing electricity from the grid are lower than the intermediate



(a) Annuity



(b) CO_2



(c) Annuity

Abbildung 5.12: Sensitivity analysis of various system variables using the previously defined degrees of freedom.

storage of local electricity in hydrogen. This leads to a little more CO_2 being emitted.

The course of the EEG levy is similar to the electricity price in terms of annuity and CO_2 emissions. When the EEG is reduced, the purchase of electricity from the grid again becomes cheap, and the intermediate storage of electricity thus becomes obsolete. The amount of electricity flowing from the CHP and PV to the ELY decreases slowly as the electricity is fed into the public grid instead. This in turn leads to higher CO_2 emissions. If the EEG is completely omitted, a large part of the PV electricity is fed into the grid. If, on the other hand, the EEG increases, more CHP and PV electricity will be used for hydrogen production.

The variability of the PV output has little effect on the annuity. The increase in PV output leads to an increase in the amount of electricity fed into the public grid and thus to a slight increase in the remuneration. In addition, the feed-in to the grid reduces the emission values. It has hardly any influence on the production of hydrogen.

The reduction of the PV feed-in tariff has a similarly low effect to the change in production volume. The incentive to feed PV electricity into the public grid gradually decreases. In the end, PV electricity is used almost exclusively for self-consumption. This increases the amount of CHP electricity that is fed into the public grid. The emission values hardly change. It also has hardly any effect on hydrogen production. On one hand, a little more PV electricity is used for hydrogen production, while on the other hand, less CHP electricity is used for this purpose.

The variation of the CHP feed-in tariff has a large impact on the emission value and on hydrogen production but little impact on the annuity. Instead, when CHP feed-in tariff is reduced, more CHP electricity is used for hydrogen production, which is discontinuous from below −20 %. In addition, the amount of electricity generated by the CHP unit is reduced, which means that less electricity is fed into the grid, thus increasing the emission value. If, however, the CHP feed-in tariff increases, the amount of electricity from the CHP to the ELY decreases, and less hydrogen is produced. In addition, the amount of electricity from the CHP unit that is fed into the electricity grid gradually increases. If the CHP feed-in tariff increases by 100 %, the entire CHP electricity flows into the electricity grid, meaning that a high CO_2 credit takes place at the same time. However, in order to be able to cover the electricity demand, large amounts of electricity are drawn from the public grid, meaning that the annuity increases again.

Changing the efficiency of the ELY has no effect on annuity or emissions. However, the lossless system (30 % variation) has the highest increase in hydrogen production of the systems studied

The increase in FC efficiency from 90 % to 100 % again has hardly any effect on annuity and emissions. Interestingly, however, there is no increase in hydrogen production here.

5.6 | Discussion and Outlook

As shown in the results discussed in the previous chapter, the planning of distributed energy supply concepts using PtGtP as seasonal storage is multi-layered and complex. The presented planning tool using an energy system simulation and multi-criteria decision tools can be seen as a helpful supplement in the market establishment of such systems.

With the help of these tools, we were able to show that, for our case study, under the current German framework conditions, the construction of an PtGtP, even a small one, is neither economically nor ecologically profitable and that the systems of PV and CHP currently established on the market are the most worthwhile (cf. Figures 5.10 and 5.11). While the PtGtP can deliver real economic value in operation, the current investment costs in such a system are far too high. Unfortunately, the system cannot yet deliver any added value ecologically in operation, as the electricity grid is still heavily supplied by fossil fuels, and local storage therefore does not necessarily mean a reduction in emissions. If the construction and demolition of the plants had also been taken into account in the ecological assessment, the result would have been even worse. However, we suggest that such systems should not only be considered from a hard economic and ecological point of view, but also from a marketing and long-term sustainability point of view, which would make an investment more likely today. However, these objectives are significantly more complex to quantify and are therefore part of further investigation.

We were able to show through our research that the combination of different storage technologies with different time horizons and efficiencies during operation can fulfill their intended tasks well in order to keep the local system efficient and optimal (cf. Figure 5.9). The energy simulation shows very well how in hybrid, sector-coupled systems, the energy-generating and energy-storage plants complement each other depending on the market situation and framework conditions in order to generate an advantage for companies, benefitting from the national regulatory framework.

Nevertheless, the results of this simulation should be treated with caution, as a number of simplifications have been made, which in the end are decisive for real operation. On the thermal side, the system only calculates energy quantities in kWh without considering the actual restrictions caused by different temperatures in the supply and return flow. Likewise, only hourly averages are simulated, but the system behaviour within these time steps can deviate massively and have a negative influence on the system. Furthermore, the simulation always assumes a perfectly predictable future, where weather changes and stock exchange prices are always known, which simplifies the use of seasonal storage tremendously. For the use of such a system in the field, an intelligent and dynamic energy management system is therefore indispensable.

By adding a sensitivity analysis to the methodology, more in-depth findings can be derived, including specific recommendations for action. For the case study, it can be seen that an increase in the efficiency of technical installations has a relatively small effect. On the other hand, the use of PtGtP can be specifically promoted by a clever change in the political framework conditions.

However, even these statements only represent half the truth, since in this classical sensitivity analysis, it was assumed that only one parameter changes at a time. In the real market, for example, an increase in the price of NG also directly changes the price of electricity, and the abolition of the EEG levy would also lead to a reduction in the PV feed-in tariff. However, when looking at the results of hydrogen production, it is clear that several, well-aligned changes would be needed to achieve a significant effect.

For example, a Monte Carlo Simulation could be used for this purpose, in which a large number of different scenarios could be built and analysed using statistical future models of the parameters and their correlation [206, 207]. This would give more reliable and better information on the systems' performance, as it would provide a large amount of information and reflect realistic modelling. A major disadvantage, however, would be the high computational time and the high modelling effort.

Directly considering the uncertainties in the optimal sizing would be even better. Appropriate approaches to this already exist in the literature (e.g., [85, 277]), but they require even more resources and are more modelling-intensive. The choice of a possible optimisation approach is therefore very diverse and depends to a large extent on the objective, the availability of data and resources, and the project status. The optimisation method used here, although not entirely new and not particularly efficient, provides very reliable, realistic, and detailed results. By choosing an extremely simple optimal sizing algorithm and an open source tool for optimising plant operation, the basic structure can be transferred to other regions and countries without restrictions and with only slight modifications. Limitations only arise when the choice of technology would become too large, which would be made possible with more efficient optimisation tools (e.g., genetic algorithms) or a simplification of the technical models.

5.7 | Conclusions

This publication presented a planning tool for hybrid, distributed energy systems and assessed the installation of PtGtP systems using an industrial case study. Based on the current German market conditions, it was investigated whether such a system in combination with an established PV, battery and CHP combination offers economic or ecological advantages.

After detailed literature research on the integration of hydrogen technologies in energy systems, a novel methodology for the overall planning process of HES was explained. A brute force optimal sizing approach based on energy system simulation and modelling of real system components available on the market was used. This was applied to the case study of a dairy for which the German legal framework valid in early 2020 was assumed to apply. Over an observation period of 10 a, different technology sizes were iterated, and the Pareto optimal solutions with regard to economic and ecological objectives were determined. A sensitivity analysis was conducted to determine the future opportunities and risks of hydrogen technology. For this purpose, uncertain parameters were identified and individually varied.

It has been shown that HESs provide worthwhile added values for companies in terms of economic efficiency and emission values. A CHP unit, especially, has a considerable positive influence on economic and ecologic dimension. The use of a small PtGtP plant, on the other hand, is not worthwhile under the current German framework conditions and for the case study used. This is due on the one hand to high investment costs, and on the other hand to cheap energy imports and high feed-in tariffs. However, it is foreseeable that this statement could be revised in the short term due to legal changes and the current development of energy prices.

Author Contributions: Conceptualisation and methodology, L.S.; software, L.S. and A.A.I.B.; validation, L.S.; formal analysis, A.A.I.B. and L.S.; data curation, A.A.I.B. and L.S.; writing—original draft preparation, L.S. and A.A.I.B.; writing—review and editing, P.K. and B.H.; visualisation, L.S.; supervision, H.H., P.K., B.H. and K.v.M.; project administration, L.S., H.H. and P.K.; funding acquisition, H.H., P.K., B.H. and K.v.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Federal Ministry for Economic Affairs and Climate Action (BMWK) and the Federal Ministry of Education and Research (BMBF) of Germany in the project ENaQ (project number 03SBE111).

Acknowledgements: The authors thank all the other ENaQ project partners for support, inspiration, and fruitful discussions. We would also like to thank the dairy for providing the required data on energy consumption and the PtGtP manufacturers for providing the data sheets and answering our questions. Finally, a special thanks is due to Cody Hancock (DLR), who proofread the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

6 | A generalised optimal design methodology for distributed energy systems

The content of this chapter is identical to the following journal article:

Schmeling, L.; Schönfeldt, P.; Klement, P.; Vorspel, L.; Hanke, B.; von Maydell, K.; Agert, C.; A generalised optimal design methodology for distributed energy systems. Renewable Energy 2022, 200 (2), 1223-1239. doi:10.1016/j. renene.2022.10.029

Article

A generalised optimal design methodology for distributed energy systems

Lucas Schmeling[1,2,3,*], Patrik Schönfeldt[1], Peter Klement[1], Lena Vorspel[4], Benedikt Hanke[1], Karsten von Maydell[1], Carsten Agert[1]

[1] German Aerospace Center (DLR), Institute of Networked Energy Systems, Carl-von-Ossietzky-Str. 15, 26129 Oldenburg, Germany
[2] KEHAG Energiehandel GmbH, Im Technologiepark 4, 26129 Oldenburg, Germany
[3] Lintas Green Energy GmbH, Alter Stadthafen 3b, 26122 Oldenburg, Germany
[4] Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM, Wiener Str. 12, 28359 Bremen, Germany
* Corresponding author: lucas.schmeling@dlr.de; +49 441 99906-536

Received: 28 March 2022 / Revised: 25 August 2022 / Accepted: 07 October 2022 / Published: 14 October 2022

Abstract: The optimal combination of energy conversion and storage technologies with local energy demand is a key but in its result not obvious challenge of distributed energy. Although a variety of possible approaches to the optimal design of limited technology selections can be found in the literature, the previous design step, the actual technology selection, and the subsequent step, the selection of the optimal operating strategy, are often neglected. We develop and demonstrate a methodology, which can optimise energy systems with arbitrary technology selection and under multi-criteria optimality definitions. The energy system modelled in *oemof.solph* is optimised using a MOEA/D approach with regard to economic, ecological and technical key performance indicators. The aim is to find trends and tendencies with a methodology that is as generalised as possible in order to integrate it into the decision-making process in energy system planning. We demonstrate the method by means of a German district for which an integrated supply concept is being sought. Different evaluation and visualisation possibilities are presented and the chances and limitations of the developed methodology are identified. We show that not only the choice of technology, but especially its sizing and operational strategy have a decisive influence on the optimality.

Keywords: Multiobjective Optimisation; Energy System Planning; Energy System Simulation; Pareto Front; District Energy System

6.1 | Introduction

The needs-based and target-oriented planning of distributed energy supply concepts can hardly be adequately represented using classical planning methods. Every supply object, be it a residential neighbourhood, a school or an industrial area, has different requirements and aspects of optimality associated with the provision of energy. At the same time, there is a wide range of different conversion and storage technologies which, alone or in combination with others, are suitable for ensuring supply according to precisely these requirements. The optimal technology choice and sizing along with the right operating strategy for a particular application, known as optimal design, is rarely obvious at first glance and depends on an large number of factors. In addition to natural law and technical regularities, these are above all economic and legal conditions which are undergoing dynamic changes and vary greatly internationally. In order to be able to react quickly to such developments in the future and to find the optimum energy supply concept for each application, planning tools are required which can evaluate and optimise the design and operational management of energy systems using computer-aided simulation and optimisation. The results of these tools can then be used to support decision-making in the usual planning processes of distributed energy supply concepts.

In the literature, various approaches are developed and discussed that design methodologies for exactly this purpose or certain subaspects. Especially in recent years, research in this area has increased massively. It is therefore not possible to provide a comprehensive description of all publications here, so the reader is referred to meta studies that provide more in-depth information on this topic [56, 278–281]. However, to give an impression of the diversity of the topic, Table 6.1 analyses various relevant publications without any claim to completeness. It is noticeable that there is a particular focus on the design of PV/wind/battery systems. Overall, however, it can be stated that only a rather limited selection of technologies is taken into account along with the limitation to electricity or heat sector. Many of the approaches to date are relatively far from being realistic in terms of overall modelling and application as well as being difficult to transfer to other use cases. Some utilise inefficient optimisation algorithms like brute force for sizing and block diagrams for operational management. Of course, this does not apply to all publications, but it is difficult to identify a methodology which, due to its comprehensive and realistic modelling, would be suitable for a wide range of real-life projects in the long term.

In addition to these comprehensive publications on the optimal design of energy systems, there are a large number of different sub-aspects that can be found in detail in the literature. Various meta-studies deal with the choice of suitable software to simulate operating strategies (e.g. [168, 314]), but often come to the conclusion that there is no universal remedy. The choice of the best algorithm for optimal design is also hotly debated (e.g. [200, 315]), although metaheuristics in the form of nature-inspired swarm intelligence, evolutionary or genetic methods or simulated annealing provide the best results nowadays and are suitable for a wide range of applications. For energy management, this choice does not seem to be so clear-cut and a wide variety of different approaches can be found [316, 317]. Furthermore, the modelling of plant technology for simulation (e.g. [318, 319]) as well as the methods for evaluating the energy system (e.g. [320, 321]) are already sufficiently

Tabelle 6.1: Overview of currently interesting publications on the optimal design of various energy systems and the classification of this publication in this context. Here ✓ describes the aspects considered in the publication, ✗ those explicitly not considered. The framework we present is only demonstrated here on a limited case study, but is actually able to cover more aspects, which are put in brackets here.

Publication	Energy Demand			Grid Connected	Technologies											Target			Algorithms		Case Study
	Electricity	Heat	Cold		Gas Boiler	Pellet Boiler	(C)CHP/Diesel	Heat Pump	Solar Thermal	Thermal Storage	Power2Heat	PV	Wind Turbine	Battery	Others	Economic	Ecologic	Technical	Sizing	Operation	
Wang et al. [248]	✓	✓	✓	✓	✓		✓			✓		✓	✓	✓	✓	✓	✓	✓	NSGA-II	Block diagram	Residential Community
Shahinzadeh et al. [282]	✓			✓			✓					✓	✓	✓		✓			HOMER		Neighbourhood
Ramli et al. [283]	✓			✗			✓					✓	✓	✓		✓		✓	MOSaDE	Block diagram	Single Household
Franco and Fantozzi [284]	✓	✓	✓	✓				✓		✓		✓						✓	Brute Force	Unclear	Single Household
Testi et al. [285, 286]	✓	✓	✓	✓				✓	✓	✓		✓			✓	✓			Brute Force	Block diagram	Hostel
Nguyen et al. [240]	✓			✗								✓	✓	✓	✓	✓	✓	✓	fuzzy-TOPSIS	EPoPA	Waste Water Treatment Plant
Das and Hasan [287]	✓	✓		✓/✗	✓			✓				✓	✓	✓		✓	✓		HOMER		Neighbourhood
Yimen et al. [288]	✓			✗			✓					✓	✓	✓		✓			Genetic Algorithm	Block diagram	Village
Li et al. [289]	✓			✓					✓	✓	✓		✓			✓			JADE	MILP	Households
Li [290]	✓			✓								✓		✓		✓			Genetic Algorithm	Genetic Algorithm	Households
Bukar et al. [291]	✓			✗			✓					✓	✓	✓		✓			Grasshopper	Rule based	Residential Microgrid
Zhou et al. [292]	✓			✓								✓		✓		✓			Genetic Algorithm	DICOPT	Housholds
Akram et al. [293]	✓			✓								✓	✓	✓		✓		✓	Brute Force	Rule based	City
Elmaadawy et al. [294]	✓			✓			✓					✓	✓	✓		✓	✓	✓	HOMER		Desalination Plant
Benalcazar [295]	✓	✓		✓	✓		✓			✓						✓			MILP	MILP	District Heating
Buchholz et al. [296]	✓	✓		✓	✓		✓			✓		✓			✓	✓	✓		Brute Force	MILP (oemof.solph)	Dairy
Berendes et al. [297]	✓			✗			✓					✓		✓		✓		✓	MILP(oemof.solph)/HOMER		Island
Wegener et al. [298]	✓	✓	✓	✓		✓	✓	✓		✓		✓		✓	✓	✓	✓		Brute Force	TRNSYS	Museum
Liu et al. [299]	✓			✓									✓	✓		✓			Genetic Algorithm	Rule based	Wind Park
Baniasadi et al. [300]	✓			✓				✓		✓		✓		✓		✓			Particle Swarm	Particle Swarm	Residential Building
Alberizzi et al. [301]	✓			✗			✓					✓	✓	✓		✓			MILP	MILP	Mountain hut
Diab et al. [302]	✓			✗			✓					✓	✓	✓		✓		✓	WOA, WCA, MFO, PSO	Block diagram	Village
Luta and Raji [241]	✓			✗								✓		✓	✓	✓		✓	HOMER		Commercial Facility
Firtina-Ertis et al. [246]	✓			✗									✓		✓			✓	Brute Force	Rule based	Household
Fathy et al. [303]	✓			✗								✓	✓	✓		✓			Social Spider	Block diagram	City
Ndwali et al. [304]	✓			✓								✓				✓		✓	MILP	Not needed	University Workshop
Das et al. [305]	✓			✗			✓					✓			✓	✓			HOMER		Residential Community
Salman et al. [306]	✓			✓/✗			✓						✓	✓		✓			GAMS		Residential Community
Mohseni and Moghaddas-Tafreshi [307]	✓			✗									✓	✓	✓	✓			Particle Swarm	Multi Agent	Residential Area
Bakhtiari and Naghizadeh [53]	✓			✗								✓	✓	✓	✓	✓		✓	ε-constraint	Unknown	Unknown
Urbanucci et al. [166]	✓	✓		✓	✓		✓			✓						✓			Genetic Algorithm	MILP	Secondary School
Zhu et al. [96]	✓			✗			✓					✓	✓	✓	✓	✓		✓	Grey Wolf	Rule based	Island
Eltamaly and Mohamed [308]	✓			✓			✓					✓	✓	✓		✓			Particle Swarm	Rule based	City
Berbaoui et al. [309]	✓			✗			✓					✓		✓		✓		✓	Virus colony	Unknown	District
Goel and Sharma [310]	✓			✗			✓								✓	✓			HOMER		Farm
Hadidian-Moghaddam et al. [311]	✓			✗												✓		✓	Ant Lion	Unknown	IEEE 33/69 bus
Khenissi et al. [91]	✓			✗								✓		✓		✓			Particle Swarm	Rule based	Household
Sawas and Farag [312]	✓			✓			✓					✓	✓		✓	✓		✓	Unknown		IEEE 30 bus
Zare and Iqbal [313]	✓			✓/✗								✓		✓		✓		✓	HOMER		Household
Our Publication	✓	✓	(✓)	✓/(✗)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	(✓)	✓	✓	✓	MOEA/D	MILP (oemof.solph)	Neighbourhood

understood and explained as sub-disciplines.

