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# District Energy Systems: Challenges and New Tools for Planning and Evaluation

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Received: 23 January 2020; Accepted: 27 May 2020; Published: 9 June 2020



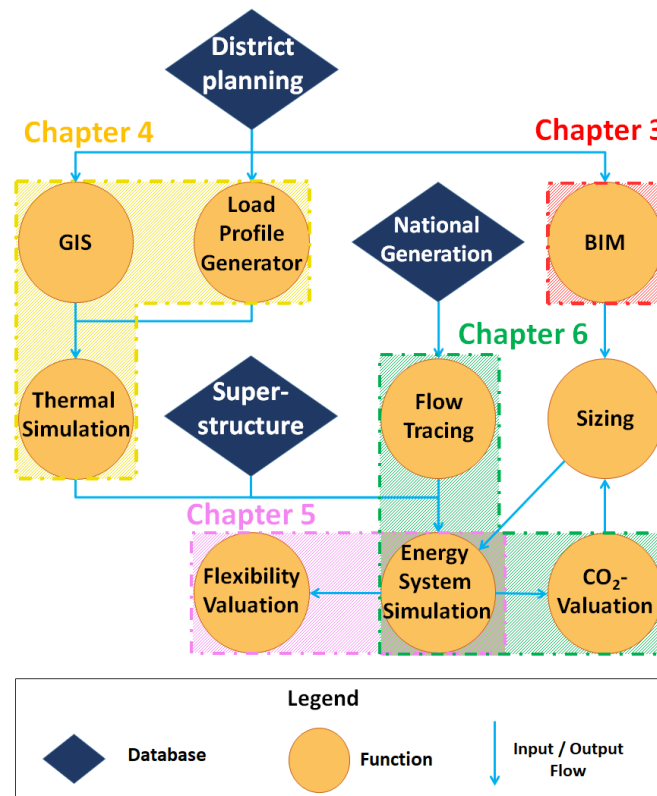
**Abstract:** The change from a centralized to a decentralized energy supply creates new challenges in the planning of such energy supply concepts. Specialized planning tools that can cope with the complex requirements and multi-layered boundary conditions of local energy use are therefore needed. Existing methods need to be further developed and optimized to suit the complex stakeholder structures encountered in innovative district projects, as well as for research purposes. This paper presents selected aspects and challenges in the development of an application-oriented planning tool. Using a North German district as a case study, the usability of a Building Information Model as an aggregated data platform is tested in the context of a residential energy district planning process. In addition, the modeling of heating grids using a combination of Geographic Information System and open source thermodynamic tools is presented. Economic valuation methods are examined to determine the extent to which the value of flexibility and access to local flexibility markets can be taken into account. Finally, an approach for evaluating the ecological aspects of the district energy supply is presented, based on the dynamic assessment of imported and exported energy quantities.

**Keywords:** district energy systems; energy system planning; building information modeling; heat grid simulation; flexibility valuation; local flexibility markets; emission valuation; flow tracing

## 1. Introduction & Motivation

In order to cope with the challenges posed by distributed supply structures based on renewable energies, innovative methods have to be developed that meet the diverse requirements of such infrastructure projects. The areas of energy supply and sector coupling in particular have a significant impact on the lives of consumers. To offer guidance, the Federal Ministry for Economic Affairs and Energy published a manual for living labs and outlined the need for practical research and evidence-based experiments [1]. Living labs enable input from active participation to be used to address technical, economic, legal-institutional, ecological, and social issues [2]. Early and comprehensive participation of citizens, potential residents, businesses, and other relevant stakeholders is of central importance. In this way, technology is put at the service of stakeholders, ensuring a high level of public support and systems that meet the real needs of their users [3,4]. One such concept is the Energetic Neighborhood District (German: Energetisches Nachbarschaftsquartier; ENaQ). This project and the

research behind it is briefly described in Section 2. This so-called living lab is a residential district with an integrated local energy supply system. The system will be both affordable and with low CO<sub>2</sub> emissions. The planning process and tools, mainly the Energy System Simulation for the energy supply concept of the ENaQ project, have already been developed and presented by Schmeling et al. [5]. In this paper, challenges relating to the planning tool and energetic simulation are examined more closely. For ease of understanding, the core elements of the planning process and their relevance to this paper will be briefly explained. Figure 1 shows the main aspects of this paper in the context of holistic energy system simulation.



