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

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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

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 2 the *ENaQ* case study is presented in more detail. In Section 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) all stakeholders agree on a common goal. In the Synthesis phase (Section 5) the selection and basic interaction of the technologic components is agreed upon. In the Design phase (Section 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 7) the later system operation is designed and corresponding operation strategies are developed. The paper concludes in Section 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.

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 [1]. In addition to this participatory process, the Smart City Vision of the city was developed in parallel and published in 2017 [2]. 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.

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 [3,4]. 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 [5,6]. Applied in various specialized sub-areas like disaster management (cf. e.g., [7,8]) or medicine (cf. e.g., [9,10]), decision theory has also been studied in detail in the energy sector. Majidi et al. [11] compare different approaches of decision theory to energy problems, Andreotti et al. [12] use decision theory for the integration of storage systems in distributed supply scenarios, and Yang et al. [13] 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 [4,14,15]. 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* [16] or *ELECTRE* [17] to solve MCDA problems. These approaches are used in various disciplines, e.g., transport [18,19] or healthcare [20,21], 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. [22], who, with the help of *PROMETHEE*, make the choice for renewable energy power plants in Turkey. Kirppu et al. [23] describe the application of an MCDA method for selecting heat generation technologies for a district heating system in Finland. Sahabmanesh and Saboohi [24] 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. [25] or Erdinc and Uzunoglu [26]. 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. [27] 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. [28] 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. [29] 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. [30] choose a similar approach for an industrial area in Italy and Urbanucci et al. [31] for a school building in California.

Specialized simulation tools are often used to map these quite complex processes. Connolly et al. [32] present and compare 37 different planning tools for energy systems, Schmeling et al. [33] develop an evaluation approach based on nine tools and Allegrini et al. [34] 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. [35] 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 [36] 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 [37] and identify suitable software tools. A similar, phase-based approach is described by Frangopoulos et al. [38]. 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. [38] 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 1.

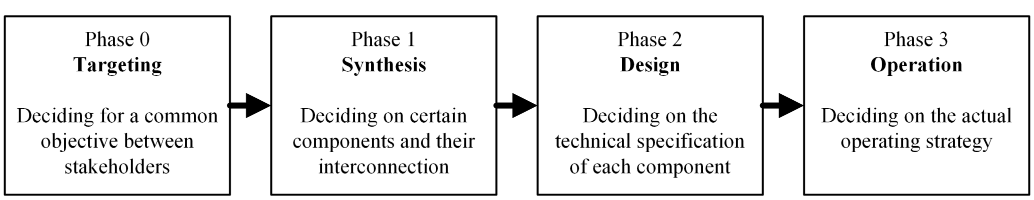


Figure 1. Presentation of the successive planning processes for designing an energy supply solution in complex actor structures. The phases are run through one after the other with the participation of various stakeholders. Each phase involves important decisions that will have a significant impact on 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. 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 1.

Table 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 [39]. This is easiest for the technical part, which corresponds to the degree of own consumption generally known in distributed generation [40]. 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 [41]. When external electricity is purchased, this happens dynamically, depending on national generation and consumption in accordance with [42,43]. 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 [44]. These three quantifiable targets are used below as key performance indicators (KPIs) to assess the energy supply concept.

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 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.

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 2. This forms the basis for all further planning processes.

Table 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
Cogeneration (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.

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.

5.3. Superstructure Design

After the initially very extensive technology catalog (Table 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 [45]. 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 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.