What is missing up to now is a comprehensive and, as far as possible, universally valid methodology in combination with a powerful software solution which can simulate and design distributed energy systems rather independently of their size, requirements and objectives and which is open to both manufacturers and technologies. There are other approaches to develop such methods and frameworks such as REopt Lite [322] but these are often still in the children's feet and either too complex in their use or not usable in their expressiveness and proximity to reality for real life projects. In the following, we will introduce such a methodology using an established phase-based planning process, present the software solution we have developed based on open source energy system simulation and demonstrate it using a case study. The classification of the solution developed here in the research discourse can be found at the end of Table 6.1 as well. The focus here is on a detailed and realistic modelling of the energy system especially in terms of regulatory and economic viability in order to be able to establish the methodology in the long term in the real world decision-making processes in planning offices and authorities. The aim here is explicitly not to obtain ready-made decisions for a specific energy system, but to find trends and recommendations that will then contribute to the objectification of decisions in the further decision-making process.

For this, a methodology is developed and presented in Chapter 6.2 that can optimise operation and sizing of distributed energy systems based on energy system simulation and by using different optimisation algorithms. This methodology is demonstrated by the case study of a German residential district that is briefly presented in Chapter 6.3. The results of this process are presented in detail in Chapter 6.4 and possible ways of evaluating them are shown. Finally, Chapter 6.5 critically examines the developed methodology and places it in the larger context of sustainable energy system planning.

6.2 | Optimisation of distributed energy systems

According to our previous work (Schmeling et al. [132] the planning process of distributed energy supply can be divided into 4 phases (targeting, synthesis, design and operation). This publication focuses on a novel methodology for use in the third phase (design) and presents tools and processes in this phase in more detail. The two previous phases are described briefly, but the results are assumed to be given and are in regard to the case study used later. For a complete description of those phases please refer to the previous work.

6.2.1 | Quantification of targets

Optimality of energy supply is in the eye of the beholder and can vary greatly depend on the boundary conditions and the stakeholders involved. These targets are understood as Key Performance Indicators (KPIs) of the overall technical system which thus have a decisive influence on the success of the project. In general, the methodology outlined is intended for such individual KPI definitions (as long as they can be objectively quantified) and any number of KPIs. For later demonstration and to give the reader an impression of frequently used KPIs, three dimensions (economic, ecologic and technical) are motivated and their approach to quantification is explained below. They were developed in consultation with various stakeholders of the case study that we will use later to demonstrate the methodology.

6.2.1.1 | Economic objective function The affordability of energy is a central problem in many countries of the world [323]. Especially low-income households often have problems to pay their energy bills [324]. The transformation of the energy sector, such as is currently taking place e.g. in the context of the German “Energiewende”, is leading to a significant increase in household energy prices [325]. Making affordable energy available to the general public is therefore a major goal in the design of distributed generation when challenging classical supply solutions.

The economy of an energy supply concept can be evaluated in many different ways. Classical methods such as net present value or internal rate of return [326] can be applied or more modern, dynamic methods such as real options analysis [256]. Each of these have their own advantages and disadvantages, which is why a methodology that is objective, transparent and proven has been chosen here. For this reason, we chose an approach based on the German industrial standard VDI 2067 [179], which is based on annuity analysis. This has the advantage that, if correctly applied, the procedure and assumptions are transparent, recognised and comprehensible. With this, the annual costs A_{N} incurred on the basis of capital- ($A_{\mathrm{N,C}}$), demand- ($A_{\mathrm{N,D}}$) and operation-related ($A_{\mathrm{N,O}}$) costs and proceeds ($A_{\mathrm{N,P}}$) over an observation period T to be defined are indicated.

$$A_{\mathrm{N}} = A_{\mathrm{N,P}} - \left(A_{\mathrm{N,C}} + A_{\mathrm{N,D}} + A_{\mathrm{N,O}}\right) \tag{6.1}$$

The individual annuities $A_{\mathrm{N},X}$ per cost type $X \in [\mathrm{C},\mathrm{D},\mathrm{O},\mathrm{P}]$ result from the costs of the first year A_{X1} multiplied by an annuity factor a and a price dynamic cash value factor b_X, which in turn depends on an interest factor q and a price change factor r.

$$\begin{aligned} A_{\mathrm{N},X} &= A_{X1} \cdot a \cdot b_X \\ &= A_{X1} \cdot \frac{q^T \cdot (q-1)}{q^T - 1} \cdot \frac{1 - \left(\frac{r_X}{q}\right)^T}{q - r_X} \end{aligned} \tag{6.2}$$

The resulting annuity then describes the annually recurring payments of the same amount over the observation period, caused by the energy system [179, 252]. The system with the highest annuity, i.e. the lowest losses or, if the energy is supplied to third parties, the highest profits, is the best identified option for implementation. No business models of the stakeholders involved in the energy supply are imputed here, but the minimum costs over the observation period are objectively sought from the point of view of the stakeholder community.

6.2.1.2 | Ecologic objective function Against the background of both climate change and the finite nature of fossil fuels, a global rethink is taking place towards a responsible and moderate use of resources. Quantifying and communicating the externalities of energy consumption is therefore definitely an essential part in modern energy system planning.

Environmental impact assessment can also be carried out in different ways like Life Cycle Assessment (LCA) [327, 328]. At this point, a balancing boundary procedure based on Wehkamp et al. [256] was agreed upon in which only the operating phase is considered and the energy flows across the borders of the supplied object are assigned to the specific CO_2 emissions. The annual emission E resp. emission $E(t)$ at time t is quantified by multiplying the amount of energy $a_X(t)$ with the specific emission $e_X(t)$ at this time step for every energy type F:

$$E = \sum_t E(t) = \sum_t \sum_F a_F(t) \cdot e_F(t) \tag{6.3}$$

The CO_2 emissions of carbon-based energy sources are assumed to be constant, while the emissions from electricity grid purchases and feed-in are calculated dynamically on the basis of the current national energy source mix using the flow tracing method [177, 329]. Incoming quantities are counted positive, outgoing quantities negative. The emissions related to the use environmental energy (sun, wind, environmental heat) is considered to be 0 g/kWh. The time course of the specific emissions can be seen in Figure 6.1, whereby the emissions of the carbon-containing energy sources are taken from [257] and the dynamic emissions of electricity were calculated using a custom tool build by Windmeier [258].

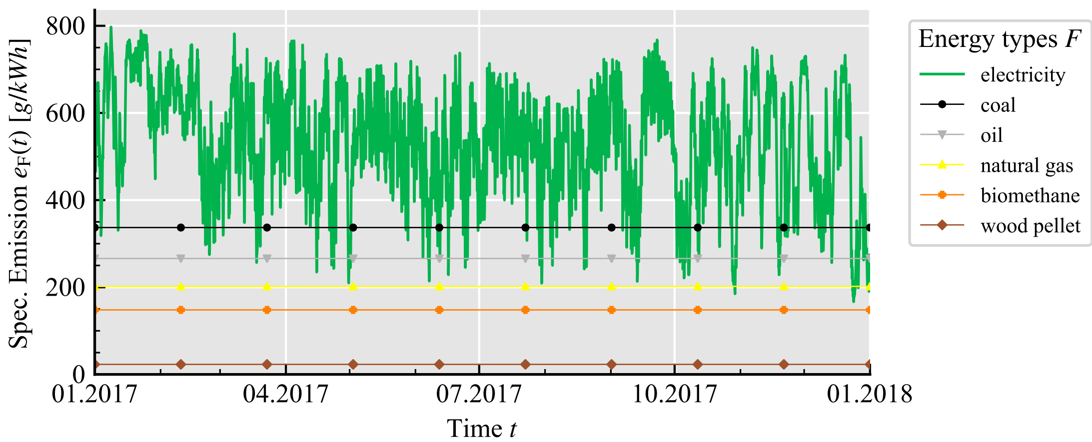


Abbildung 6.1: Time course of the specific CO_2 emissions of various energy sources to assess the ecological impact of the energy system using a balancing boundary method for Germany in the year 2017.

6.2.1.3 | Technical objective function Technically optimal is certainly the most controversial topic in this triad, since a varying definition can be expected depending on the external conditions and the underlying question. However, the technical side of energy use in urban areas, as relevant in the later case study, is usually characterised by limited local energy resources, often an unfavourable ratio of existing roof area for Photovoltaic (PV) or solar thermal use and energy required [330]. It is therefore a legitimate goal to use these limited resources as efficiently as possible.

This can be quantified with the help of own consumption, which is defined as the quotient of locally produced and locally used energy with the total local energy available [331]. Here B describes the annual locally produced and consumed energy whereas C describes the annual locally produced but exported quantities. The approach is illustrated in Figure 6.2, the own consumption O can then be calculated as:

$$O = \frac{B}{B + C} \tag{6.4}$$

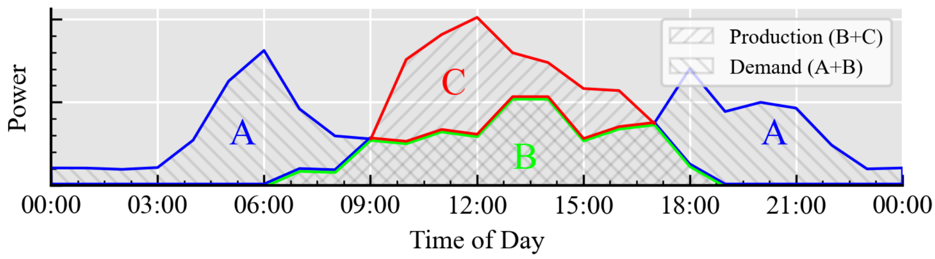


Abbildung 6.2: Graphical representation of own consumption using the example of a typical day of PV production and consumption. (based on Luthander et al. [331]). Area A (blue) is the share of electricity imported from outside, area B (green) is the amount of energy produced and used locally and area C (red) is the export of locally produced energy.

The definition here is limited to the electricity sector only. In the case of locally generated thermal energy, it is assumed that this cannot be exported and is always consumed entirely locally.

6.2.2 | Energy systems modelling

In order to be able to quantify the previously defined targets in dependence of the used technology, a simulation of the energy flows of the energy system is required. For this purpose, a model has to be built that represents both, the individual technologies, including their techno-economic properties, as well as the interaction of these technologies.

6.2.2.1 | Superstructure A superstructure represents all energy technologies and their interconnections that are conceivable at that planning phase, but with unspecified size, even if they are partly redundant [180]. A superstructure is the key result of the second phase of energy system planning (synthesis) acc. to Schmeling et al. [132] which can be derived as follows:

Starting with an open collection of all possible technologies involved in the energy supply system, a project-specific decision is made as to which technologies can realistically be implemented for the project under consideration. This is done both in terms of boundary conditions (e.g. resource availability or legislation) as well as technological maturity and willingness to invest of the stakeholders, until a final technology selection is made. The selected technologies must then be combined in a meaningful way, i.e. their interactions must be defined. This results in the superstructure, which is decisive for the further design process and which is shown as an example in Figure 6.3. Part of the superstructure are also energy-economic and legal framework conditions, such as energy prices, technical minimum requirements or funding for renewable energies (not included in the figure).

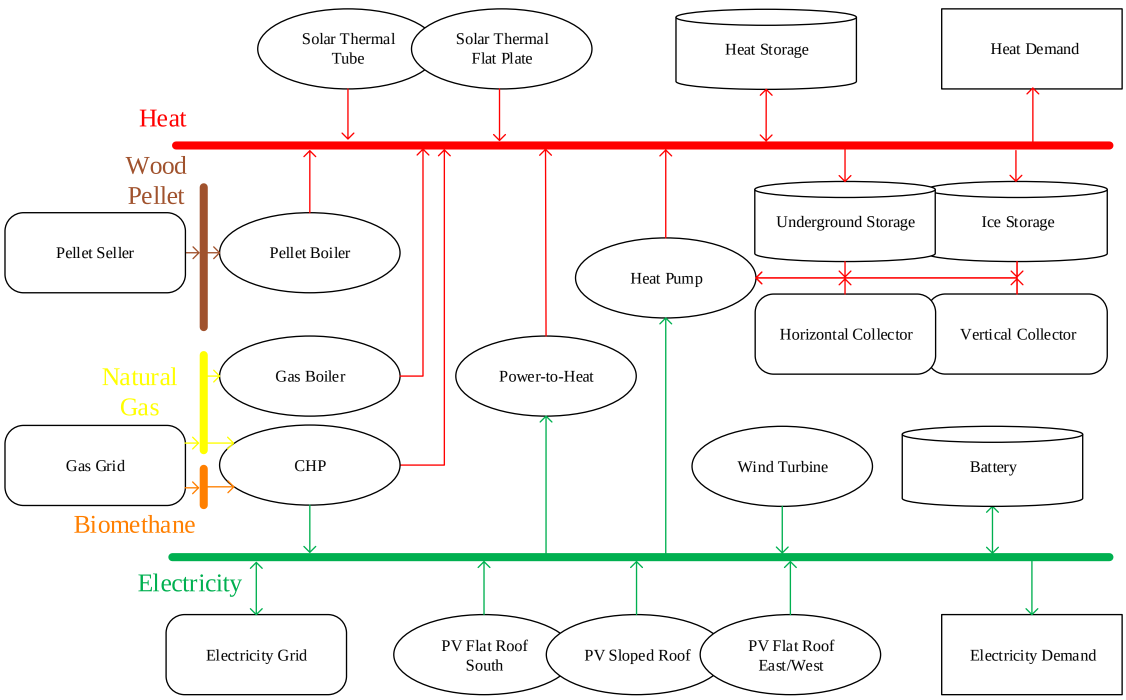


Abbildung 6.3: Exemplary representation of a superstructure as used in the later case study. Here, rounded rectangles represent energy sources, ovals energy converters, cylinders energy storage and rectangles energy demands. Details on the individual technologies can be found in Table 6.2.

The roof areas can be used for either solar thermal or PV. For flat roofs, we distinguish between a pure south orientation (PV Flat Roof South) and an east-west orientation (PV Flat Roof East/West) for PV. Sloped roofs are used without further elevation (PV Sloped Roof). In the case of solar thermal energy, a technological distinction is made between tube and flat plate collectors, which are always aligned to the south due to technical restrictions.

6.2.2.2 | Energy technologies modelling The modelling of most technologies of the superstructure is, at least at the level required here, either trivial (e.g. gas boilers) or scientifically already well understood and documented as we will show. Therefore, the approach used will only be briefly demonstrated here as an example using the Combined Heat and Power (CHP).

For each technology, a manipulable variable is selected to which all other technical and economic properties are then scaled. In the case of the CHP, this is the electric power at full load, because it also serves as a distinguishing feature between different systems, e.g. on technical data sheets. The basis of the modelling in this case is a product database of different manufacturers, which comprises 54 different CHPs with electric outputs between 5 kW and 2 000 kW. The manipulable variable is then plotted against all other variable values of the product database in a point cloud and regressions are performed. In other cases, such as the feed-in tariff, the product database does not have to be used, but the regulations can be translated directly into dependency of the installed capacity. This results in a mathematical continuous modelling of the average system properties as a function of only one variable. This is exemplified in Figure 6.4. In this way, the change of all system properties can be modelled in the later optimal design using only one degree of freedom per technology.

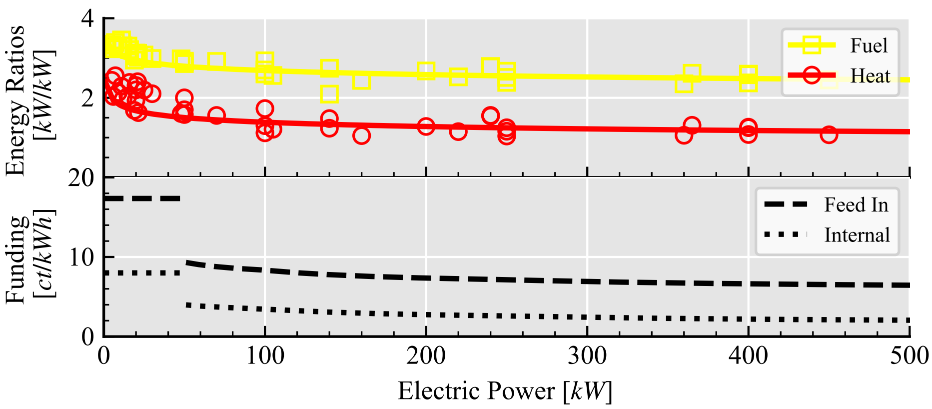


Abbildung 6.4: Representation of the continuous modelling of the CHP for the German market and under the funding conditions of the KWKG (German CHP Act). The ratio of thermal and fuel energy to electrical energy is shown above, and the state funding for own consumption and grid feed-in is shown below.

All the technologies contained in the superstructure were modelled in this or similar ways. In Table 6.2, we provide an overview of the technologies used in the later case study and their modelling fundamentals. This table is only intended to reflect the technology selection used in the later case study; almost any conversion and storage technologies can be modelled and optimised with this methodology due to the chosen architecture; an overview of planned as well as already implemented additions can be found in the table as well. The exploration of hydrogen storage systems could be particularly interesting in this context. However, since we found under similar legal and economic conditions that these currently offer neither economic nor ecological added value [133], they are neglected for the later case study, at least for the time being.

Tabelle 6.2: Overview and description of the used and additional energy generation and storage technologies and their modelling fundamentals. In this context, technologies are referred to as trivial if they can be modelled with constant conversion efficiencies without further dependencies.

	Name	Description	References
Used in Case Study	Gas Boiler	Gas Condensing Boiler	trivial
	Pellet Boiler	Wood Pellet Boiler	trivial
	CHP	Gas Engine CHP	[332]
	PV	Roof-mounted PV (different orientations)	[333, 334]
	Solar Thermal	Flat Plate and Vacuum Tube Collectors	[333]
	Heat Pump	Brine/Water Compression Heat Pump	[335]
	Horizontal Collector	Horizontal Collector Pipes for Heat Pump	[336]
	Ice Storage	Ice Storage	trivial (only phase change energy considered)
	Vertical Collector	Geothermal Borehole for Heat Pump	[336]
	Underground Storage	Seasonal Thermal Energy Storage	[337]
	Power-to-Heat	Electrode Boiler	trivial
	Battery	Lithium-Ion Battery	[338, 339]
	Wind Turbine	Horizontal Axis Roof-mounted Wind Turbine	[340]
	Heat Storage	Water-based Sensible Heat Storage	[337]
Additional	Power-to-Gas	Electrolyser generating Hydrogen	
	Gas-to-Power	Fuel Cell for Hydrogen	
	Air Conditioning	Heat Pump for Cooling	
	PVT	Hybrid Solar Modules	
		...	