**Figure 1.** Interfaces between the main aspects of this paper and the system simulation described in Reference [5].

The planning approach has four phases: In the first phase (**Targeting**), the objectives of the supply concept are agreed upon with the participation of all stakeholders. These can be, for example, low costs or low emissions. Often, the chosen objectives in such projects are also known as Key Performance Indicators (KPI) [6,7]. In the second phase (**Synthesis**), a superstructure of the technical solution is designed, which includes all conceivable energy generating, storing and consuming devices of any size and their interconnection, as well as the relevant boundary conditions [8]. Based on this superstructure, a simulation model is then set up in the third phase (**Design**). This determines the optimum plant size using an optimal sizing algorithm (compare, e.g., Reference [9,10]) and Monte Carlo based risk analysis (compare, e.g., Reference [11,12]). The last phase (**Operation**) then deals with the operational management of the overall concepts. It takes into account aspects, such as the coordination of the energy supply and the residents' demand in combination with concepts, for example, local energy markets [13,14] and the intelligent planning of maintenance operations [15], as well as a regular review of and improvement to the supply concept.

The entire decision-making and planning process is explicitly designed to be transferable. The basic idea is always to provide decision makers with valid and objective decision templates and tools. The planning approach described above is shown in Figure 1 under Sizing and Energy

System Simulation. The superstructure itself functions as a database for energy technologies and as a facility for input flow.

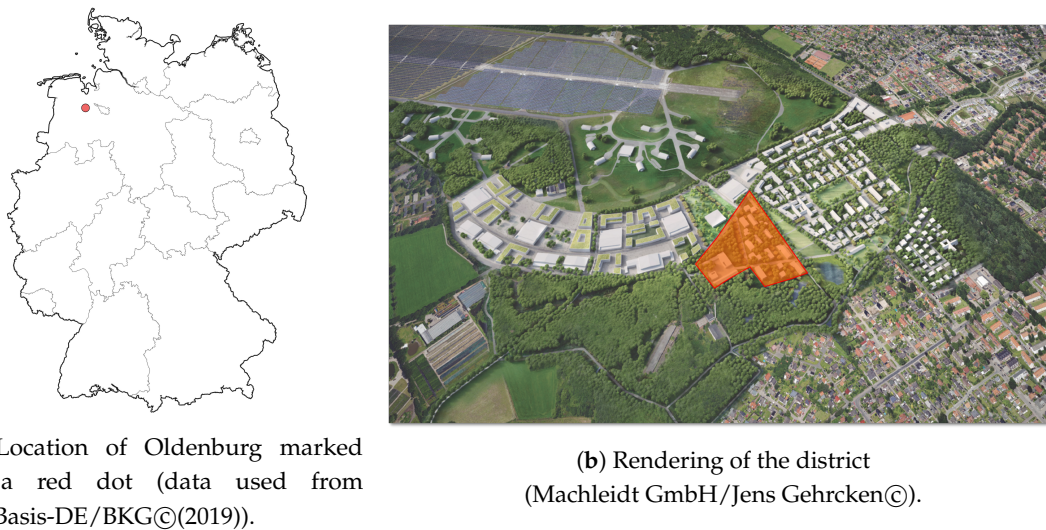
The design phase itself requires an extensive use of simulation and other specialized tools for all possible aspects of planning and valuation. A comparison of different simulation frameworks can be found, for example, in Schmeling et al. [16] or Allegrini et al. [17]. Currently, promising approaches to energy system simulation include, for example, Energy Hub [18], HyFlow [19], or Calliope [20]. The core of the energy system simulation in ENaQ, however, is the open energy modeling framework (*oemof*) [21]. This open source solution has the advantage that it is permanently enhanced by a large community and is well validated and established (compare Reference [22,23]) and already provides a wide range of functionalities without being too complicated to use. In principle, however, many of the commercially and open source tools available are suitable for this purpose and the approach elaborated in this paper is explicitly not limited to a single software solution but should be as universally applicable as possible.

Despite the large number of different approaches and solutions for modeling and simulating distributed energy supply concepts at district level, research in this area is by no means complete. For some selected aspects, the open research questions, approaches, and solutions are presented and discussed in this publication.