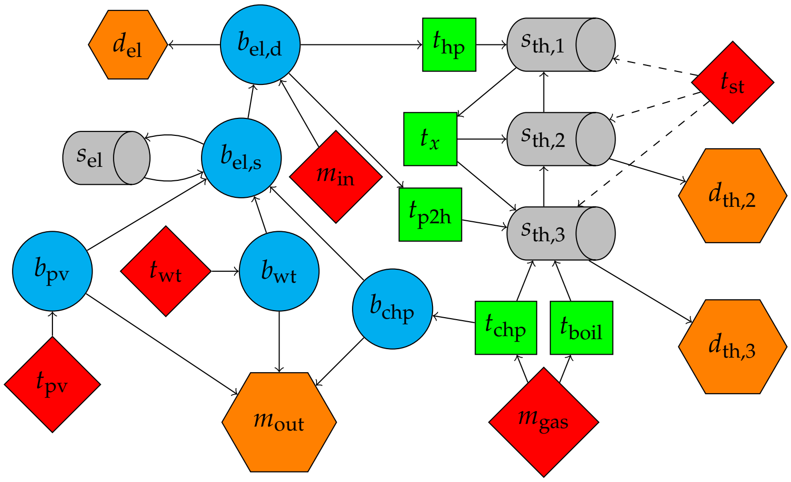


Figure 2. Depiction of the directed graph meta-model used as base-layout for the integrated energy system. Note that technologies may be optimized out (to have zero size). On display are, among others, energy-generating technologies (e.g., photovoltaic $t_{\rm pv}$, solar thermal $t_{\rm st}$), energy-converting technologies (e.g., heat pump $t_{\rm hp}$, CHP $t_{\rm chp}$), energy-storing technologies (e.g., buffer storage $s_{{\rm th},i}$, battery $s_{\rm el}$), as well as energy sinks (heat demand $d_{{\rm th},i}$, electricity demand $d_{\rm el}$, national energy markets for export $m_{\rm out}$) and external energy sources (external electricity procurement markets $m_{\rm in}$, gas markets $m_{\rm gas}$). The dashed line connecting the solar thermal collector $t_{\rm st}$ and the three thermal storages $s_{{\rm th},i}$ indicate that only one of these can be active at a time.

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.

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 [46–48]. *ENaQ* will make use of the LoadProfileGenerator [49] 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.

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 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 [32–34]. 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* [50]—part of the *Open Energy Modelling Framework* (*oemof*) [51]—has proven to be the best suitably highlighted. It is already thoroughly tested and valid (cf. e.g., [52–55]). *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* [56,57] is used in the project for this purpose.

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 [58]), to simple brute force approaches (e.g., [59,60]) to very sophisticated methods (e.g., [61–63]). 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 [26]. An overview of existing approaches can be found at Twaha and Ramli [64], Prakash and Khatod [65], or Mekontso et al. [66].

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 [67]. 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) 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* [68,69], especially the "Improved Harmony Search" algorithm [70], 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 3. The results of an exemplary optimization are plotted in a three-dimensional Pareto front in Figure 4.

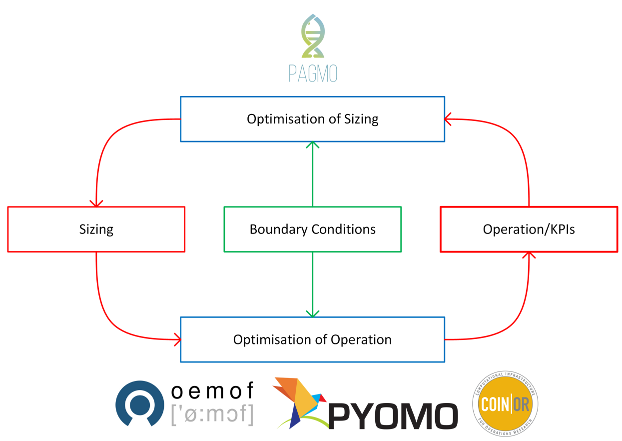
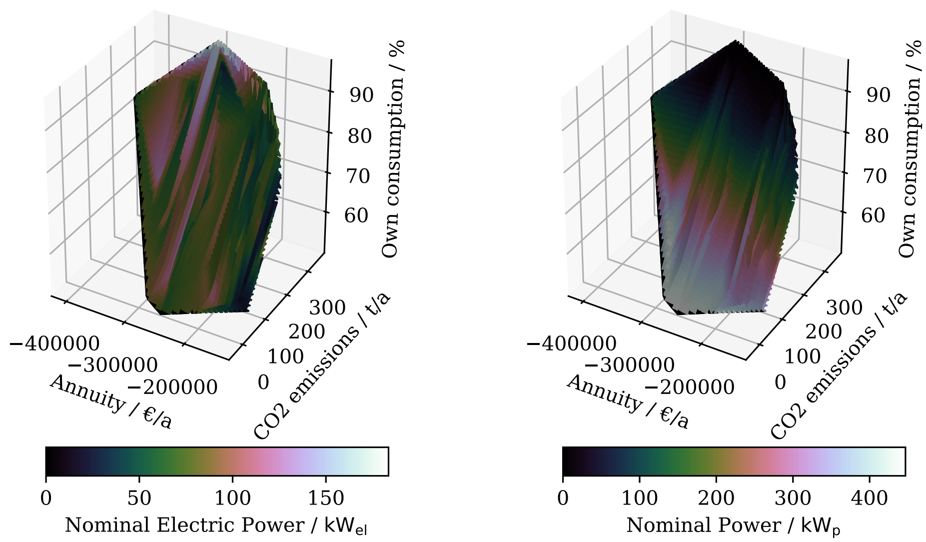


Figure 3. Flow chart of the energy system optimal sizing loop. The interaction of the various existing software solutions and their interfaces, as well as the necessary consideration of the boundary conditions, is to be seen particularly. All this is implemented in a holistic *Python* based approach.



(**a**) CHP (**b**) PV

Figure 4. Presentation of exemplary optimal sizing results generated by the described methodology. It shows the Pareto front between the three key performance indicators (KPIs) (Section 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 photovoltaics (PV) there is a high dependency on own consumption and CO_2 emissions.