Modelling is based on power flows inside and between the technologies. As a result, aspects such as hydraulics or voltage stability are neglected. To model temperature-dependent efficiencies nonetheless, discrete temperature levels were introduced. A comprehensive description is given by Schönfeldt et al. [337], here a qualitative description will do: The main benefit of this method is, that it allows to optimise power flows and temperature at the same time using a linear model. Heat sources raise the temperature from one level to a higher one while adding energy. On the other hand, it is always possible to use energy at a higher temperature level for demands at a lower one. Where needed, virtual copies of a technology are created for every applicable temperature level. For example, a solar thermal collector can produce a certain amount of heat at one temperature or a lower amount at a higher temperature. To make sure, that the combination of these copies does not produce more heat then the real device could do, all the copies share a common resource. In the present example, it could be the solar radiation but technically it can be an abstract quantity without any physical meaning.

Since only power flows are considered here, the modelling of the local electricity grid is not planned, but the interaction with the public grid must be modelled. It is generally assumed that the supply area is connected to the public grid at one point and can both feed surplus electricity into it and draw missing electricity from it. Of course, physically it is not possible to do this at the same time and also economically it makes little sense to sell and buy electricity at the same time. The model therefore ensures that electricity can only flow in one direction at a time, but that this direction can change between two points in time.

The problem at this point is that the electricity feed-in can come from different generation plants. Depending on the funding, these can receive different feed-in tariffs. In order to be able to calculate the subsidies correctly, a method must therefore be used to allocate the amount of energy fed into the grid to the generation plants. Here, we use the arbitrary priority regulation ("Gewillkürte Vorrangregelung"[1]) that is common in Germany, in which a feed-in priority is set. The plant with the highest priority feeds into the grid first in the event of excess electricity, while the electricity from the lower-priority plants remains in the supply area.

6.2.2.3 | Energy demand modelling In addition to modelling the technical systems for energy conversion and storage, the time courses of the energy demand must also be known in order to map and optimise the entire system. As already shown in Figure 6.3, various final energy demands can arise, primarily electricity and heat. Especially in industry, other forms of final energy such as cold, steam or compressed air may be required, all of which would have to be modelled and included into the superstructure.

The easiest way to obtain these time series would of course be to install metering equipment on site and record over a longer period of time. In many cases, however, this equipment is neither available nor is it being read out reliably and regularly enough to provide sufficient data for the upcoming simulation and optimisation of the supply concept. In addition, the reason for planning a supply concept is frequently that new energy requirements arise from the construction of new buildings or the expansion of production capacities where it has not yet been possible to measure anything. For this reason, methods must often be found to estimate load profiles and generate them synthetically. Although there are standardised load profiles, especially for electricity demand, which are used, for example, to organise small customers on energy markets or for network planning, these are usually not suitable for actual planning, so more sophisticated methods should be used [341]. Such methods differ significantly depending on the use case and are extensively described in the literature [184, 342, 343].

[1] https://www.clearingstelle-eeg-kwkg.de/sites/default/files/Votum_2015_11_1.pdf

6.2.3 | Optimisation algorithms

The process of optimal design consists of two parts: 1. The choice of optimal technology combinations and their sizes and 2. the choice of optimal operating strategy. There are approaches to solve these two parts simultaneously with only one algorithm (e.g. [344]), but the requirements for optimisation of our set-up can not be fulfilled with this approach. Thus, we use two separate algorithms that build on each other and exchange data. In doing so, the first optimisation step (optimisation of sizing) suggests a possible combination and dimensioning of the technologies in the superstructure. Their timely behaviour is then calculated in the second optimisation step (optimisation of operation) and the KPIs are evaluated. With this information, the first algorithm proposes new, potentially better technology sizes. The system thereby converges towards the ideal design. In Figure 6.5 this process is shown schematically.

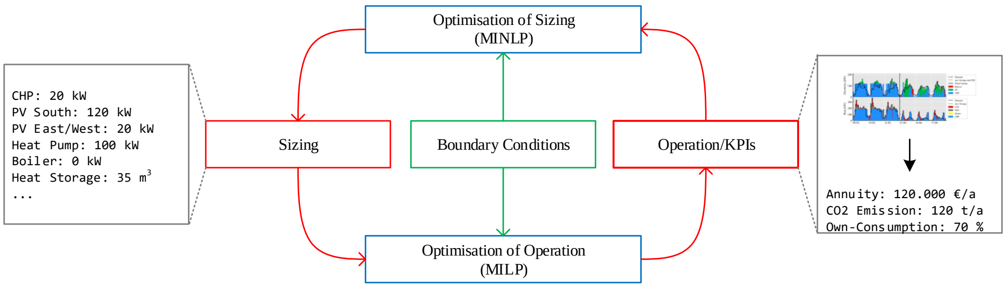


Abbildung 6.5: Schematic representation of the optimisation strategy as an iterative process between optimisation of operation and optimisation of sizing and the software used for this purpose. Exemplary data are shown. (Based on Schmeling et al. [132])

6.2.3.1 | Optimisation of operation In this part it is calculated how a given technology combination affects the operation and therefore the KPIs. This concerns the timely operation of each individual energy system also known as optimal dispatch. This optimisation is implemented using *oemof.solph* [266], an open source python-based tool for energy systems modelling. In *oemof.solph*, the energy system is built up from different sources and sinks as well as transformers which are connected to a directed graph. Each vertex (source, sink, transformer) can be assigned different technical properties (time series, efficiencies, ...) while the edges hold information on how an energy flow in this direction affects the optimisation function, e.g. costs. Even more complex model properties, such as minimum uptime of technologies or capacity charges can be defined. *oemof.solph* then translates this graph into a mathematically solvable Mixed Integer Linear Programming (MILP) problem where the operational status and energy flows at every timestep are degrees of freedoms of the optimisation.

The optimisation problem is solved using the python tool *pyomo* [345, 346], which in turn utilises different numerical MILP solvers of which *CBC* [191] has been used here. This solver has proven to be the most performant in comparison to other open source solvers.

Usually *oemof.solph* minimises the operating costs that are incurred for energy flows in the model. Thus, there is no static dispatch ranking or control strategy of the various technologies that could be represented in graphical form, but rather the operational management is decided anew for each point in time by mathematical optimisation. In terms of the previously introduced economic valuation using annuities (Section 6.2.1.1), the target function corresponds to the demand- and operation-related costs combined with the proceeds of the first year ($A_{D1} + A_{O1} - A_{P1}$). Deviating from this, an internal CO_2 penalty $p_{CO_2} \in [0€/t, 180€/t]$ payable per tonne of emitted CO_2 E is introduced for the optimisation of operation, but not for the subsequent economic KPI evaluation. In this way, it is possible to tune the operation of the system towards one or the other KPI for the same sizing. As a result, a technically identical system may be calculated several times with different operating strategies. The maximum of 180€/t corresponds to the total external costs of the emission as determined by the German Federal Environment Agency [274], which could be internalised in this way. This is not compulsory for own consumption, as there is already enough incentive to use electricity locally due to state subsidies and the chosen CO_2 assessment approach.

The objective function of the operational optimiser can therefore be formulated as follows:

$$\min \left(A_{D1} + A_{O1} - A_{P1} + p_{CO_2} \cdot E \right) \tag{6.5}$$

The *oemof.solph* model developed by us, including further necessary components for optimising the operation, are published under the name MTRESS (Model Template for Residential Energy Supply Systems") as open source software [347].

With this model, we manage to optimise the large number of technologies used in the superstructure. While in the literature (Table 6.1) only a few technology combinations have been optimised so far, our model allows to represent this multitude and to solve it in realistic computing times. The calculation time does not increase linearly with more technologies, but increases significantly with each new technology. The computational effort of such systems depends to a large extent on the complexity, i.e. the number of degrees of freedom to be optimised and their interconnection. The time required thus grows exponentially with the number of technologies, depending on the technology used.

6.2.3.2 | Optimisation of sizing Unlike the optimisation of operation, the optimal sizing has significantly less degrees of freedom (here: number of technologies), but the problem can no longer be linearised. This is mainly due to discontinuities caused by regulatory intervention (cf. Figure 6.4) and strong economies of scale in the costs and efficiency of technical components. Therefore this part of the optimisation is carried out as Mixed Integer Nonlinear Programming (MINLP).

In addition, optimisation can no longer be carried out on the basis of just one objective as before, but all three KPIs have to be taken into account, referred to as Multi-objective Optimisation (MO) optimisation. Due to the partly contradictory objectives, when comparing two solution vectors, it is not necessarily possible to determine which one is overall better, as they may differ in several dimensions. Solutions are therefore sought where one objective function cannot be improved without worsening another. The totality of these solutions is called Pareto-optimal and can be represented graphically in the form of Pareto fronts. Thus the optimisation problem can be mathematically defined in dependence on the technology sizes $\vec{x}$ as the maximisation of annuity $A_N(\vec{x})$, minimisation of emissions $E(\vec{x})$ and maximisation of own consumption $O(\vec{x})$:

$$\max\left(A_{\mathrm{N}}(\vec{x}), -E(\vec{x}), O(\vec{x})\right) \quad \text{s.t.} \quad \vec{x} \in X \tag{6.6}$$

Here, X refers to the solution space of the potential technology components sizes which, depending on the case study, would theoretically be conceivable within the superstructure. Often a value of zero, i.e. non-existence, can be assumed as the minimum plant size. At the upper end of the scale, systems such as PV or solar thermal systems are limited by the available roof area, while heat generators such as boilers or heat pumps can be limited simply by the maximum thermal load of the heat demand. The previously introduced internal CO_2 penalty is as well part of the solution space and is altered in the optimisation for different operating strategies.

Again, a fundamental problem of modelling is the large number of technologies used and the associated high mathematical optimisation effort; the choice of a suitable optimisation algorithm is thus critical in order to keep the computational effort within limits. There are many comparisons of possible approaches to solving such problems in the literature (e.g. [161, 200]), but the consensus is mostly that it depends strongly on the individual use case which approach is most successful. Therefore, various approaches such as classical optimisation algorithms as used in the optimisation of operation, swarm intelligence and genetic algorithms were tested and evaluated based on their performance. For this purpose, a shortened time period of the later case study was processed using different optimiser and their performance were compared based on convergence and computation time. In this, a Multi-Objective Evolutionary Algorithm with Decomposition (MOEA/D) algorithm has proven to be best suited for the problem at hand, which will at least be briefly described here:

The basis of this algorithm is an Evolutionary Algorithm (EA), a special form of metaheuristic, which uses processes known from biological evolution to perform mathematical optimisations. Several solution vectors, which are called individuals and in their entirety population, are placed randomly in the solution space and developed by environmental pressure towards the global optimum. This is achieved by a process of population reproduction over several generations. The higher the fitness of an individual in the solution space, i.e. the better it is adapted to its environment, the more likely it is to pass on its characteristics to the next generation [348].

In these, however, usually only scalar problems are solved, so the fitness of the individuals are directly comparable. As already described, this is not necessarily the case for MO optimisation, which is why these algorithms have to be modified. In MOEA/D decomposition is used for this purpose [349, 350]. The original large problem is broken down into sub-problems, which are then solved simultaneously. We choose an approach according to Tchebycheff [351] to generate these sub-problems, in which the objectives are combined using a weight vector resulting in a scalar fitness value. The best solution of a sub-problem in the current generation is combined with neighbouring sub-problems in the course of the optimisation, leading to an exchange of information along the Pareto front.

The MOEA/D implementation in *pygmo*/*pagmo* [352] is used, which uses further advanced techniques in addition to the basic framework to solve MO problems reliably and efficiently. For example, the CPU architecture of modern computers is used to separately optimise populations on different islands (threads) of an archipelago, while individuals can migrate between those islands [353].

In addition, other techniques must be applied to guarantee successful optimisation. For example, non-box constraints (in this case e.g. the legal minimum requirements for the renewable heat share or the restriction that roof tops cannot be used for PV and solar thermal at the same time) have to be modelled. This is realised with a dynamic penalty approach [354], in which the target function is artificially worsened if such constraints are not met in dependence of the violation. Initial guesses were also placed on the islands at the beginning of the optimisation in order to give the optimiser a first impression of the search space. These are classically designed systems, which can be further optimised depending on their quality but do not have to.

Nevertheless, the runtime of the optimisation framework described here is several weeks to months per case study on a recent consumer hardware PC until sufficient convergence is achieved which is mainly down to the runtime of the *oemof.solph*/MILP optimisation.

6.3 | Case study: Helleheide

The methodology shown above will now be applied in an exemplary way to demonstrate it in an application-oriented manner. The Helleheide district planned in Oldenburg, Germany, will be used for this purpose. This is a new urban district on a former military airbase, which will be used as a living lab for various Smart City activities. The living lab activities and the related stakeholder involvement in the development of innovative business models is described in detail by Brandt et al. [355]. More details about the district and the associated research projects can as well be found in Klement et al. [98], Schmeling et al. [132], Wehkamp et al. [256].

The buildings of the district are currently in the planning phase. It is to consist of seven buildings, whereby two existing buildings from military times could be preserved but have to be lavishly renovated. The district is characterised by a heterogeneous resident structure. In addition, a commercial enterprise is to be established in the neighborhood; currently, the establishment of a canteen kitchen and bistro is probable. Their energy demand profile is assumed in the following. It is also planned to create a student dormitory.

The district has to be supplied with electricity and heat for space heating and Domestic Hot Water (DHW). Cooling is rather uncommon in German residential buildings and is therefore not considered here. The process of determining the load profiles for the case study's energy demands is a multi-stage process. With the help of the software QuaSi [356], simplified cubatures, building material properties, weather data and usage profiles were used for each building to simulate the buildings energetic behaviour and thereby create hourly load profiles for space heating using a generic thermal building model based on EnergyPlus® [357]. These were compared to the annual heat demand according to energy performance certificates following DIN 4108 [358] and scaled accordingly. After validating against energy performance certificates, the buildings were simulated again, this time without internal gains due to electricity usage, because electricity and DHW hourly demand profiles were created using the LoadProfileGenerator [184]. However, since part of the space heating demand does not have to be covered by the heating system, but instead is covered by internal gains from electricity usage, the electricity demand time series was subtracted from the previous space heating time series, which, of course, can never be less than zero. The addition of this space heating time series with the DHW time series then results in the heat demand of the individual buildings. Since these buildings are to be supplied from a common heating centre, additionally the losses of a district heating network have to be taken into account. This is done according to a methodology described by Wehkamp et al. [256] and thus results in the heat time series to be provided at the outlet of the central heating system, which can then be used in the superstructure according to Figure 6.3. The district heating has a flow temperature of approx. 40 °C and can therefore be classified in the transition between third and fourth generation district heating [359].

Weather data of the year 2017 were used here and in any subsequent steps, since according to an internal survey, these can be regarded representative for the chosen location. The use of test reference years is not possible here, as the model also requires real electricity market data as input, which is strongly influenced by meteorological conditions. Both time series are therefore to be taken from the same year.

A graphic representation of the resulting energy demand is shown in Figure 6.6. Summed up over the year, this results in electricity demand of 535 MWh/a and heat demand of 541 MWh/a.

What can be seen for heat is a seasonally strongly fluctuating demand, especially in the winter months, supplemented by a relatively constant demand for DHW. Larger load peaks are to be expected during the day. Electricity demand, on the other hand, is affected less by seasonal fluctuations and is also better distributed over the day. Here, peak loads occur mainly in the morning and evening hours.

The aim of this study is to provide a recommendation that is as application-oriented as possible. Therefore the German legal framework is implemented as accurately as possible. This includes the support regimes for PV and wind under the Renewable Energy Sources Act (EEG), the funding of CHP plants under the CHP Act (KWKG) and the minimum requirements for renewable heat supply under the Building Energy Law (GEG). Current costs for energy procurement and feed-in as well as the associated state-induced levies and taxes as of 2021 are also taken into account. Furthermore, it is assumed that electricity is bought and sold on the EEX day-ahead market, i.e. new prices have to be considered every hour. In contrast, natural gas is purchased at fixed prices.

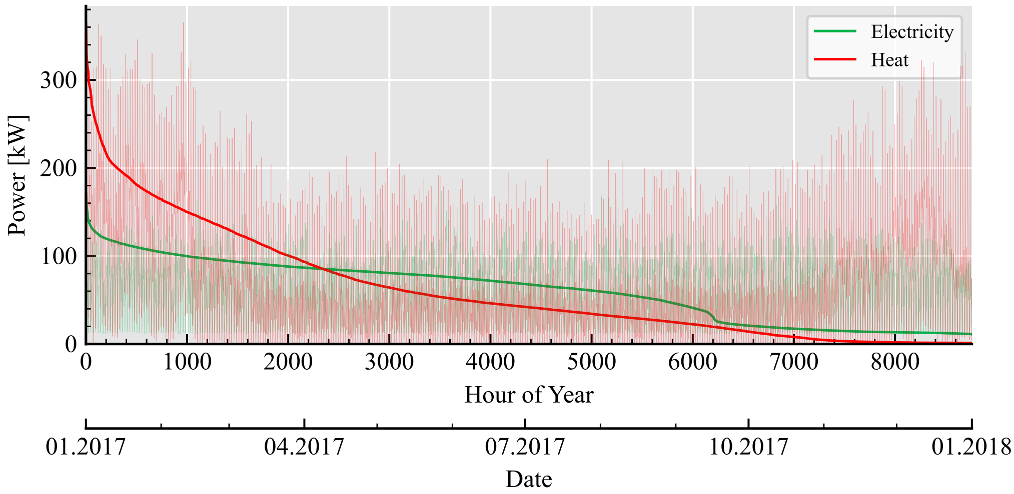


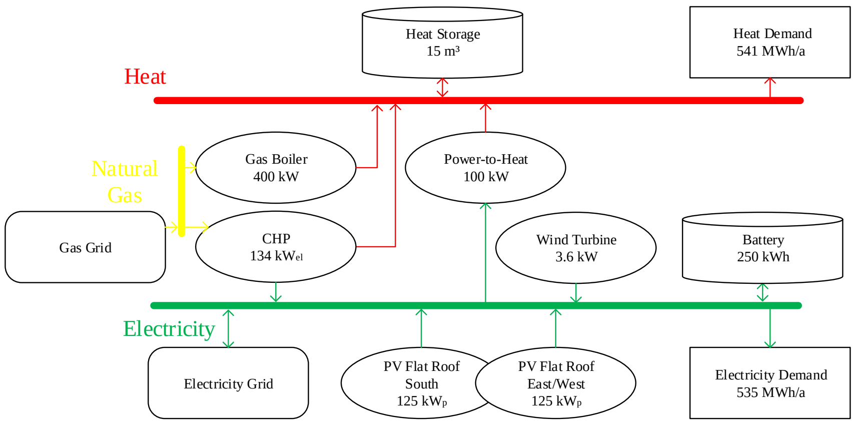
Abbildung 6.6: Time course of the hourly electricity and heat demands of the case study as time series and load duration curve.