Section 3 deals with a standardized Building Information Model (*BIM*) for collecting building data. The model-based data transfer ensures high data consistency. Restrictions for system sizing can be derived from the district and building planning. Building data for the purposes of energy system sizing can also be part of the *BIM* model. This paper investigates how the use of *BIM* can improve the quality of data for the planning of energy districts. Section 4 presents the transfer of heat grids from Geographic Information System (*GIS*) to a non-geographically referenced tool for Thermal Simulation. The latter allows for a more detailed computation of temperature levels and heat losses along the district heat pipes, which is, of course, important information for designing heat grids using a large share of renewable energies. The time-resolved thermodynamic calculations allow a higher accuracy in the design of the energy system, which we regard as a promising approach for future new districts and the refurbishment of energy systems in existing districts. Sections 5 and 6 present different valuation approaches for district energy systems. Section 5 examines the current research in the field of conventional financial valuation methods to determine whether they are applicable in the context of renewable energy power plants and decentralization. The research is mainly concerned with the consideration of flexibility in the valuation of energy plants and their access to different local flexibility markets. Growth in the use of renewable energies will increase the need for flexibility and thus the need for different flexibility options. One of the system-balancing options is local flexibility trading, which is provided for by regulatory frameworks. In order to reduce the economic risk of investments in flexible energy systems, suitable instruments are needed to determine the value of these investments. To this end, the valuation bases and methods are reviewed. In contrast, Section 6 takes an ecological valuation approach and presents a possible methodology to dynamically assess the CO<sub>2</sub> emissions of a district energy system. This would be used, for example, for optimal sizing or operational management. Special emphasis is placed on comprehensibility and practicability.

## 2. The Energetic Neighborhood District ENaQ

In the city of Oldenburg, located in northwest Germany (see Figure 2a), the old military airbase Fliegerhorst with a size of 309 ha is being transformed into a residential and commercial area. On the aerial photo of the area, the grey 3D building models represent the future city district Fliegerhorst (see Figure 2b). The orange-highlighted part of the site, covering an area of 3.9 ha, is called “Helleheide” and will be developed into a living lab. The creation of ENaQ is part of Oldenburg’s strategy to develop a Smart City [24].



**Figure 2.** Geographical location of the project area.

The primary goal of the ENaQ project is to develop a multisectoral, distributed energy system that addresses the central issues of the current societal discourse and suggest appropriate solutions for the Helleheide district. The challenges to be met include, in particular, energy affordability, low emissions, and a meaningful involvement of residents, as well as a high level of resilience and security of supply. Decision-making for a given energy system is thus a complex and highly interdisciplinary problem in which a wide range of stakeholders have different interests. Energy technology is certainly a central issue, but fields, such as business model development, energy economics and law, participation research, and software development, also play a decisive role in designing the living lab. Even if concrete parameters emerge from ENaQ, the decision process is designed generically so that it is readily transferable to other projects.

Creating the Energetic Neighborhood District involves the construction and implementation of an energy infrastructure concept that connects the sector's electricity, heat, and mobility into a holistic multi-sectoral supply concept. Additionally, the project will examine the feasibility of a digital service platform for intelligent load and procurement management at the district level, available for use by energy producers, consumers, and prosumers. This platform is intended to be the digital twin of the physical platform. It can be used, for example, for creating and operating a local energy cooperative or other business models at the district level. The connection between the platforms would enable the creation of individual incentives in relation to, for example, energy consumption behavior, participation in e-mobility-sharing, or neighborhood participation.

### 3. Linking BIM and Energy System Simulation

Building information modeling *BIM* is to be used within the ENaQ project. One of the goals is to establish a link to energy simulation. Model-based digital management and processing of information essentially characterizes the way *BIM* works. With *BIM* technology, an accurate virtual model of a building is created digitally, which is called a Building Information Model [25]. A *BIM* model comprises 3D models, which are filled with information. It is subdivided into various submodels, which are created with the appropriate special technical software.

It can be used for planning, design, construction, and operation of the facility [25]. Important advantages include the direct usability of the model for a wide range of calculation and analysis tools and the seamless re-use of the digital information for the building management phase. By reducing the need for different individual models for different applications, each of them containing the same building data, one *BIM* model can be used, thus avoiding the manual re-entry of data and the associated information errors and disruptions; moreover, consistency of the data can be improved [26].

The planning chain can thus be tracked digitally from a central point and sources of error in the transfer of data can be minimized, as the information is only available once at one information base [27].

The ENaQ research project uses *BIM* as a documentation and input model based on 3D models. After completion of the building design, this model will be made available for the sizing optimization of the energy system simulation.

The *BIM* model will initially include the building cubatures and building locations. In addition, relevant energy infrastructure facilities, such as heat storages, will be added to the model. From this, model relevant parameters for the energy system simulation can be taken, both at building and district level (e.g., roof areas or boundary regulations for infrastructure). The models and information usually change during the planning process. *BIM* ensures that the data and models are kept updated.