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 [71], 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.

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 [27,72–75].

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 [67]. 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 [76]:

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

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 [3,77]:

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 [78].

The subsequent **risk analysis** is carried out with an MCS. In the literature, a variety of alternative approaches, such as sensitivity analyses [79,80] or SWOT analyses [77,81], 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 [82] 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 5. The exemplary graphical analysis of the distribution function of the economic KPI for different cases can be seen in Figure 6.

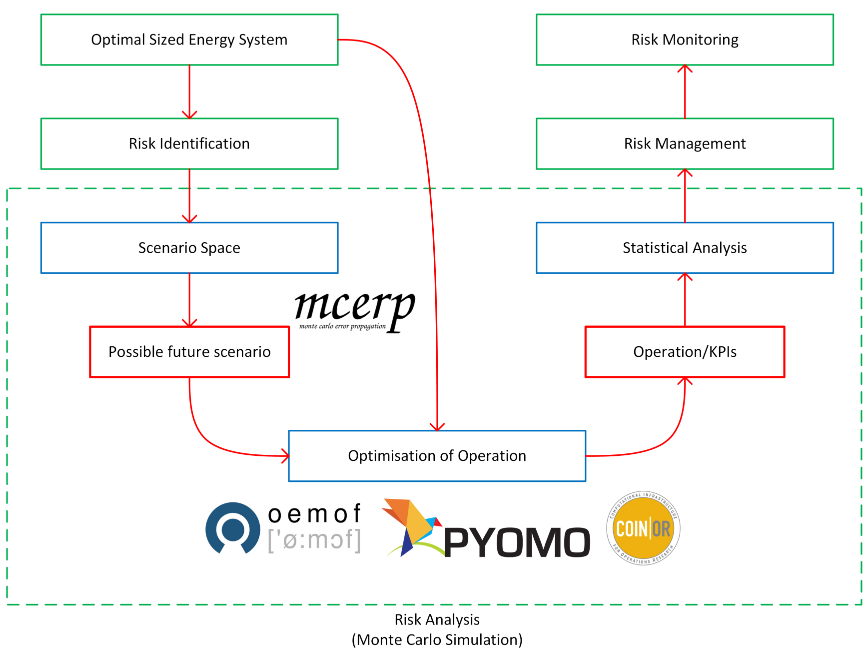


Figure 5. Flow chart of Monte Carlo based risk analysis of the optimized energy supply scheme. Here, too, the interaction of the selected software solutions is shown in particular, which is also realized in Python.

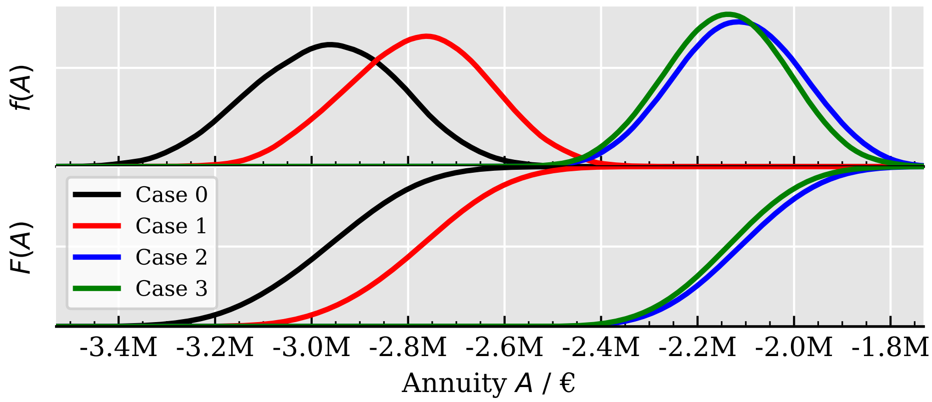


Figure 6. Presentation of exemplary Monte Carlo Simulation (MCS)-based risk analysis results generated by the described methodology. The statistical analysis of the economic KPI as an annuity according to VDI 2067 for four different design alternatives can be seen, which differ both in the average expected result and in their distribution around this point.

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 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.

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) 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 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.

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.

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 [83–86], 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., [87–89]) 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.

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 [90–92] 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.

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 [93,94]. 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 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.

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
- ...

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 2.

In Section 3, the basic planning and decision-making approach was first presented, which is divided into four phases.

The first phase, targeting, in Section 4 deals with creating a common understanding of optimality between stakeholders.

In the synthesis phase (Section 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 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 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 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.

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Abbreviations

The following abbreviations are used in this manuscript:

CHP	Combined Heat and Power
EUC	Energy Utility Company
KPI	Key Performance Indicator
MCDA	Multiple-Criteria Decision Analysis
MCS	Monte Carlo Simulation
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Nonlinear Programming
PV	Photovoltaics

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