The framework described above is of course not only suitable for such residential areas, but also for commercial and industrial environments. However, the chosen district has the advantage of combining different consumers with very different requirements, which, taken as a whole, exhibit a highly variable and counter-cyclical behaviour towards the availability of environmental energy. The design of the energy system is therefore particularly challenging. The application of this methodology to other case studies with different research questions and challenges is subject of future publications.

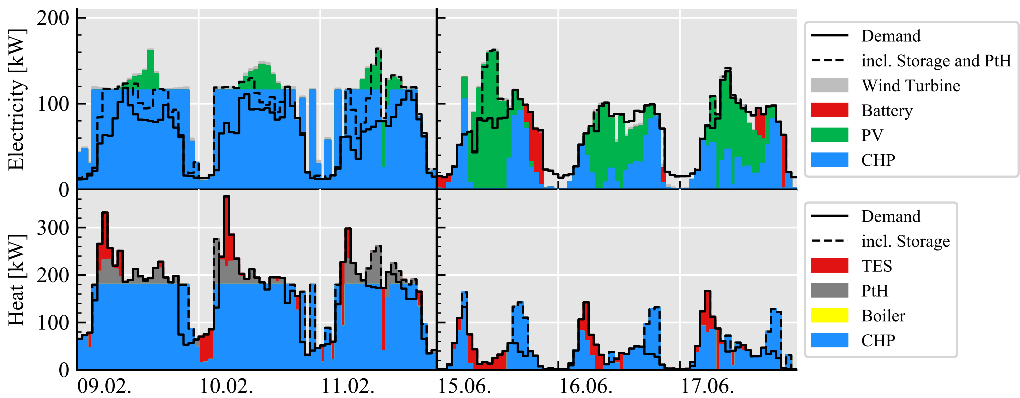
6.4 | Results of the optimal design process

The results of the optimisation of operation will be demonstrated, before the results of the overall optimal design process will be discussed in detail. Therefore two different exemplary system designs will be shown and their behaviour will be explained, starting with a CHP and PV based design. This is shown in its structure and in its exemplary behaviour in Figure 6.7.

We show here three days in February as an example for the heating season, and three days in June as an example for the summer time. The heating season is characterised by an extensive use of the CHP, which almost permanently meets all demands on both the electricity and heat sides. In contrast, the CHP is used much less in summer. This happens mainly in the morning and evening hours, as peak loads occur at this time that cannot yet be covered by the PV system on the electricity side. As soon as this is predominantly the case, the CHP unit switches off or reduces its output so that the district is self-sufficient. The resulting supply gap on the thermal side is then covered by



(a) Structure based on Figure 6.3

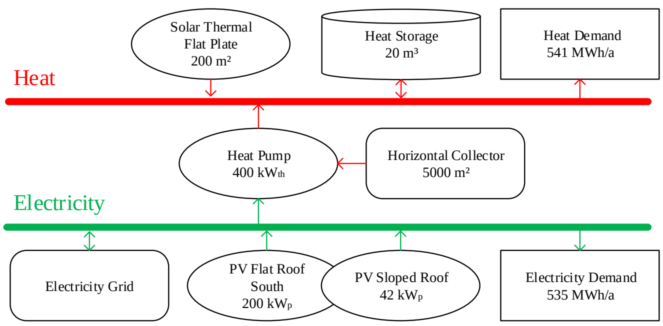


(b) Examples of the operating behaviour over three days in February and three days June.

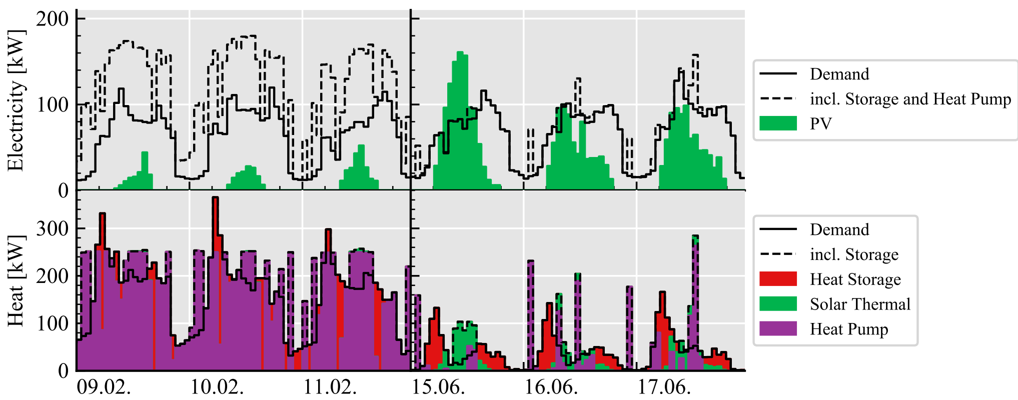
Abbildung 6.7: Exemplary illustration of a CHP and PV dominated system. This results in an annuity of 165 555 € /a, CO_2-emissions of 224.4 t/a and an own consumption of 90.5 %.

the heat storage system which has been charges beforehand. In winter, on the other hand, it is necessary to provide the missing heat via the existing Power-to-Heat (PtH) system. The relatively low PV generation is sold externally here for the most time, as the CHP is running most of the time to supply enough heat. This is another reason why the battery is mainly only used in summer, in order to shift the solar power from the midday hours to the evening hours and thus further reduce the load on the CHP unit. The wind turbine is used permanently on the electricity side, but does not play a significant and noticeable role due to its size. The boiler on the thermal side is not used here, but heat is generated via the PtH module, which apparently delivers better operating results here. Nevertheless, there may be times in the year when the boiler turns out to be better. The KPIs are good as expected, but only become truly meaningful when compared with other systems.

Additionally a system which is characterised by heat pumps, PV and solar thermal energy is shown in Figure 6.8.



(a) Structure based on Figure 6.3



(b) Examples of the operating behaviour over three days in February and three days June.

Abbildung 6.8: Exemplary illustration of a heat pump dominated system. This results in an annuity of 174 712€ /a, CO_2-emissions of 258.7 t/a and an own consumption of 87.2 %.

In this case, it is noticeable that the PV is adequately designed for the summer months, but is significantly undersized in the winter months. This is in stark contrast to the electricity demand, which is significantly higher than in the CHP case due to the heat pump and must therefore be covered mainly by grid electricity. In summer, the advantage of the large heat pump becomes apparent, as it manages to cover the needs of the district with very short running times. The combination of PV and solar thermal seems to be disadvantageous here, as a high electricity supply always coincides with a high heat production, which makes it unattractive to use the heat pump. This system is now worse than the previous one in all KPIs, if only slightly. Despite the extremely different technology combination and operation modes, the results are nevertheless comparable. This underlines the complexity of finding optimal supply design from a gut feeling.

Within the scope of the optimal design, about 53 000 such different designs were calculated and optimised multicriterially with the help of the presented methodology. Of these, about 42 000 were valid and realisable solutions which do not violate the boundary conditions. In turn, 1 909 points of this are Pareto optimal. This results in the three-dimensional Pareto front shown in Figure 6.9 whereas in Figure 6.10 the same information is displayed in two-dimensional space with the technical dimension in form of a colour bar.

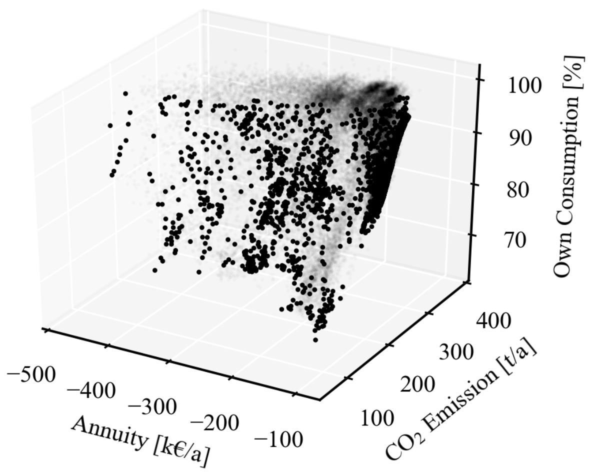


Abbildung 6.9: Visualisation of the solution vectors computed for the case study in terms of the defined KPIs, with the grey transparent dots representing all computed and feasible solutions while the black dots represent the Pareto optimal points thereof. Here it is shown in three-dimensional KPI space, the surface spanned by the Pareto-optimal points represents the three-dimensional Pareto front of the case study.

What can be seen here is the sufficient convergence of the optimisation as well as the expected broad Pareto front, which indicates a strong trade-off between the chosen KPIs. In contrast to many other studies, we do not expect a perfectly smooth front here due to the partly non-linear modelling of the individual technologies, but rather discontinuities in the representation. Further

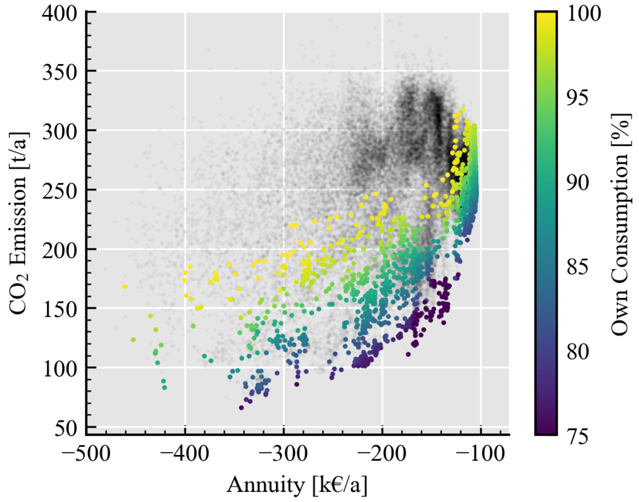


Abbildung 6.10: Visualisation of the optimisation results similar to Figure 6.9, whereby the technical KPI is shown as a colour bar, resulting in a 2D representation. The information displayed is the same. Anyhow, it is easier for the human eye to understand while there is a known perception bias in favour of the KPIs displayed on the axes.

optimization would lead to further filling of the existing gaps. However, a highly precise front is not essential here, as the methodology should rather provide tendencies and recommendations for decision-making in the planning process and not bring about a final decision.

Such important tendencies can be seen in this figure, e.g. the previously assumed conflict of objectives of the selected KPIs. While the degree of self-consumption can easily be pushed close to the technical maximum of 100 % and never falls below 65 %, a wide range of solutions are conceivable in terms of costs and emissions. The most cost-effective and climate-friendly solutions differ by a factor of 3.3 in terms of costs and even by a factor of 3.7 in terms of emissions. It is interesting that despite many discontinuities in the modelling of the individual technologies, the front appears rather smooth, so it should be very easy to find satisfactory compromises later on. This can be explained by a strong change in the combination of technologies, which will be analysed later as well as by the large amount of different technologies considered, as one should always find a suitable stopgap.

Starting with this thought, and to further understand the results, we look at how many technologies are involved in the energy supply for each design. This forms an additional dimension in the representation, which is why the previous visualisation methods are only of limited use. According to Filipič and Tušar [360], other methods were chosen. Here first a scatter plot matrix (Figure 6.11), in which all possible combinations of KPIs are represented as a cloud of points and the number of technologies contributing to the energy supply as a colour bar. We define a contribution as a system size that reaches at least 5 % of the previously defined maximum size.

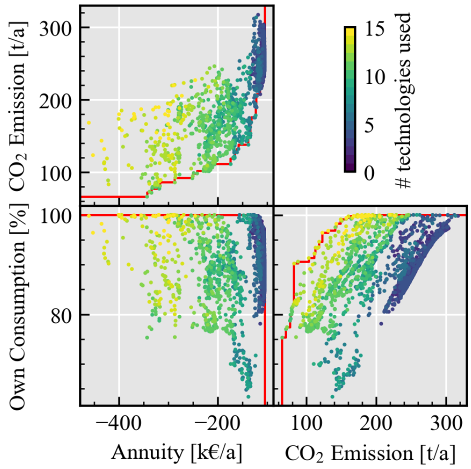
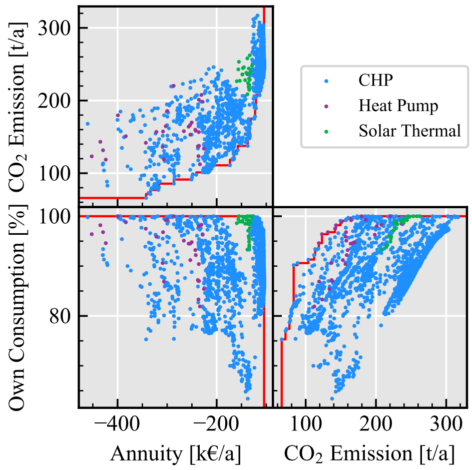


Abbildung 6.11: Renewed visualisation of the Pareto scatter matrix with the total number of plants of contributing size (>5 % of the maximum size) in the form of a colour bar.

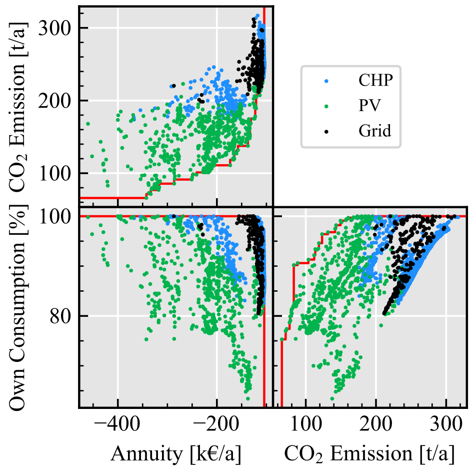
The very clear trend in this analysis is that systems with fewer technologies involved tend to be cheaper, which is of course due to the lower capital-related costs. However, these systems also show higher emissions than systems with more components. This may be due to the lack of flexibility in generation and storage. While systems with many, sometimes very different, supply components can find an optimal mode of operation at any time, those with fewer components are unable to do so. On the other hand, the number of components seems to have less influence on the degree of own consumption. The transitions here are fluid, which strengthens the previous hypothesis: The optimiser manages to find technologies very well that allow certain KPI fulfilment levels in an adequate size without leaving large gaps.

In order to go further into the analysis of the involved technologies, we analyse which of the technologies used provide the largest amount of secondary energy, electricity or heat, and thus dominates this energy sector (Figure 6.12). Again, a Pareto matrix is used, one for electricity and one for heat.

Looking first at the thermal side (Figure 6.12a), it emerges that of the seven potential technologies, only three, namely CHP, solar thermal and heat pump, seem to be able to dominantly provide the case study's energy supply in a pareto-optimal manner. The CHP is clearly the most common and universal solution in this, which, depending on the technology combination, results in monoobjective optima for all three KPIs. The heat pumps come into play mainly for designs with lower emissions and higher own-consumptions. Solar thermal energy merely fills a small gap between the best economic CHP systems and the other solutions. In general, the solution front seems to show discontinuities at this point, which could be due to discontinuities in government subsidies for CHPs (Figure 6.4). On the electrical side (Figure 6.12b), similarly strong tendencies can be seen. While grid-based systems lead to low costs and high levels of self-consumption, they usually



(a) Heat



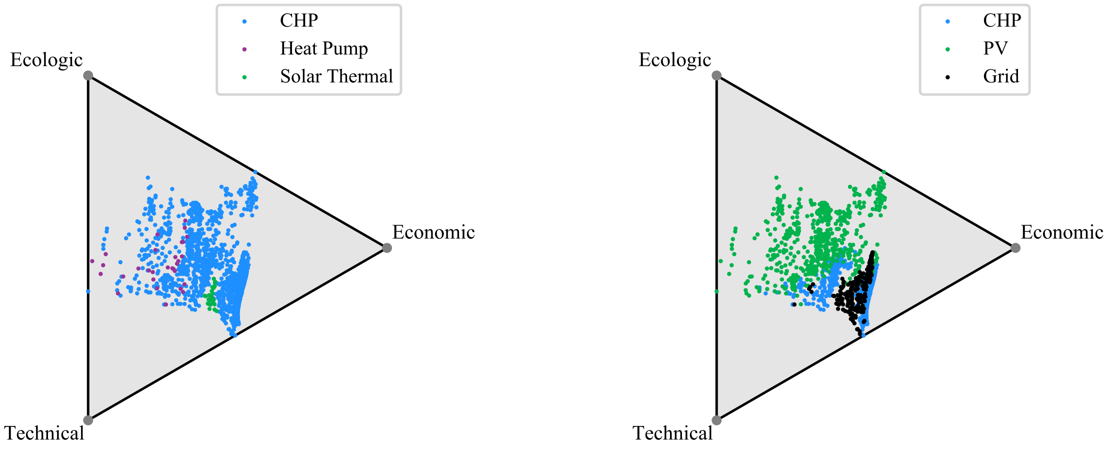
(b) Electricity

Abbildung 6.12: Illustration of the Pareto-optimal solutions in the form of a scatter plot matrix, in which each pair of KPIs is presented separately. The dominant technology for the two secondary energy forms, electricity and heat, is represented by a colour code. The structure of the figure at the top left corresponds to coloured points of Figure 6.10.

emit larger amounts of CO_2. In contrast, a dominant share of PV electricity leads to low emission but slightly higher cost. The own consumption in PV based systems is rather variable. Systems dominated by CHP electricity interestingly occure at two different occasions: Firstly, as the absolutely cheapest but most climate-damaging variety, and then as a middle ground between grid and acPV-dominated systems, which again shows the changeability of the CHPs.

When combined considering the number of technologies (Figure 6.11) and the dominant technologies (Figure 6.12), it is noticeable that CHP units can dominate in both smaller and larger technology combinations. Solar thermal, on the other hand, tends to dominate in smaller configurations, while heat pumps tend to dominate in larger ones. This is because technologies such as heat pumps only act as energy converters, converting different local energy resources into one another, e.g. heat from deep boreholes and electricity from PV into usable heat, whereas solar thermal energy or CHP units only require backup, e.g. from a gas boiler to work. On the electrical side, PV systems also tend to show their advantages in larger systems parks. This is due to the fact that they are particularly worthwhile, for example, in combination with heat pumps or PtH for heat generation or with batteries for storage. Here, too, CHP units tend to get by with fewer other technologies or, as the case may be, a grid connection theoretically does not require any technology at all.