The *BIM* model is managed with a *BIM* coordination tool (here: *Ceapoint Desite Md*) and enriched with submodels and data from different planners. As an example, the architects use the architect's planning tool *Nemetschek Allplan* for building design. The data exchange to the *BIM* model takes place in .ifc-format. The data exchange between the *BIM* coordination tool and the sizing takes place via an automated Application Programming Interface (API). The automation API provides various functions that can be used for recurring tasks. This approach was tested with the example of roof areas (position in coordinate space and area). In the case of ENaQ, the roof area attributes relevant for the energy system sizing are automatically exported to a text file. The energy system simulation user is then able to import this file. Each time the *BIM* model is changed, an automated export of the current data is performed. The individual submodels, which contain information about the district, are contained in aggregated form in *BIM*. All use-cases, which use this information, refer to the *BIM* model. This minimizes the potential sources of error due to the automated process. *BIM* thus eliminates time-consuming and error-prone re-entry of information and significantly improves data exchange and increases the overall efficiency of the planning process [26].

Listing 1 shows the output file of the automation API as an example of a roof area data file. The attributes describe the roof type (i.e., flat roof, gabled roof), the roof pitch, the roof orientation (cardinal), and the number of possible modules (size).

Listing 1: Example of Python script to automate Shodan queries.

```
1 BuildingID1:
2     type: gabled
3     Roof1:
4         slope: 30.00
5         cardinal: 147.60
6         size: 20
7     Roof2:
8         slope: 30.00
9         cardinal: 327.60
10        size: 20
11 BuildingID2:
12     type: monopitch
13     Roof1:
14         slope: 0.00
15         cardinal: 57.60
16         size: 30
```

To our knowledge, research work in the field of linking energy system simulation and *BIM* was mainly carried out at building level. The ENaQ project and district will be used to validate our approach linking *BIM* and energy system simulation. This should be of great benefit for increasing the actuality of the data and reducing the sources of error from different discrepant databases.



#### 4. Heat Demand Time Series for Districts

The optimization of the energy system requires boundary conditions which clearly define ways and limitations of producing net energy on the one side and demand time series on the other, as the demand has to be covered at all times. In the case of district heat grids, both the demand of residents and possible losses in the grid have to be taken into account. The demand time series of residents can, in the case of existing districts, be based on recorded heating and hot water consumption. If there are no records available, for example, in the case of new districts, various tools exist to compute the demand based on building properties, such as insulation and floor space, typical regional weather conditions, and statistics about the residents, such as occupation and age. These tools allow demand time series for individual buildings to be calculated. The demand time series of a district has to take grid heat losses—should there be any—and simultaneity into account. To calculate such district demand time series, routines are developed combining in *GIS* and *TESPy* (Thermal Engineering Systems in *Python*) applications [28]. As *TESPy* is a package of *oemof*, the transfer of data, i.e., the resulting heat demand time series, to the energy system optimization is fast and uncomplicated.

The positions of buildings, roads, heat generators, and relevant characteristics of the heat supply, i.e., the peak heat load for cold winter days, have to be known when designing heat grids. Usually, *GIS* is used when spatially resolved information has to be combined with further object-specific data in maps. In the case of designing heat grids, this includes, for example, heat consumption, number and habits of residents, as well as temperature levels. In the following, the preliminary design and definition of heat grids in *GIS* is briefly presented. Subsequently, the information needed to transfer a geometrically resolved grid from *GIS* to a thermodynamical code in *Python* is defined. Finally, the more detailed calculation of the heat demand time series of full districts is explained, taking heat losses into account.

##### 4.1. Translating Spatially Resolved Heat Grids from GIS to Generic Objects

One of the objectives of ENaQ is energy trading between prosumers. In general, both electrical energy and heat can be traded between prosumers. Recent publications have investigated the effects of decentralized feed-in to heat grids. In one study, possible earnings of heat grids with decentralized feed-in using an optimized control strategy were compared to those from conventional systems, i.e., systems using purely central heat generation. The conventional system performed better at almost all times over the course of a year. At times, both systems performed equally well, and only occasionally was the performance of the system with decentralized feed-in better, even though investment costs were ignored in this study [29]. It is indeed likely, that the investment costs of a decentralized feed-in heat network would weaken its overall cost-effectiveness—the installation of solar thermal modules, decentralized pumps, and the more complex control strategy are just some of the reasons.