An alternative method of visualisation, which has not been used much in the literature so far but which visualises the tendencies just explained even better, are so-called RadViz plots ([361], Figure 6.13). In this method, the KPIs are evenly distributed on the unit circle, which are used as anchors. Each Pareto-optimal point is then attached to these anchors with springs, where the spring tension is proportional to the degree of achievement of the KPI. The points are positioned in the force equilibrium of these springs, so the more a solution is dominated by a certain KPI, the closer it is to this anchor point. Thus, one expects mono-optimal solutions close to the anchors, compromises midway between them.



(a) Heat (b) Electricity

Abbildung 6.13: Illustration of the Pareto-optimal solutions in the form of a RadViz plot, where solutions are placed closer to the corresponding anchor points the more optimal they are in this respect. The dominant technology for each secondary energy form is shown by colour code.

On the thermal side (Figure 6.13a), it can similarly be seen that in a CHP-dominated system, it is possible to achieve optimality in all dimensions. In contrast, the heat pump-based solutions strive for good compromise between ecologic and technical KPI. Solar thermal energy again proves to be a gap-filler with high economic and potentially technical optimality. On the electricity side (Figure 6.13b), the important role of PVs dominance for the ecological KPI is again evident. CHPs seem to be more economically and technical optimal which is as well true for grid-based systems. Thus, the previously made statements can be confirmed here anew and the identified dominant technology islands can be understood even better.

Aside from the dominant technologies many other technologies are involved in the success of the systems, as noted earlier. Quantifying the influence of each individual component and its size is particularly difficult due to the high dimensionality. Here, a visualisation approach was chosen in which each plant size is correlated with each KPI individually and correlation coefficients are determined. The representation can be found in Figure 6.14.

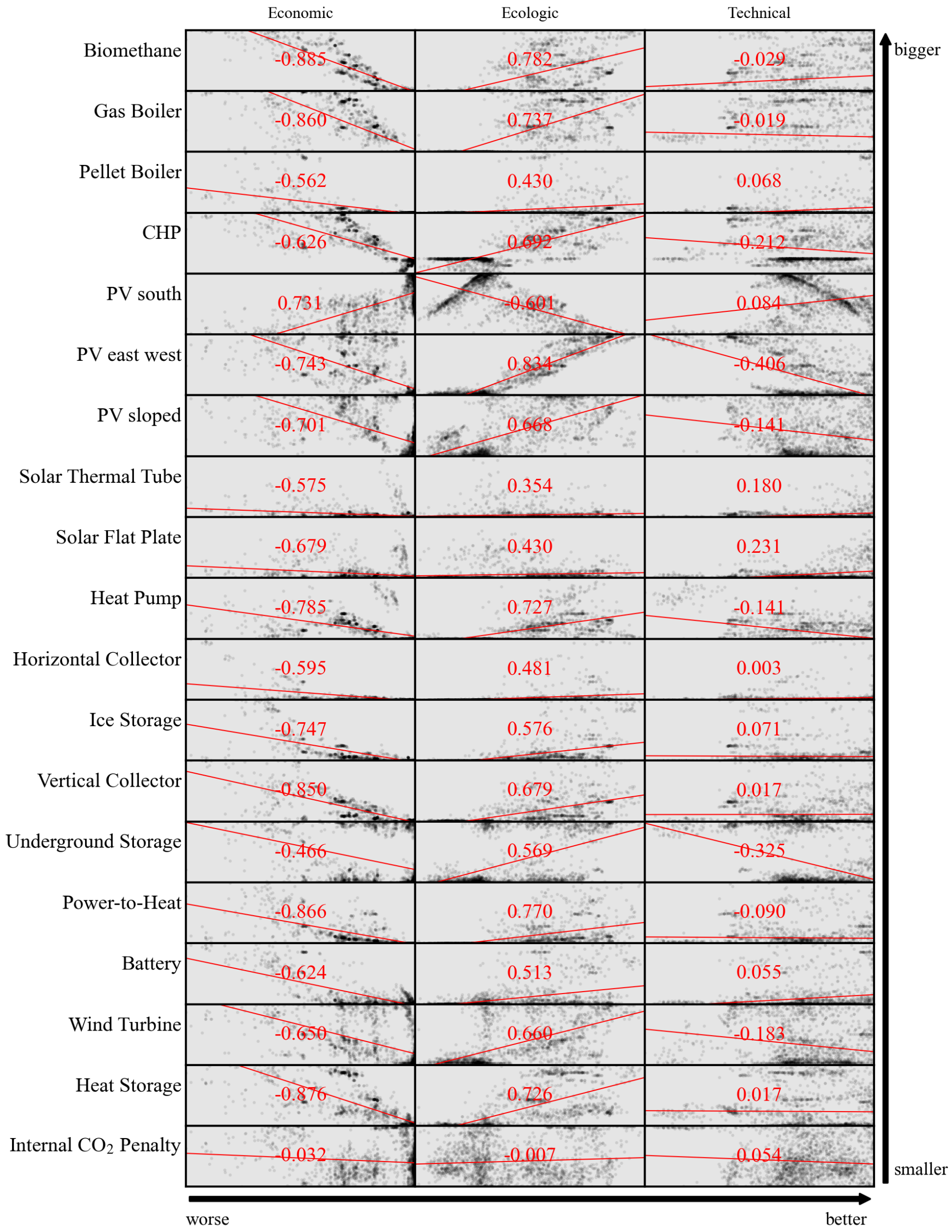


Abbildung 6.14: Correlation of KPIs and technology sizes as a scatter matrix. Only the Pareto optimal points are considered here. Linear regressions and the corresponding correlation coefficients are shown in red.

Only rough trends can be identified as the scatter range per technology is sometimes rather high. There seem to be few completely unattractive technologies (e.g. solar thermal tubes and horizontal ground collectors), but also no completely dominant technologies, as it seemed before with CHPs. The general conclusion is confirmed that many system components lead to good emissions and few components lead to good costs, while this has little influence on own consumption. It can be seen that in the economic KPI, very small CHP units are often used, which are frequently supplemented with medium expansion stages of PV and sometime solar thermal. On the other hand, very large CHPs fired with biomethane and supplemented with large PV systems are used for ecological optimality. For further flexibility, PtH and large thermal as well as electrical storage facilities are added. As already shown, heat pumps play a role in the trade-off between economic efficiency and climate protection. There is no clearly preferred heat source for heat pumps, but they seem to be frequently combined with CHP units, at least in part and contrary to current standard concepts. Very interesting here is the replacement of the more east-west oriented PV plants for good ecological KPI with more south oriented plants for a good economic KPI. There seems to be a clear competition for roof space, which solar thermal tends to lose. In the case of own consumption, on the other hand, far less clear trends can be discerned. Although PV systems and CHP units in particular seem to have a negative influence as their size increases, while solar thermal has a slightly positive influence, it is very difficult to generalise here. The positive influence of solar thermal is interesting, which can be explained by the competition for roof space with PV. In order to optimise own-consumption, the tendency again seems to be clearly towards south-oriented PV systems. This is in line with the experience in the design of PV systems for residential buildings, which in Germany are mostly oriented east-west for good own-consumption. What is also noticeable is that the virtual CO_2 price added to manipulate operations has almost no influence on the KPIs. There are economic optima despite high CO_2 prices, which are hardly more expensive than those without this pricing. It can be deduced from this that, contrary to what was originally assumed and is already the case today, an economically optimised mode of operation of the plants coincides with good ecological optimisation.

We could now go on and pick out individual energy systems and analyse them in more detail as shown in Figure 6.7 and Figure 6.8. Similarly, one could use complex algorithmic and methods to make finite decisions for a single energy system like TOPSIS [240]. However, as already explained, the framework developed and presented here is intended to identify trends and support the decision-making process in the overall context of energy system planning. Therefore, the analysis of the results ends here.

6.5 | Discussion

As has been shown with the case study, a simulation-based optimal design can provide interesting insights into the impact of plant sizes on KPIs and can help to make objective, valid and optimal decisions. The approach chosen here as a combination of an MILP optimiser for optimisation of operation in combination with a metaheuristic for optimisation of sizing offers the great advantage of being able to model realistic and comprehensive energy systems. The use and linkage of the two open source tools *oemof.solph* and *pygmo* has proven to be particularly beneficial in this, as it allows for a variety of necessary custom developments, improves the understanding of the results and significantly increases the transferability.

The possible insights and discernible trends that were possible due to the evaluation methods introduced do not lead to significant re-evaluations of the energy technologies studied and their raison d'être for the case study, but it is nevertheless interesting to see how to achieve similar results with very different system designs. However, this will largely be due to government influence and targeted promotion and can of course only be assessed here on the basis of a single case study. In order to be able to give conclusive assessments of the current German market situation, as well as economic analyses and possibly policy recommendations based on these, a large number of different case studies as well as sensitivity analysis are required.

The disadvantage of the chosen approach is the high computing time of several weeks due to the necessary complexity as well as the need for a lot of detailed data on the technologies used and the local conditions of the case study which are most of the times hard to collect. It is therefore essential at this point to develop further tools and, in particular, processes to either record such information on a project-specific basis or to approximate it using advanced methods. Caution is advised here, especially in the choice of KPIs, as these have a significant influence on the result. The KPIs chosen in this study are more of a national and public nature and do not, for example, reflect the actual contractual arrangements and business models of the case study. For this and many other reasons, the integration of the developed methodology into the big picture of phase-based energy system planning needs to be further investigated and the effect of such planning processes on the future national energy system needs to be quantified in more detail. In this way, a future integration of such software solutions supporting the decision-making process into the daily business of engineering offices and government agencies can be achieved in the long term, thus contributing to the efficient and sustainable energy supply of a wide variety of projects.

6.6 | Conclusion and Outlook

It has been shown that the optimisation of energy systems in terms of technology choice, sizing and operation is a well-understood problem in certain aspects, but the need to combine these individual facets into a common framework and thus gain insights into different complex types of energy supply concepts is particularly important. With the framework presented here, it will be possible to comprehensively investigate a wide variety of different technologies and especially their interaction for various use cases in an application-oriented manner. A special focus was placed on realistic modelling in order to be able to integrate this process into existing planning processes in industry in the future. The aim is not to make final decisions for the energy system, but to be able to provide trends and recommendations on the basis of which the relevant decision-makers can then make valid choices. The framework that has been created and the case study of an urban district shown here are only the starting point for a wide range of development and analysis options that will be expanded and intensified in subsequent studies like the use in industry, the addition of innovative technologies or the effects of such methodologies on a national level.

Author Contributions: Conceptualisation: LS; Methodology: LS; Software: LS and PS; Data Curation: LS, PS and LV; Formal Analysis: LS; Visualisation: LS; Writing – Original Draft Preparation: LS; Writing – Review and Editing: PS, PK, LV and BH; Project Administration: LS and PK; Supervision: BH, KvM and CA

Acknowledgments: The authors thank all the other *ENaQ* project partners for support, inspiration, and fruitful discussions. A special thanks is due to Timo Erfurth, Thorsten Jöhnk and Jan Kästner of KEHAG as well as Steffen Wehkamp of OFFIS.

Funding: This research was funded by the Federal Ministry for Economic Affairs and Climate Action (BMWK) and the Federal Ministry of Education and Research (BMBF) of Germany in the project *ENaQ* (project number 03SBE111).

7 | Multi-Stakeholder Optimal Energy Supply for Multi-Family Houses under 2021 German Market Conditions

The content of this chapter is identical to the following journal article:

Schmeling, L.; Walter, F.; Erfurth, E.; Klement, P.; Hanke, B.; von Maydell, K.; Agert, C.; Siebenhüner, B.; Multi-Stakeholder Optimal Energy Supply for Multi-Family Houses under 2021 German Market Conditions. Journal of Civil Engineering and Management 2024, 30(6), 481–493. doi:10.3846/jcem.2024.20924

Article

Multi-Stakeholder Optimal Energy Supply for Multi-Family Houses under 2021 German Market Conditions

Lucas Schmeling[1,2,3,*], Florian Walter[1], Timo Erfurth[1,4], Peter Klement[3], Benedikt Hanke[3], Karsten von Maydell[3], Carsten Agert[3], Bernd Siebenhüner[5]

[1] KEHAG Energiehandel GmbH, Im Technologiepark 4, 26129 Oldenburg, Germany
[2] Lintas Green Energy GmbH, Alter Stadthafen 3b, 26122 Oldenburg, Germany
[3] German Aerospace Center (DLR), Institute of Networked Energy Systems, Carl-von-Ossietzky-Str. 15, 26129 Oldenburg, Germany
[4] Energiebüro Erfurth, Am Born 3, 31171 Nordstemmen, Germany
[5] Ecological Economics Group, Carl von Ossietzky University of Oldenburg, Ammerländer Heerstraße 114-118, 26129 Oldenburg, Germany
* Corresponding author: l.schmeling@lintas-greenenergy.de / lucas.schmeling@dlr.de

Received: 25 July 2022 / Revised: 09 November 2023 / Accepted: 22 December 2023 / Published: 04 July 2024

Abstract: Especially in the energy supply of multi-family houses, a wide variety of stakeholders are involved, from owners, to users, to energy service providers and society. They usually have different requirements and understandings of optimality, but ultimately have to make joint decisions and thus sensible compromises. In Germany in particular, there are a large number of multi-family houses and, at the same time, many government restrictions and subsidies in terms of energy supply. This makes it difficult to make clear recommendations for the choice of an energy supply concept that takes all stakeholder interests into account. We first identify the relevant stakeholders and define their objectives. In order to relate these with one another, we present a methodology based on energy system simulation and TOPSIS to make energy concepts objectively evaluable. A generic multi-family house with 40 residential units is examined, combining different energy technologies and insulation standards. There is no energy concept that satisfies all stakeholders equally and it is difficult to build coalitions between them. The best results are achieved by air-source heat pumps in combination with photovoltaic.

Keywords: Energy System Optimisation; Energy System Simulation; Distributed Generation; Multiple-Criteria Decision Analysis; TOPSIS; DIN V 18599

7.1 | Introduction

The energy supply of buildings rarely concerns only individual stakeholders, but often encompasses a large number of different stakeholders who are affected in various ways by the chosen energy concept. In recent years, while the number of feasible generation and storage technologies has increased significantly, the objectives of stakeholders have diversified. Previously electricity simply came from the grid and heat was generated in gas or oil boilers, but today distributed energy generators such as Combined Heat and Power (CHP), Heat Pumps (HPs), Photovoltaic (PV) or Solar Thermal (ST) are available. These energy sources can not only optimise costs, but also reduce emissions and stabilise the overall power grid. In the planning of distributed energy supply solutions, objective methods to combine the technical aspects of energy supply with the wishes of the stakeholders and to provide decision support are rarely used. Instead, decisions are often made by individual stakeholders and political intervention is needed, for example, to ensure environmental protection and social justice.

Multi-family rental buildings in particular bring together a wide range of interests from different stakeholders, which is why they are particularly interesting for more comprehensive and objective methods. Outside of energy systems, the interests of landlords for the highest possible rental income collide with those of tenants for the lowest possible rental costs. Then when it comes to energy supply, there are even more stakeholders and in order to satisfy all of them compromise is inevitable. What is particularly interesting here is the trade-off between better energy efficiency through better insulation or through better energy generation. An energy concept always consists of the interaction between these two factors.

In this respect, Germany is a particularly interesting market. The country wants to be a pioneer in climate protection and the energy transition, and therefore has great incentives to include renewable energies in the energy supply of buildings, both in new construction and in renovation. The majority of Germans do not own a house or land (52%) [362], about 54.5 % of households are situated in multi-family housing [363]. A successful decarbonisation of the building sector can, to a large extent, therefore not be achieved by individuals in single-family houses. Instead it must take into account various stakeholders who are dependent on making compromises as described above.

The optimisation of energy systems is a widespread problem in the scientific literature, on which there are countless approaches and publications.

Specifically for the German market, there are various studies on which energy system is to be preferred and why. Mailach and Oschatz [364] are investigating a single-family house and a 6-family house along with various energy systems in new buildings. For this purpose, the cost annuities are evaluated, which are highest for CHP systems and lowest for Air-source Heat Pump (AHP) systems, for example. Other factors than this rather microeconomic view do not play a role in their study. [365] focus specifically on what cost-optimal energy systems in zero energy buildings in Germany could look like. The unique facets of tenant electricity supply under current German subsidy conditions and the associated optimal energy systems are dealt with by Braeuer et al. [366]. The latter studies in particular, however, contradict each other depending on the time of preparation, the framework conditions and the modelling assumptions and usually only highlight special cases of building energy supply.

The methods chosen for the analysis of optimal energy supply are highly diverse and there is a wide range of methods for the design and evaluation of energy systems on the basis of certain Key Performance Indicators (KPIs). For example, Schmeling et al. [134] present an approach for the multi-criteria optimisation of a residential neighbourhood using a metaheuristic. Here, too, a rather general valuation approach is chosen, but the energy technologies can be put together in almost any size and combination. Hancock et al. [367] extends this approach even further and looks not only at energy technology, but also at improving the building envelope of single-family homes. Similar approaches can be found with Wegener et al. [298] for a museum or Berendes et al. [297] for a small island. What is often missing, however, is the view of the different stakeholders, who do not only look at system costs or system emissions but pursue other individual goals.

Roloff [368] defines multi-stakeholder networks as those in which "business, civil society and governmental or supranational institutions come together in order to find a common approach to an issue that affects them all and that is too complex to be addressed effectively without collaboration". The involvement of local stakeholders in the design of energy systems is particularly important, as Kelly and Pollitt [369] points out. They specifically target local governments to create small-scale solutions within the boundary conditions they are familiar with. Hettinga et al. [370] highlight the need for the participation of different stakeholders in local solutions, which in their view are indispensable for achieving climate goals. They note that stakeholders have different perspectives on the optimisation and boundary conditions of an acceptable local energy system due to their different knowledge and skills. These can be understood as KPIs of the system and can vary greatly.

There are also methods for comparing and ranking different non-comparable goals, which are generally summarised under the term Multiple-Criteria Decision Analysis (MCDA). For instance, Mela et al. [371] use various MCDA methods to make optimal design decisions in the building context. They demonstrate established processes to optimise, for example, the wall construction of a single-family house in terms of cost, thermal insulation and customer satisfaction. Kirppu et al. [158] apply such a methodology to choose a heat generation technology for the district heating network in Helsinki with the help of industry experts. Baumann et al. [372] demonstrate different techniques using the example of selecting an energy storage technology. A more detailed insight into MCDA and the relevant methods will be given in a later chapter.

What has not been found so far is now the combination of these different approaches. Our goal is to be able to make statements about energy systems under the current German framework conditions by using MCDA and multi-stakeholder methods. We hope to provide decision-makers with a guideline for energy system design and to give politicians insights into the effects of current subsidy policies. It is our conviction that only through the full engagement and participation of all relevant stakeholders in the decision-making process towards the decarbonisation of the energy supply of residential buildings can be successfully and satisfactorily achieved.

In order to better understand this market and to be able to derive optimal energy concepts as a compromise of the interests of different stakeholders, a methodology is presented below and an analysis is carried out for a generic German multi-family house. Chapter 7.2 identifies the stakeholders relevant to the investigated subject and defines their objectives as KPIs. Chapter 7.3 then presents a method for multi-stakeholder decision making based on an energy system simulation and a decision-making methodology. Chapter 7.4 outlines the case study of a German multi-family house, the results of which are discussed and generalised in Chapter 7.5. The aim is to find general market trends and to be able to make generally valid recommendations by making assumptions about the German market that are as generic as possible.

7.2 | Identifying relevant stakeholders and quantifying their objectives

Depending on the particular arrangement, a large number of different stakeholders may be involved in the energy supply of a building. In order to do justice to the claim of providing general statements about the current market situation and to demonstrate a methodology for investigating such questions, only the stakeholders directly involved in the energy supply are defined directly. This includes the building owner, the building user (e.g. tenant), and the energy service provider. All interests going beyond this are subsumed in a stakeholder referred to as “society”. Indirectly, but still important is the legislator. The legislator sets the framework for action that they want fulfilled. An overview of the relevant stakeholders and their relationships can be seen in Figure 7.1, their exact role and objectives are explained below. However, the stakeholders identified for the purpose of this study and their objectives here are only to be understood as exemplary for the application in the case study used later. Depending on the nation and the associated framework conditions, there may be other stakeholders or other objectives. The methodology used is nevertheless transferable without restriction.

The **owner** owns the property and is therefore responsible for all decisions and investments concerning the building components. Income is generated by the sale or rental of the premises. It is therefore in their interest that the investment costs remain as low as possible, that they receive a high state subsidy (which, in addition to monetary incentives, also brings benefits in terms of reputation and marketing), and that they can rent out/sell as much space as possible, i.e. that the wall structures do not become too thick and thus reduce the room sizes. The investment costs for the insulation are estimated according to Schöndube et al. [373]. The state subsidy amounts are derived from the KfW’s BEG subsidy program (Credit Institute for Reconstruction – Federal funding for efficient buildings) as of mid 2021 and are treated as a separate KPI. Under this programme, buildings are subsidised with a 15 % (KfW55) or 20 % (KfW40) repayment subsidy if they comply with certain minimum energy standards. A further 2.5 % is added if the system covers its heat from at least 55 % renewable energies (KfW55EE/KfW40EE) [374].

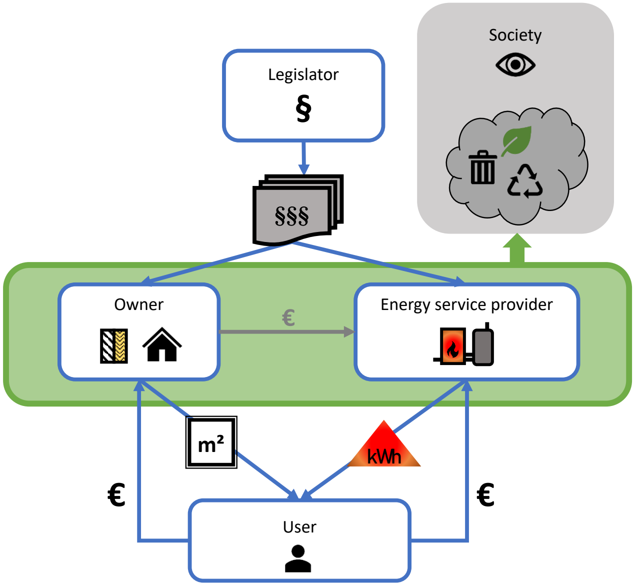


Abbildung 7.1: Graphical representation of the main relevant stakeholders identified for multi-family home energy supply and their interactions as modelled and discussed in this study.

The **energy service provider** invests in and operates the energy generating facilities. The costs incurred for this are charged to the user. In order to offer the user a marketable energy price, they may be dependent on a subsidy for construction costs from the owner, who must take these costs into account in their investments. They are trying to maximise their profits. In order to ensure this with as little risk as possible, it is advantageous for them to have a high percentage of Capital Expenditures (CapEx) and a low percentage of Operational Expenditures (OpEx), since the energy procurement costs and the energy purchase quantities can fluctuate strongly. The profits are calculated by KEHAG Energiehandel, an energy service provider operating in Germany, using internal tools and assumptions.

The **user**, in turn, wants to have the lowest possible heating costs. For them, a high proportion of OpEx is advantageous, since they can then achieve a high effect on their heating costs by changing their behaviour. The calculation of the residents' energy costs is also based on internal calculations with the support of KEHAG Energiehandel.

While the other stakeholders mainly look at economic parameters, **society** focuses on the environmental impact of energy supply. The aim is to release as few emissions as possible. Here, too, a higher proportion of emissions during the use phase is advantageous, since these can be optimised by changing user behaviour. For this purpose, the Global Warming Potential (GWP) is calculated, i.e. the CO_2 equivalents from construction over an operation period of 20 years to disposal. If the life expectancy of the components is higher or lower, these are taken into account proportionally.

Emission data from various sources are included in the calculation [375–377].

Table 7.1 provides an overview of the identified objectives. Due to the claim of an investigation that is as generic as possible, the objectives and their exact calculation were not developed by the stakeholders themselves, as the later case study corresponds to a generic multi-family house and not a real project, but through expert interviews and KEHAG Energiehandel's many years of experience as a provider of energy supply solutions for residential buildings. If the method should be applied to a real real estate project, there is no reason why the KPIs of the stakeholders should not be quantified individually through appropriate interviews and surveys and used for the analysis.

Tabelle 7.1: Tabular overview of the stakeholders and their exemplary objectives. The arrows in front of the objectives indicate the direction of the ideal solution.

Stakeholder	KPI
Owner	↓ Investment for energy system ↓ Increase in wall thickness ↑ State Funding
Energy Service Provider	↑ Profit ↓ Sensitivity (OpEx vs. CapEx)
User	↓ Heating cost ↑ Sensitivity (Energy vs. Basic Rate)
Society	↓ GWPt20 ↑ Sensitivity (Variable vs. Fixed Emissions)

Of course, it can happen that certain stakeholder groups overlap, e.g. the owner is also the user of the property. Especially in these cases, it is advisable to discuss the objectives used for the project with the local stakeholders and adapt them individually. In the above-mentioned case of an identical owner and user, the focus would presumably be placed on the overall system costs, i.e. CapEx plus OpEx, as these are borne by the same person. However, as it is quite common in Germany to live in multifamily houses for rent (cf. Chapter 7.1), these groups of people are considered separately and their interests are only brought together with the MCDA later on.

7.3 | Design of a methodology for multi-stakeholder energy system valuation

Now that we have a better understanding of the exemplary stakeholder goals, an objective methodology is needed to make different energy systems comparable. First of all, a methodology is needed to be able to calculate the KPIs altogether, which simulates and evaluates the different energy system depending on the design. This is presented in the next subsection. Based on this, a method is needed to make the different alternatives comparable on the basis of stakeholder interests and to create an objective, global ranking of the alternatives. More details on this can be found in the chapter after the next. The process is depicted graphically in Figure 7.2.

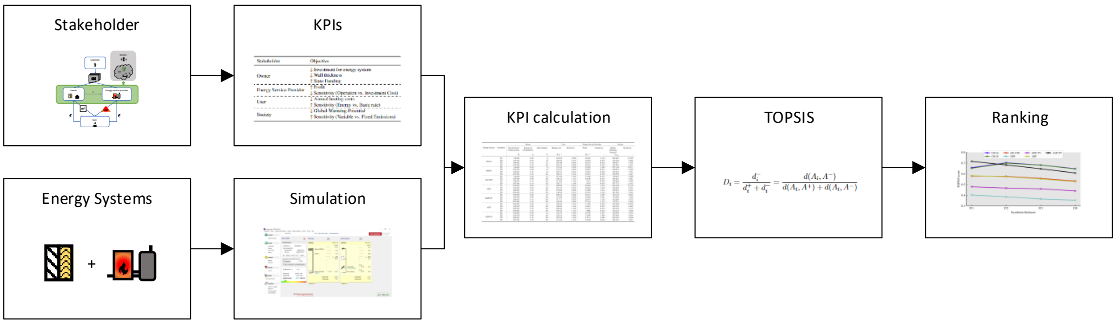


Abbildung 7.2: Illustration of the chosen methodology for the valuation of different energy supply concepts from the point of view of different stakeholders.

7.3.1 | Energy System Modelling and Simulation

In order to use the previously defined methodology, the identified stakeholder KPIs must be quantified. This requires more detailed specifications and analyses, e.g., of the energy system sizing as well as their mode of operation during the year. For this purpose, both the building envelope and the energy systems used must be modelled and simulated in an appropriate way. In addition to purely technical modelling, this includes country-specific features such as legal framework conditions or subsidy programs.

In many countries it is even required by law that such a simulation be carried out according to a technical standard for new buildings or extensive renovations. In the EU, this is regulated in the "Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of building" [378], implementation is up to the member states. Legal limits are then set and subsidies are offered if the planned building complies with certain framework conditions. The aim is to ensure that buildings become more energy-efficient and thus more climate-friendly in the future in order to make an active contribution to climate protection. In Germany, the Building Energy Act (Gebäudeenergiegesetz, GEG) stipulates that every new building or comprehensive building renovation must be assessed in accordance with DIN V 18599-1:2018-09. The basics of the calculation are roughly outlined here, for more information please refer to the standard.

For simulation, the building is first defined based on its dimensions and location. Afterwards, catalogues are created in which each component (exterior wall, windows, roof area, floor slab, ...) is defined with its building physics properties and orientation. The technical building equipment including the required distribution and transmission are also specified. The standard then determines the useful heat demand in a monthly process from the internal and solar gains, which are offset by losses due to transmission, thermal bridges and ventilation. The difference between gains and losses must then be provided by the heating system, which, also suffers losses in the conversion from primary energy to useful energy. The most important results in terms of legislation are, firstly, the primary energy demand of the building Q_p and, secondly, the transmission heat loss H_T.

The primary energy demand Q_p is defined as the sum of the final energy used $Q_{f,in,j}$ multiplied by a fuel-specific primary energy factor f_{p_j} per energy form used j, which is 1.8 for electricity and 1.1 for natural gas. This factor takes into account the upstream chain of energy production and the fossil primary energy used in this process. Energy generated in or on the building (e.g. from PV) that cannot be used directly but is fed into the grid $Q_{f,out,j}$ must be deducted from this. The primary energy factors may differ depending on the direction of the flow. This results mathematically in:

$$Q_p = Q_{p,in} - Q_{p,out} = \sum_j Q_{f,in,j} \cdot f_{p_j} - \sum_j Q_{f,out,j} \cdot f_{p_j} \tag{7.1}$$

The transmission heat loss H_T, on the other hand, is calculated only from the building physics and neglects the technical building equipment. For this purpose, the aforementioned component catalogue is used and the area A_i of each component i is multiplied by its U-value U_i. A correction factor F_{Xi} is applied, which takes into account that heat losses to the outside air are higher than to the ground. A general thermal bridge surcharge ΔU_{WB} is then added, which is also calculated from the component areas. Thus, the entire expression reads:

$$H_T = \sum_i (U_i \cdot A_i \cdot F_{Xi}) + \Delta U_{WB} \sum_i A_i \tag{7.2}$$

Details of how the characteristic values are determined and, in particular, how the performance during the year is calculated in relation to buildings and energy technology are set out in DIN V 18599 on aprox. 1900 pages. Some of the guidelines are extremely complex and concern a large number of special cases and innovative technologies. Accordingly, there are many software solutions on the market that meet precisely these requirements and are developed and distributed commercially. An overview for the relevant German market can be found at Behaneck [379] or Venzmer [380]. We are using the software "Hottgenroth Energieberater 18599 3D PLUS"[1] for the following analysis. However, there are also open source solutions such as energyPLUS [381] which have been developed in academia and can therefore be used rather universally but which lack many usability features.

7.3.2 | Joint decision-making using TOPSIS

As shown in Chapter 7.1, the goals of the relevant stakeholders are very different, but as shown in Chapter 7.3.1, they can be quantified relatively easily with suitable software solutions. In many cases the goals even contradict each other, e.g. the user demands a high OpEx share that he

[1] https://www.hottgenroth.de/M/SOFTWARE/EnergieNachweise/Energieberater-18599-3D/Seite.html,73274,80422

can influence, while the energy service provider favours a high CapEx share for risk minimisation. The same can be argued for the climate protection demanded by society in contrast to the affordability and profit of the other stakeholders. Nevertheless, in the end, joint decisions have to be made, taking into account all stakeholder objectives, and an energy system has to be selected and implemented. It will be impossible to satisfy all stakeholders comprehensively, but the aim should be to find suitable compromises. In abstract terms, this means that different options for action have to be evaluated on the basis of certain indicators that cannot be compared with one another. The decision-making problem between different stakeholders considered here is thus a group decision-making problem.

In science, various tools and methods are known for this purpose, which allow to support such decision processes and to make reasonable compromises. The methods are grouped under the umbrella term MCDA. A general overview of the methods can be found e.g. at Løken [150] or Abdullah et al. [382]. Matsatsinis and Samaras [383] find that for the problem of group decision support described here, MCDA is well suited to achieving consensus or at least reducing conflict between stakeholder. Here we will briefly outline the most important MCDA methods and justify our selection.

In **Analytic Hierarchy Process (AHP)**, the alternatives are evaluated in pairs by experts, thereby creating an alternative matrix that can then be mathematically transformed into a ranking [384]. AHP is one of the simplest MCDA methods, but requires a lot of expert knowledge. In addition, the technique is susceptible to rank reversal.

Elimination and choice translating reality (ELECTRE) incorporates various methods and can evaluate a large number of very different problems, including those under uncertainty [385]. However, the methodology and results are difficult to apply as well as to explain.

Preference ranking organization method for enrichment evaluation (PROMETHEE) is similar in approach and scope to ELECTRE, both belonging to the European school of MCDA Brans and Mareschal [151].

In **Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)** the alternative is sought that is not only close to the optimum but also far from the pessimum [386]. It is much easier to set up and follow than the previous ones and still provides reliable results.

A very similar approach to TOPSIS is **Vise Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR)**, which not only results in a single ranking, but the method outputs three different rankings based on the calculated distances to the optimum [387]. The results between TOPSIS and VIKOR tend to be rather different, though for few evaluation criteria and alternatives they tend to be fairly similar [388].

An approach often used in combination with other methods, especially for complex problems, is **Decision Making Trial and Evaluation Laboratory (DEMATEL)**. What is particularly interesting about this method is that even complex alternatives can be represented in a graphical method [389].

According to Mela et al. [371], which compares the MCDA methods presented here and others in the context of the construction industry, the methodology of choice is the one that provides a good compromise between user-friendliness and informative value. We have therefore chosen the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method, which allows us to identify trends relatively easily with small data sets and little effort. The seven steps of the TOPSIS method are therefore described here with reference to Pavić and Novoselac [386]:

Problem formation: Out of m different options A_i which differ in n different criteria x_{ij} the best option is to be chosen. The criteria are divided into benefit ($x_1, ..., x_k$, monotonically increasing preference) and non-benefit ($x_{k+1}, ..., x_n$, monotonically decreasing preference).

Step 1 - Evaluation matrix: First, an evaluation matrix X is formed in which each column represents a criterion and each row represents an option.

$$X = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix} \tag{7.3}$$

Step 2 - Normalisation Since the criteria are not comparable with each other and represent completely different orders of magnitude, they must be normalised by replacing each value x_{ij} with a normalised value r_{ij} as follows:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{7.4}$$

Step 3 - Weighted normalised matrix Now, weights for the various criteria are defined and included on the basis of the individual criteria relevance. For this purpose, each previously normalised value is multiplied by a weighting factor w_j, where $\sum_{j=1}^{n} w_j = 1$, which results in the matrix A:

$$A = \begin{bmatrix} r_{11} \cdot w_1 & r_{12} \cdot w_2 & \dots & r_{1n} \cdot w_n \\ r_{21} \cdot w_1 & r_{22} \cdot w_2 & \dots & r_{2n} \cdot w_n \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} \cdot w_1 & r_{m2} \cdot w_2 & \dots & r_{mn} \cdot w_n \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix} \tag{7.5}$$

Step 4 - Determination of the best and worst solution Based on the normalised and weighted alternatives, the globally positive and negative optimal solution (A^+ ; A^-) vectors are now to be determined. These consist of the best and worst value per criterion, i.e. $A^+ = (a_1^+ a_2^+ \dots a_n^+)$; $A^- = (a_1^- a_2^- \dots a_n^-)$. The individual entries are to be defined from:

$$a_j^+ = \begin{cases} \max\limits_i a_{ij} & \text{for } j = 1, ..., k \\ \min\limits_i a_{ij} & \text{for } j = k+1, ..., n \end{cases} \qquad a_j^- = \begin{cases} \min\limits_i a_{ij} & \text{for } j = 1, ..., k \\ \max\limits_i a_{ij} & \text{for } j = k+1, ..., n \end{cases} \tag{7.6}$$

Step 5 - Determining the Euclidean distances For each criterion of each alternative, the distance to the optimum A^+ and pessium A^- can now be jointly determined, from which the distance vectors d^+ ; d^- result where $d^+ = (d_1^+ d_2^+ \dots d_m^+)^T$; $d^- = (d_1^- d_2^- \dots d_m^-)^T$. The Euclidean distance is calculated as follows:

$$d_i^+ = d(A_i, A^+) = \sqrt{\sum_{j=1}^{n} \left(a_{ij} - a_j^+\right)^2} \qquad d_i^- = d(A_i, A^-) = \sqrt{\sum_{j=1}^{n} \left(a_{ij} - a_j^-\right)^2} \tag{7.7}$$

Step 6 - Determination of the relative distances Finally, the distance of each alternative to the optimum and to the pessimum must be put into relation, resulting in the quality value D_i of alternative A_i:

$$D_i = \frac{d_i^-}{d_i^+ + d_i^-} = \frac{d(A_i, A^-)}{d(A_i, A^+) + d(A_i, A^-)} \tag{7.8}$$

Step 7 - Ranking Finally, the various alternatives can now be compared. The previously calculated value D_i represents an ordinal number according to which the different alternatives can be sorted. The highest value of the alternatives thus corresponds to the best solution, the lowest to the worst.