In another publication, a decentralized feed-in of solar energy for heat grids was examined, where the heat grid is used as heat storage. In contrast to other publications, the authors also investigated the effect of storage limits, i.e., the maximum capacity of the heating network to absorb a decentralized feed-in. They found that the limitations of the heat grid are a decisive factor, since a direct comparison of computations with and without limitations showed large differences in the overall balance. Thus, one of the conclusions they drew from this was the very likely overestimation in the literature of the potential of decentralized feed-in to heat networks, as most do not take into account the limitations of the heat network. They also noted that the location of the decentralized feed-in to the heat network was of critical importance as the return temperatures increase for other consumers. However, one advantage was the very small additional pump energy required for the hydraulic coupling of the grid components. It was below 7% of the feed in solar thermal energy for all cases investigated. But even those authors did not take costs for solar thermal modules or decentralized storage into account [30]. The advantages found for decentralized feed-in to district heating were therefore small, if any at all. In addition, the investment costs were not taken into account.

For ENaQ, an affordable energy price is one of the KPIs. According to the current state of the art, there is no promising solution for decentralized feed-in to district heat grids. Therefore, photovoltaics is preferred to decentralized solar thermal heat generation. Besides, a higher level of distributed, renewable electricity from photovoltaics is advantageous for the use, development, and validation of such business models. This prioritization leads to a simplification, which is taken into account in tool development: No decentralized feed-in into the heat grid has to be considered and only central heat production is allowed for. Using the district map, a grid layout can be derived, starting from the central heat generator, passing by roads towards buildings and the most remote consumer. This process can be optimized by, for example, finding the shortest or least expensive grid. In addition, automatized models in *GIS* are an option, to find possible courses of district heating grids or to find areas with large potential for district heat.

For the ENaQ district, there is no pressing necessity to optimize the layout of the grid as the district is rather small (see Figure 2b). There is only one road and a small number of buildings to be connected in the first phase of the project. Therefore, the layout is designed directly by the *GIS* user, based on the accumulated heat quantity of each building, as well as its peak heat amount and geographical position.

The geographical positions and geometrical properties of the buildings are determined in the design process or defined by buildings in realized districts. The heat demand is computed based on climate data (i.e., test reference years determined by the German Meteorological Service [31]); building properties, such as insulation and floor space; and number and habits of residents.

The preliminary dimensioning of the pipes is done using look-up tables and projected required capacity for each pipe section. That is only an estimate, as those look-up tables are based on standard values for transport heat losses. In order to determine the heat losses in the grid at each time step, the heat grid will be recalculated in more detail in a second step. *TESPy* can be used in general to calculate thermodynamic processes and components. When using it to compute district heating grids, the spatially resolved grid in *GIS* has to be transferred to a system of pipe objects in *Python*, while keeping the information of the sequence of pipes, each pipe's characteristics and possible diversions or bends, as well as capacity. Therefore, a routine is implemented in *Python* that automatically generates heat pipe objects based on information defined in *GIS*. For each pipe object, the following information is necessary:

- **Shape\_Length:** length of each pipe section in meters
- **pipe\_ID:** integer that stays constant even if the grid is extended, shortened or opened in another version of *GIS*
- **HC:** Boolean variable to distinguish between pipes that are used for house connections (true) or not (false)
- **prior\_ID:** pipe\_ID of the pipe that feeds into the current one; 0 for the pipe that is connected to the heat generator
- **passage:** Boolean variable that distinguishes the transition between two adjacent pipes; for a bend between the current and previous pipe it is true, for straight connections false
- **capacity:** transport capacity of the pipe in kW
- **DN:** norm diameter of the pipe in mm

This definition allows this tool to be used for any district, not only ENaQ, because it is based on the pipes and their relative position to each other. Thus, it is now independent of the geographic coordinates of the district.

#### 4.2. Calculating the Heat Grid in *TESPy*

Based on the automatically generated pipe objects, the enthalpy along the grid will be computed, which then allows to calculate information about temperature levels, heat, and pressure losses to

be derived. Heat transport equations between the pipes and the surrounding soil are implemented following Reference [32].

If the connection of two pipes includes a bend or junction, the pressure drop caused by these elements is represented by pressure loss coefficients taken from Reference [33]. Only 90° bends are considered, and smooth curves are rounded either to a straight course or a 90° bend, depending on the angle of deflection.