7.4 | Application to a case study

To demonstrate the methodology and to draw conclusions about optimal energy systems under the current German framework conditions, the energy concept of a typical German multi-family house will be applied. For this purpose, the building structure of the "Mehrfamilienhaus groß" (large multi-family house) is used, which was defined in 2010 by the Center for Environmentally Conscious Building (Zentrum für umweltbewusstes Bauen e.V.) as a reference building for such studies [390]. The building has 40 residential units of 71.25 m^2 each and has a flat roof with a recessed upper story. It thus corresponds to the typical new construction of German residential buildings in larger cities.

As previously indicated, we understand energy concepts not only as pure energy generation technology but always as their interaction with the insulation of the building envelope. The quality of the energy supply can only be adequately understood in the interaction of these two systems.

For the study, we consider different technology concepts which correspond to the technologies predominantly in use in Germany today. The primary energy source for newly erected buildings in Germany in 2020 was natural gas (32.3 %) geothermal energy (8.2 %), environmental thermal energy (44.6 %) and wood pellets (3.4 %) [391]. Concepts that are no longer legally permissible in new buildings (pure natural gas or oil boilers) and technologies that are not yet established on the market (such as hydrogen) are not taken into account. The same applies to district heating, as the energy sources and technologies used are highly diverse and cannot be generalised.

Table 7.2 presents the energy-related equipment used in the following, which is based on the statistically most frequent ones. The sizing was carried out by the simulation software used based on empirical formulas defined in DIN V 18599 without further optimization. The size ranges given in some cases are situations in which the sizing depends on the building's overall design. The lower the thermal demand, the smaller the heat pump can be dimensioned and also the PV system can be smaller. For boilers, the standard does not provide for such interdependence.

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Tabelle 7.2: List of the energy technology investigated for the case study and its dimensioning, as automatically designed by the simulation software. In the following, the abbreviations mentioned in the first column are used.

Abbreviation	Primary heat source	Secondary heat source	Heat Storage	Additional electricity source
GB+S	Solar Thermal 114 m^2	Gas Boiler 103 kW_{th}	6.0 m^3	—
GB+CHP	Combined Heat and Power Plant 5 kW_{el} bis 9 kW_{el}	Gas Boiler 103 kW_{th}	1.4 m^3	—
GHP	Ground-source heat pump 62 kW_{th} bis 82 kW_{th}	—	1.4 m^3	—
GHP+PV	Ground-source heat pump 62 kW_{th} bis 82 kW_{th}	—	1.4 m^3	Photovoltaic 13 kW_p bis 17 kW_p
AHP	Air-source heat pump 62 kW_{th} bis 82 kW_{th}	—	1.4 m^3	—
AHP+PV	Air-source heat pump 62 kW_{th} bis 82 kW_{th}	—	1.4 m^3	Photovoltaic 15 kW_p bis 20 kW_p
PB	Wood Pellet Boiler 132 kW_{th}	—	7.6 m^3	—

In each technology concept, the house is connected via a 2-pipe system. Domestic Hot Water (DHW) is produced locally in each flat via a fresh water station. The HP systems work with system temperatures of 40 °C for added efficiency, so to ensure legionella-free water, the fresh water stations are extended with a flow heater that brings the water up to 60 °C. All concepts are equipped with the same central ventilation system including heat recovery.

These are combined with 4 different insulation thicknesses from IT1 (low insulation) to IT4 (high insulation) which are specified in more detail in Table 7.3. IT1 corresponds to the minimum legally permissible insulation, IT4 to the maximum insulation thickness of products available on the market. IT2 and IT3 are respective intermediate steps. The wall construction, the roof construction and the basement ceiling are varied; elements such as doors and windows are assumed to be constant.

Tabelle 7.3: Overview of the insulation thicknesses used for the relevant components. The values are taken from the product database of the software used and reflect products commonly used in Germany today.

		IT1	IT2	IT3	IT4	
Wall construction	Insulation thickness	12	18	24	30	cm
	U value	0.26	0.18	0.14	0.11	$W/(m^2 K)$
Roof construction	Insulation thickness	16	21	26	30	cm
	U value	0.2	0.16	0.13	0.11	$W/(m^2 K)$
Basement ceiling	Insulation thickness	4	10	16	22	cm
	U value	0.34	0.22	0.16	0.12	$W/(m^2 K)$

All in all, this results in 7 technologies $\cdot$ 4 insulations = 28 different alternatives to be ranked.

The subject of energy prices is particularly important and is currently the focus of a great deal of political attention. Here, we take data from the German Federal Statistical Office from the first half of 2021. At that time, the electricity price was 20.12 ct/kWh, the gas price 3.70 ct/kWh and the price for wood pellets 226€ /t.

Table 7.4 shows the stakeholder KPI calculated using the simulation software for these energy systems. As previously argued, it is impossible to make even approximate statements about the quality of the systems based on this data alone, which is why they have to be analysed in TOPSIS.

The weightings shown in Table 7.5 are used for the further analysis. Each stakeholder first determines the weightings of their own objectives, which must add up to 1. In order to bring the different stakeholders and their interests together, an additional weighting of the stakeholders must be defined. These would have to be negotiated between the stakeholders for a actual project, which would incur a significant level of effort.

The weights of the overall analysis then result from the multiplication of both values and add up to 1 as well. Since we are working with an abstract case study without real stakeholders, we have determined the weightings ourselves for demonstrational purposes to the best of our knowledge and experience.

Under the given weights, we can now calculate the TOPSIS scores, both from the point of view of the individual stakeholders, if they could decide on their own, and from the point of view of the stakeholder community. The results can be found in Table 7.6.

Tabelle 7.4: Score the stakeholder KPIs shown in Table 7.1 based on the energy systems defined for the case study.

		Owner			User		Energy Service Provider		Society	
Energy System	Insulation	Investment for energy system	Increase in wall thickness	State funding	Heating cost	Sensitivity	Profit	Sensitivity	GWP	Sensitivity
		€	m	%	€ /a	-	€ /a	-	t_{CO_2}	-
GB+Ss	IT1	60 000	0.00	0	324.05	0.859	22 565	1.142	662 270	15.538
	IT2	129 539	0.06	15	300.38	0.719	22 568	0.953	556 498	8.686
	IT3	198 852	0.12	15	287.88	0.644	22 573	0.854	508 817	5.797
	IT4	267 008	0.18	20	280.59	0.600	22 564	0.796	487 684	4.327
GB+Sl	IT1	60 000	0.00	0	341.84	0.780	24 263	1.090	675 169	15.011
	IT2	129 539	0.06	15	318.27	0.652	24 287	0.915	569 674	8.562
	IT3	198 852	0.12	15	305.74	0.584	24 287	0.823	522 048	5.781
	IT4	267 008	0.18	20	298.47	0.545	24 275	0.769	500 859	4.347
GB+CHP	IT1	60 000	0.00	15	377.76	1.387	11 382	0.351	180 219	3.386
	IT2	129 539	0.06	20	336.52	1.191	10 446	0.518	248 321	3.381
	IT3	198 852	0.12	20	314.86	1.100	9 751	0.605	283 082	2.868
	IT4	267 008	0.18	20	302.71	1.046	9 397	0.658	307 774	2.443
GHP	IT1	100 000	0.00	17.5	690.00	0.424	26 048	1.364	602 539	14.133
	IT2	169 539	0.06	22.5	619.73	0.450	22 803	1.403	569 848	9.075
	IT3	238 852	0.12	22.5	578.90	0.462	21 006	1.431	560 616	6.616
	IT4	307 008	0.18	22.5	549.63	0.457	19 919	1.452	561 830	5.237
GHP+PV	IT1	100 000	0.00	15	609.12	0.329	28 515	1.038	483 176	6.025
	IT2	169 539	0.06	22.5	557.90	0.330	24 952	1.091	473 646	4.792
	IT3	238 852	0.12	22.5	517.17	0.352	22 974	1.102	442 286	3.573
	IT4	307 008	0.18	22.5	493.46	0.350	21 784	1.124	472 781	3.222
AHP	IT1	100 000	0.00	17.5	320.66	1.467	11 380	3.926	524 262	14.089
	IT2	169 539	0.06	22.5	299.00	1.433	10 621	3.872	502 122	8.628
	IT3	238 852	0.12	22.5	286.66	1.420	10 179	3.855	498 742	6.170
	IT4	307 008	0.18	22.5	279.75	1.416	9 906	3.910	503 455	4.838
AHP+PV	IT1	100 000	0.00	17.5	241.87	1.094	16 726	1.967	400 894	4.973
	IT2	169 539	0.06	22.5	232.13	0.994	15 269	1.990	376 923	3.694
	IT3	238 852	0.12	22.5	222.43	1.034	14 451	1.999	363 146	2.806
	IT4	307 008	0.18	22.5	214.43	1.041	13 942	2.038	398 545	2.601
PB	IT1	60 000	0.00	17.5	504.43	0.611	15 365	1.693	106 178	1.795
	IT2	129 539	0.06	22.5	473.13	0.513	15 115	1.534	113 915	1.056
	IT3	198 852	0.12	22.5	456.87	0.460	15 180	1.445	125 921	0.730
	IT4	267 008	0.18	22.5	447.27	0.429	15 148	1.430	141 684	0.583

Tabelle 7.5: Summary of the selected stakeholders and objective weights.

Stakeholder	Stakeholder weight	Objective	Objective weight	Overall weight
Owner	0.25	Investment for energy system	0.40	0.100
		Increase in wall thickness	0.30	0.075
		State funding	0.30	0.075
User	0.35	Heating cost	0.90	0.315
		Sensitivity	0.10	0.035
Energy Service Provider	0.25	Profit	0.95	0.238
		Sensitivity	0.05	0.013
Society	0.15	GWP	0.90	0.135
		Sensitivity	0.10	0.015
SUM	1.00			1.000

7.5 | Discussion

Table 7.4 shows clearly how different the results are depending on the energy concept and insulation. For example, the investment costs between the GB+S with IT1 and the GHP+PV with IT4 differed by a factor of 5, while the heating costs between the GHP with IT1 and the AHP+PV with IT 4 differed by a factor of 3. There are similarly dramatic differences between the alternatives in terms of emissions and profits. This makes it impressively clear how important it is not only to decide on an energy system based on individual performance indicators of individual stakeholders, but also to carry out holistic investigations and look at the decision problem from different perspectives.

Based on Table 7.6, we are able examine what would happen if the stakeholders were allowed to decide without regard to the others.

Owner

The owner shows a strong dependence on the insulation thickness. This seems logical, as stronger insulation means higher investment costs and less leasable space for the owner. The resulting possibly higher state subsidies do not seem to cancel out this effect, but they do play a role in the choice of energy technology. ST systems, for example, only receive low state subsidies, whereas CHP- and HP-based systems offer higher subsidies with the same level of insulation. The slightly higher state subsidy for heat pumps due to the use of renewable energies (KfW55EE/KfW40EE) is exactly offset in this case by the cheaper DHW system of the CHP solution. The optimal system from the owner's point of view is therefore wood pellets with low insulation, which offers both high state subsidies and the simpler DHW system and minimum investment cost.

User

However, from the point of view of the user, who mainly focuses on heating costs, a higher level of

Tabelle 7.6: Result of the TOPSIS calculation for the case study from the perspective of the individual and all stakeholders. The colour code is formed for each column and ranges from green (best result) to yellow and red (worst result) and should help to classify the results visually more quickly.

Energy System	Insulation	Owner	User	Energy Service Provider	Society	Overall
GB+Ss	IT1	0.666	0.763	0.688	0.164	0.630
	IT2	0.687	0.805	0.689	0.226	0.673
	IT3	0.446	0.825	0.690	0.294	0.657
	IT4	0.333	0.836	0.690	0.327	0.628
GB+Sl	IT1	0.666	0.725	0.776	0.155	0.627
	IT2	0.687	0.768	0.779	0.205	0.670
	IT3	0.446	0.790	0.779	0.272	0.656
	IT4	0.333	0.802	0.778	0.305	0.627
GB+CHP	IT1	0.863	0.660	0.134	0.812	0.573
	IT2	0.725	0.743	0.096	0.719	0.567
	IT3	0.489	0.787	0.078	0.663	0.545
	IT4	0.333	0.810	0.073	0.623	0.521
GHP	IT1	0.862	0.010	0.870	0.197	0.406
	IT2	0.668	0.147	0.702	0.207	0.388
	IT3	0.457	0.232	0.608	0.211	0.365
	IT4	0.334	0.293	0.552	0.204	0.352
GHP+PV	IT1	0.862	0.168	0.987	0.338	0.483
	IT2	0.668	0.275	0.814	0.352	0.469
	IT3	0.457	0.359	0.711	0.403	0.459
	IT4	0.334	0.408	0.649	0.350	0.436
AHP	IT1	0.862	0.779	0.103	0.301	0.565
	IT2	0.668	0.825	0.064	0.314	0.556
	IT3	0.457	0.849	0.041	0.312	0.535
	IT4	0.334	0.864	0.027	0.301	0.513
AHP+PV	IT1	0.862	0.930	0.385	0.476	0.697
	IT2	0.668	0.938	0.310	0.513	0.665
	IT3	0.457	0.951	0.268	0.534	0.632
	IT4	0.334	0.955	0.242	0.474	0.594
PB	IT1	0.906	0.388	0.313	0.852	0.513
	IT2	0.735	0.452	0.301	0.843	0.515
	IT3	0.508	0.485	0.304	0.835	0.499
	IT4	0.358	0.504	0.303	0.824	0.476

insulation would be advantageous, as this would reduce the consumption-dependent costs. Technologically, they would prefer systems with low total heating costs, which seem to apply especially with AHP systems. The addition of PV is also a great advantage for the user. Ground-source Heat Pumps (GHPs) are particularly disadvantageous for them, which should be mainly caused by the high investment costs. Their optimal system would therefore be an AHP and PV combination with maximum insulation.

Energy Service Provider

Again, the energy service provider has advantages from low insulation, as it can sell more energy as a result. However, the effects are in most cases not as prominent as with the other stakeholders. It is interesting to note that there is hardly any effect to be seen with ST systems. On the other hand, strong technological trends can be seen here as well. The low investment costs of the AHP and CHP solutions lead to low margins, whereas the GHP solutions with high investments make them appear attractive. In the energy service providers view, the optimal system would therefore be the most capital- and energy-intense, a GHP-PV combination with low insulation.

Society

For society, on the other hand, CHP and pellet systems are quite advantageous. The CHP ranking should be mainly due to the fact that large amounts of electricity are produced, which are still based on fossil fuels, but displace inefficient power plants on a national level. The avoided emissions elsewhere are therefore credited to this system. The same applies toHP systems with the addition of PV. The pellet system is the only one that today already relies entirely on renewable energies and has only low emissions in construction and in the upstream chain of pellet production. ST systems perform poorly due to the quantities of natural gas required, whereas HP systems come out in the middle. What is interesting here is the trade-off between higher emissions due to insulation or due to more intensive system operation. There do not seem to be any unifying trends here; instead, they are largely dependent on the technologies used. Some systems have a negative or positive effect through an increase in insulation; for some, even a medium level of insulation is the best compromise. Nevertheless, the optimal energy system from a social point of view is a pellet boiler with low insulation.

An interesting aspect to analyse is how the interests of the stakeholders relate to each other. To do so, the correlation coefficient ($r_{x,y} = \frac{\sum(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum(x_i-\bar{x})^2\sum(y_i-\bar{y})^2}}$) of the TOPSIS scores of the different alternatives is calculated. For stakeholders with similar interests, one would expect a value close to 1, and for stakeholders in strong competition, close to -1. Stakeholders with little influence on their preferences have values close to 0. These values could indicate possible coalitions and oppositions. For the multi-family house, the results are presented graphically in Figure 7.3.

It turns out that only weak trends and dependencies are evident. The strongest opposition is between society and the energy service provider. This seems logical, as society prefers efficient energy consumption, while the energy service provider profits significantly from high sales volumes. A similar reason exists for the high opposition between energy service provider and user. Moreover,

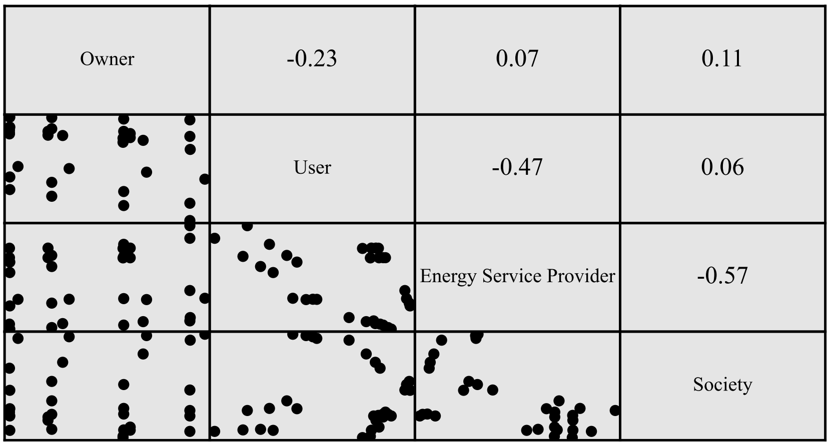

Abbildung 7.3: The optimality of the different energy concepts (TOPSIS scores) of the stakeholders are shown as a scatter plot to the other stakeholders (bottom left). The correlation coefficient is calculated from this (top right). The better the interests of these stakeholder pairs correlate the closer the value is to 1, the stronger the stakeholders have different understandings of optimality the closer to -1. A 0 means that the interests of the stakeholders are independent of each other.

in both cases the sensitivity parameters are opposite. One would therefore expect the user and the society to form a good coalition, but this is not the case. Only the user and owner still show slight negative correlations, all other stakeholder combinations hardly influence each other. It might now be thought that, on the other hand, there could be an opportunity for certain stakeholders to form coalitions, since similar energy concepts are advantageous to them, albeit for different reasons. However, no such positive correlations are found, which again underlines how important it is for all these stakeholders to participate in such decision-making processes.

The key point, however, is how the stakeholder community would decide, taking all interests into account. In addition to Table 7.4, Figure 7.4 shows a graphical evaluation of the TOPSIS scores for easier analysis.

The AHP+PV solution with TS1 insulation turns out to be the absolute best solution. Although this solution is not optimal for the energy service provider due to the low investment costs, it is very optimal for the owner as well as the user due to the low costs and high subsidies. Socially, it is in the middle. It is very interesting that for larger insulation especially this solution is directly followed by the ST solutions, which were always in the middle ground of the previous discussion. However, this solution is only problematic for society, which is given rather little consideration in the current weightings. The worst solution is clearly the pure GHP solution. Here, extremely high costs for the

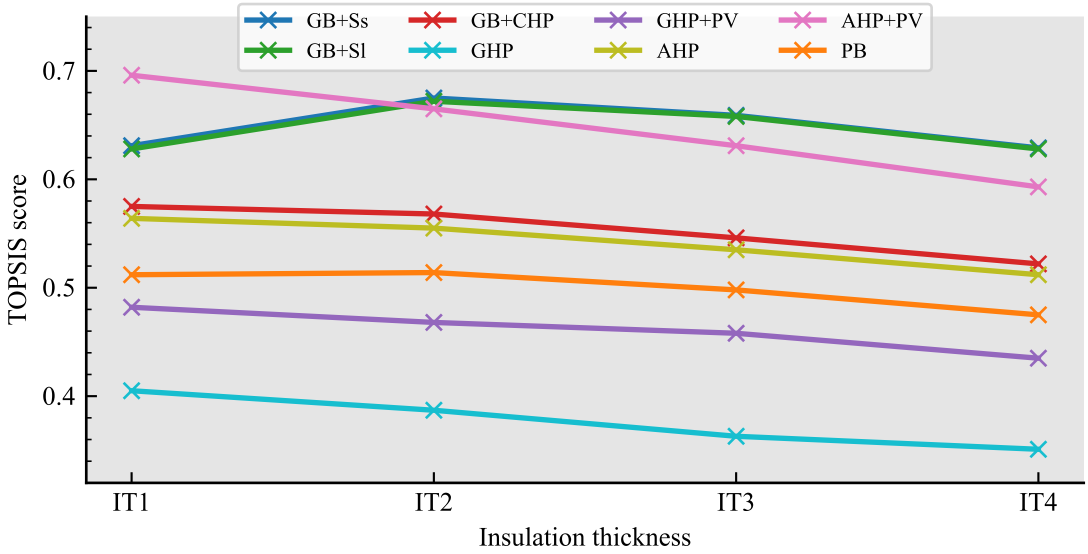

Abbildung 7.4: Visualization of the TOPSIS scores from the perspective of all stakeholders for the case study used. The different energy solutions are shown as lines over the insulation thickness (x-axis). The closer the value to 1, the better the energy concept, taking into account all stakeholder interests.

users come together with poor ecological values that cannot be compensated by the good values of the energy service provider. The addition of PV to the two HP systems is fundamentally positive and in all cases improved the score for all stakeholders. Without PV, the AHP, for example, only reaches the middle ground along with to the CHP-based system. The increase of insulation means in (almost) all cases a deterioration of the score, as here especially the owner has very strong dependencies. The only exception is ST systems, where higher state subsidies can be achieved in this way.

It can thus be abstracted from the above that under the current German framework conditions and market prices, both electricity-based heat generation (AHP) and gas-based heat generation (GB+S) can be advantageous in multi-family houses. A high standard of insulation is not necessarily beneficial, as is often assumed, but may well have a negative impact on stakeholders, who would be better off with a more efficient energy generating system. The poor performance of GHP solutions, which in our perception enjoy a very good reputation on the German market, is particularly interesting. While this solution may make a lot of sense from a physical-technical point of view, both costs and emissions are rather mediocre here. The opposite is true of the purely gas-based CHP solutions, which are viewed rather sceptically by the public. These make it into the middle rankings even without using renewable energies. However, this may change in the near future if the conditions for purchasing electricity and natural gas change significantly as a result of consistent pricing of CO_2 emissions and the increase in renewable energies in the electricity grid. Conversely, what is already worthwhile for all stakeholders today and will probably become even more important in the future is the use of radiant energy either through ST or PV systems. This basically adds value to the overall system and should therefore be considered in all cases.

Overall, however, the topic presented is highly dynamic. For example, the war in Ukraine and the associated debate about stopping the import of Russian natural gas into the EU, as well as the significant change in the funding for energy-efficient buildings by the new German government at the beginning of 2022, have shown how volatile such studies and recommendations can be. These developments were in no way foreseeable at the time this study was conducted.

It must be pointed out again that the building presented here and the assumed stakeholders are characteristic of the German building stock, but of course do not represent the entire real estate market. This study provides only insights and trends as to which strategies should be used to approach energy concepts in multi-family houses, but there will always be exceptions and special cases. In these cases, however, it can be of great value to apply the method used here on a project-specific basis and to use it individually for the building and the existing stakeholders in order to reach the best possible compromises.

7.6 | Conclusion and Outlook

In summary, methods such as the one used here can provide insight into the interrelationships of energy system design and can be helpful in the decision-making process. We were able to show that finding a compromise is not always obvious and that energy concepts include not only energy production but also energy savings in the building envelope. The methodology used can be easily transferred to other countries and sectors and can be used both for generic studies such as this one and for project-specific analyses.

With regard to the German market and multi-family houses analyzed, it can be stated that both gas- and electricity-based systems continue to be attractive solutions. A focus should be on ST systems and AHPs, but CHP systems are also competitive. The use of PV has a generally positive effect on HPs. The technical components seem to be the deciding factor. Excessive insulation has a negative effect on any energy system. However, this is of course only a snapshot, which is very dynamic due to both further technical development and political will.

Basically, one can ask at this point whether the results of this study reflect the will of German politics, i.e. whether the current incentives are set correctly. They would like to change the heat market as quickly as possible from gas-fired systems to heat pumps and the use of solar radiant energy. Currently, it is more attractive to use large quantities of natural gas in CHPs than to install an efficient GHP.

Author Contributions: Conceptualisation and Methodology: LS; Software: FW and LS; Data Curation: FW, LS and TE; Formal Analysis: LS and FW; Validation: LS and TE; Visualisation: LS; Writing – Original Draft Preparation: LS; Writing – Review and Editing: FW, PK, BH and BS; Project Administration: LS, TE and PK; Supervision: TE, PK, BH, KvM, CA and BS

Acknowledgments: The authors would like to thank Cody Hancock (DLR VE), Nemanja Katic (Energiebüro Erfurth) and Pedro Durán (Lintas Green Energy GmbH) for proofreading the manuscript.

Funding: This research was funded by the Federal Ministry for Economic Affairs and Climate Action (BMWK) and the Federal Ministry of Education and Research (BMBF) of Germany in the project *ENaQ* (project number 03SBE111).

8 | Conclusion and Outlook

This thesis examined approaches for optimising the operation and design of hybrid, distributed energy systems, specifically incorporating the views of various stakeholders in the decision-making. A key finding in this regard is that there is no ultimate universally valid methodology, but that which methodology is chosen depends on various factors. It could be shown that the scientific literature has already dealt with a wide range of different approaches and that there are nevertheless constant enhancements and improvements to existing methods, such as those in this thesis, so that these methods are better suited to a particular application.

In specific terms, this thesis initially clarified that such simulation-based methods have to be integrated into the wider context of energy system planning and can make a valuable but only somewhat definitive contribution to making decisions on complex decision-making issues related to the design and operation of distributed generation. The example of the Helleheide neighbourhood chosen for this purpose highlighted in particular the need for a specific target in the energy system design, which is to be used as a key input in the further planning process and in which all relevant stakeholders must be actively involved.

Building on this, the following case studies of increasing stakeholder complexity and variable energy system modelling complexity showed how such planning tools could be defined very individually in some cases, as in the example of the dairy, and also very generalistically in the renewed example of the Helleheide neighbourhood.

It has become clear that there are no simple, obvious solutions for any of the case studies shown, but that the type and nature of the technical solution actually depend massively on the target and therefore on the stakeholders. What is particularly interesting in this context is the discrepancy that became clear in the last publication between the high acceptance of gas-based solutions by the stakeholders in stark contrast to the political objective from whose point of view a clear and unmistakable trend towards electric heat generators regulated by subsidies and taxes would have to be expected.

This also makes it clear that the tools described and demonstrated here are not only aimed at actual key stakeholders of a project, such as the owners or tenants, but that remotely relevant stakeholders such as political decision-makers, grid operators, or environmental organisations would equally benefit from a more in-depth look at digital planning methodologies and decision-making tools.

This, in turn, requires even more intensive analysis and further research into the methods and approaches to support these sometimes very different stakeholders in their decision-making problems in a purposeful manner. Although efforts were made to find methods and develop them in a manner that would allow them to be used in everyday real-life projects, it is clear that the step to using them in as many projects as possible outside of academia is difficult and has not yet been achieved. In principle, it is possible to adapt the methods shown in this thesis to various other case studies thanks to the open source approaches chosen. In reality, the actual project implementation requires comprehensive expert knowledge, from the modelling of energy systems and the technical characteristics of individual systems to energy industry opportunities and energy law restrictions at national level. This specialist knowledge and the associated tools need to be embedded in a framework for designing distributed energy systems that is as easy to understand and intuitive to use as possible.

Thus, this thesis provides the necessary template for this further process. The aim must be to use the methods shown in a more realistic and project-orientated manner in order to utilise the demonstrated insights into decision-making consequences to make better decisions. This will not be achieved if, like most of the publications analysed in recent years, more and more work is put into even more detailed models or faster algorithms, but rather by further expanding the possibilities for involving stakeholders in an easy and straightforward manner. Ultimately, as stated in the introduction, the energy transition is crucial to be successful, which will only be possible with the broad and long-term acceptance of a wide range of stakeholders in a wide variety of projects. A failure of the energy transition and the consequences for climate change would be fatal if this were to be jeopardised. Thanks to their different starting points and easy transferability, the simulation-based approaches shown here can make a decisive contribution to increasing this acceptance in real projects by objectifying compromises and decisions.

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Publication List

The following publications were published as a direct or indirect part of the dissertation:

Peer-reviewed articles

Wehkamp, S.; **Schmeling, L.**; Vorspel, L.; Roelcke, F.; Windmeier, K.-L. District Energy Systems: Challenges and New Tools for Planning and Evaluation. Energies 2020, 13, 2967, doi:10.3390/en13112967.

Schmeling, L.; Schönfeldt, P.; Klement, P.; Wehkamp, S.; Hanke, B.; Agert, C. Development of a Decision-Making Framework for Distributed Energy Systems in a German District. Energies 2020, 13, 552, doi:10.3390/en13030552.

Schmeling, L.; Buchholz, A.A.I.; Heineke, H.; Klement, P.; Hanke, B.; von Maydell, K. Planning, Optimisation and Evaluation of Small Power-to-Gas-to-Power Systems: Case Study of a German Dairy. Sustainability 2022, 14, 6050. doi:10.3390/su14106050

Klement, P.; Brandt, T.; **Schmeling, L.**; de Bronstein, A.A.; Wehkamp, S.; Penaherrera Vaca, F.A.; Lanezki, M.; Schönfeldt, P.; Hill, A.; Katić, N. Local Energy Markets in Action: Smart Integration of National Markets, Distributed Energy Resources and Incentivisation to Promote Citizen Participation. Energies 2022, 15, 2749. doi:10.3390/en15082749.

Schmeling, L.; Schönfeldt, P.; Klement, P.; Vorspel, L.; Hanke, B.; von Maydell, K.; Agert, C.; A generalised optimal design methodology for distributed energy systems. Renewable Energy 2022, 200 (2), 1223-1239. doi:10.1016/j. renene.2022.10.029

Hancock, C.; Klement, P.; **Schmeling, L.**; Hanke, B.; von Maydell, K.. Optimization of the refurbishment of German single family homes based on construction era. Energy Strategy Reviews 2023, 49, 101156, doi:10.1016/j.esr.2023.101156.

Schmeling, L.; Walter, F.; Erfurth, E.; Klement, P.; Hanke, B.; von Maydell, K.; Agert, C.; Siebenhüner, B.; Multi-Stakeholder Optimal Energy Supply for Multi-Family Houses under 2021 German Market Conditions. Journal of Civil Engineering and Management 2024, 30(6), 481–493. doi:10.3846/jcem.2024.20924

Chapter in a peer-reviewed book

Brandt, T.; **Schmeling, L.**; Alcorta de Bronstein, A.; Schäfer, E.; Unger, A. Smart Energy Sharing in a German Living Lab. In Resilience, Entrepreneurship and ICT: Latest Research from Germany, South Africa, Mozambique and Namibia: Halberstadt, J.; Marx Gómez, J.; Greyling, J.; Mufeti, T.K.; Faasch, H., Eds.; Springer International Publishing: Cham, 2021; pp. 221–262. doi:10.1007/978-3-030-78941-1_11.

Wehkamp, S., **Schmeling, L.**; Leonhardt, S. Regulatory and Legal Challenges for District Energy Systems in Practice and Research. In Innovations and challenges of the energy transition in smart city districts: Leonhardt, S.; Nusser, T.; Görres, J.; Rosinger, S.; Stryi-Hipp, G.; Eckhard, M., Eds.; De Gruyter: Berlin, Boston, 2024; pp. 17-34. doi:10.1515/9783110777567-002.

Klement, P.; Schönfeldt, P.; **Schmeling, L.** Multi-Objective Design Optimisation of District Energy Supply – The Influence of Different Domestic Hot Water Concepts. In Innovations and challenges of the energy transition in smart city districts: Leonhardt, S.; Nusser, T.; Görres, J.; Rosinger, S.; Stryi-Hipp, G.; Eckhard, M., Eds.; De Gruyter: Berlin, Boston, 2024; pp. 35-52. doi:10.1515/9783110777567-003.

Katić, N.; **Schmeling, L.** Designing a marketplace for energy exchange among neighbors. In Innovations for Transformation - Entrepreneurship and Technology for Sustainable Development: Halberstadt, J.; Marx Gómez, J.; Timm, J.-M.; Alcorta de Bronstein, A.; Faasch, H.; Mufeti, T. K., Eds.; Springer International Publishing: Cham, 2024, In Press

Conference Proceeding

Schmeling, L.; Klement, P.; Erfurth, T.; Kästner, J.; Hanke, B.; Maydell, K. von; Agert, C. Review of different Software Solutions for the holistic Simulation of distributed hybrid Energy Systems for the commercial Energy Supply. In 33rd European Photovoltaic Solar Energy Conference and Exhibition, Amsterdam, The Netherlands; 2017; pp 1994–1998, doi:10.4229/EUPVSEC20172017-6CO.14.4 .

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Student supervision

The doctoral candidate supervised the following theses and interns, at least some of which had a direct influence on the doctoral thesis:

Katić, N. Entwurf eines Marktplatzes für den Energieaustausch unter Nachbarn. Bachelor Thesis Wirtschaftsingenieurswesen - Bauwirtschaft, Jade University of Applied Sciences, 2019.

Windmeier, K.-L. Länderspezifische Berechnung der spezifischen CO_2-Emissionen des Stromverbrauchs im europäischen Verbundnetz. Internship Systems Engineering, University of Bremen, 2019.

Buchholz, A. Projektierung und techno-ökonomische Optimierung innovativer Power-to-Gas-to-Power Kompaktsysteme für den Einsatz in ganzheitlichen Energieversorgungskonzepten. Master Thesis Produktionstechnik, University of Bremen, 2020.

Shin, J. Data warehouses for operation and optimisation of distributed energy supply concepts. Internship Computer Science, University of California, 2020.

Turhan, E. The Effect of Technical Risks on the Achievement of Goals for Distributed Energy Supply Concepts in Residential Neighbourhoods. Master Thesis Sustainable Systems Engineering, University of Freiburg, 2021.

Walter, F. Bewertung von Energiekonzepten für Niedrigstenergiegebäude aus der Sicht verschiedener Stakeholder. Bachelor Thesis Wirtschaftsingenieurswesen - Bauwirtschaft, Jade University of Applied Sciences, 2021.

Katić, N. Bewohner*innenakzeptanz energietechnischer Anlagen in Wohnquartieren. Master Thesis Management Consulting, University of Oldenburg / University of Applied Sciences Emden/Leer, 2022.

Walter, F. Bewertung dezentraler Energieversorgungkonzepte im Ökosystem Energiequartier aus der Sicht verschiedener Akteure. Master Thesis Wirtschaftsingenieurswesen, Jade University of Applied Sciences, 2022.

Goldbach, K. Analyse des Werts verschiedener Formen von Flexibilität für Photovoltaik-Prosumer. Bachelor Thesis Thesis Wirtschaftsingenieurswesen - Bauwirtschaft, Jade University of Applied Sciences, 2022.

Hancock, C. Optimization of Building Envelope and Energy System during Renovation of German Single Family Homes from Different Construction Eras. Master Thesis Postgraduate Programme Renewable Energy, University of Oldenburg, 2022.

Wirth, M. Simulationsbasierter Technologievergleich von elektrischen Prozesswärmeerzeugern in der Industrie. Master Thesis Wirtschaftsingenieurswesen, University of Duisburg-Essen, 2023.

Baumbach, K. Vergleichende Analyse der deutschen und schweizerischen Rahmenbedingungen für die dezentrale Energieversorgung in der Industrie. Master Thesis Green Energy, FH Westküste University of Applied Sciences, 2023.

Wagner, L. Entwicklung einer Gebotsstrategie mittels Reinforcement Learning: Eine Untersuchung am Day-Ahead- und Primärregelleistungsmarkt. Master Thesis Informatik, University of Oldenburg, 2023.

Böttcher, J. Konzeptionierung einer EEG geförderten wasserstoffbasierten Stromspeicherung am Beispiel Windpark Stollhamm. Bachelor Thesis Maschinenbau, Jade University of Applied Sciences, 2024.

Harmeling, C. Untersuchung der Einflussfaktoren bei der Abschaltung von industriellen KWK-Anlagen. Bachelor Thesis Umweltingenieurwesen und -management, Technische Hochschule Lübeck, 2024.

Curriculum Vitae

Professional career

04/22-today	Head of Integrated Energy Systems / Head of Energy Solutions at Lintas Green Energy GmbH
12/19-12/24	Gastwissenschaftler at DLR-Institut für Vernetzte Energiesysteme
09/16-03/22	Projektingenieur at KEHAG Energiehandel GmbH
02/15-08/16	Wissenschaftlicher Mitarbeiter at energy & meteo systems GmbH

Study and School Career

10/15-08/17	M.Sc. Engineering Physics at University of Oldenburg and University of Applied Sciences Emden/Leer
10/12-09/15	B.Eng. Engineering Physics at University of Oldenburg and University of Applied Sciences Emden/Leer
08/03-06/12	Allgemeine Hochschulreife at Friedrich-Leopold-Woeste-Gymnasium

Eidesstattliche Erklärung

Hiermit versichere ich, die vorliegende Arbeit selbstständig verfasst, keine anderen als die angegebenen Quellen und Hilfsmittel verwendet und die Leitlinien guter wissenschaftlicher Praxis der Carl von Ossietzky Universität Oldenburg befolgt zu haben. Die Arbeit hat weder in ihrer Gesamtheit noch in Teilen einer anderen Hochschule zur Begutachtung in einem Promotionsverfahren vorgelegen und im Zusammenhang mit dem Promotionsvorhaben wurden keine kommerziellen Vermittlungs- oder Beratungsdienste in Anspruch genommen.

Oldenburg, den 03.04.2025

Lucas Schmeling