Based on the results, the preliminary design of the pipe diameter can be checked, as well as the heat losses of the whole grid. In addition, the results allow a correction of the time series of the heat demand while taking heat losses into account. The heat demands of each building and losses in the grid at each time step amount to the heat that has to be produced to fulfill continuous heat supply. The corrected time series can then be used as a boundary condition for the optimization of the energy system described in Reference [5].

## 5. Valuation of Flexibility Aggregating Business Models

The ever-increasing use of renewable energy sources calls for greater flexibility in the electricity sector. The decentralized nature of renewable energies is increasingly creating bottlenecks, as the electricity grid was initially designed for central supply. In the current market design of the EU, these bottlenecks hamper the use of electricity from renewable sources, which must be offset by congestion management. Especially in the field of energy supply, changes usually also cause significant challenges, since the security of supply must be guaranteed continuously at all times. In addition to the safety of supply being the highest priority, a sustainable, affordable, and consumer-friendly system must be created. In recent decades, research has focused on various energy generation technologies and flexibility options (i.e., Reference [34]). To address network limitations, different congestion management methods were examined and compared in addition to network expansion (e.g., Reference [35–38]). Especially, the USA and European electricity networks have been challenged due to the high penetration of renewable energies (e.g., Pillay et al. [39]). Hsieh and Anderson [40] showed the changes within the energy system for the USA system and mostly emphasized the need for flexibility. In 2016, the European Union proposed to focus more on local flexibility markets (LFM) [41,42].

### 5.1. Integration of Local Flexibility Markets

In this section, we will look, in particular, at the potential role of an aggregator participating in market-based congestion management based on aggregated demand response flexibilities or generation flexibilities. In developing possible market designs, different archetypes have already been investigated. They propose innovative market roles or extend the competences of existing ones [43]. Due to the high degree of interdisciplinarity in the field of energy supply, a broad range of research topics has already been examined. These include the planning of district supply systems in residential areas and the supply of commercial energy plants [44,45], the associated optimization of operations [46–48], and possible market design approaches to incentivise flexibility [49]. The definitions of new markets and market roles differ internationally and deployment is already being initiated in practical research projects.

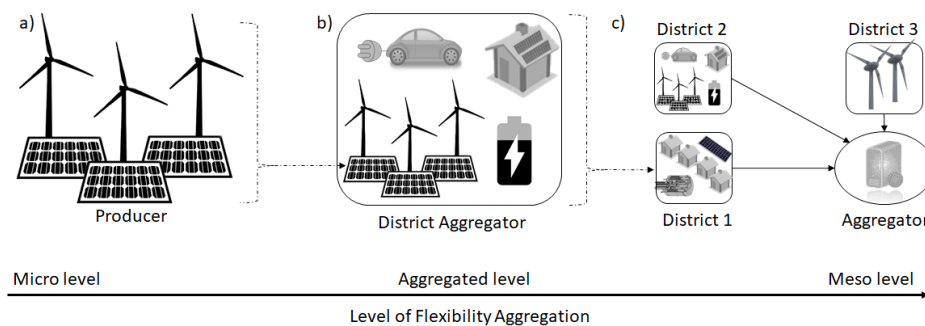
A solution for the aggregation of flexibilities is the introduction of the market role of an aggregator [50]. Forfia et al. [51] presented the Transactive Energy Framework, which has been discussed and supported by the National Institute of Standards (NIST)—U.S. Department of Commerce. GridWise<sup>®</sup> Architecture Council has been working on this Framework since 2010 and presented the results first as a draft in 2013 and as a final version (1.0) in 2015. Parallel to the USA development, the Universal Smart Energy Framework (USEF) was founded in 2014 by a Dutch economic consortium to design and embed the market role of an aggregator. This role was specifically examined in the research project EnergieKoplopers in Heerhugowaard (Netherlands) on 203 households for a Demand Response Market [52,53]. This study looked at the availability of prosumer flexibility using the USEF [54]. USEF was created in the context of the European regulatory framework. For the



practical operation, the software *PowerMatcher* was used, which enables the trade of flexibility [55]. Haque et al. [56] presented *PowerMatcher* and used it in a case study in a real-time simulation [57]. These examples are intended to illustrate that the need for such a framework has already been recognized in the USA and European electricity industries and that work is underway on the solutions. The application of *USEF* is reasonable within the ENaQ project since the associated research project is a national project in Germany and thus in Europe.

Against the background of this framework, this paper will consider which conventional financial valuation methods are applicable to the business models presented here. The largest valuation area of the classical valuation methods is the business valuation. However, sub-sets of companies, i.e., smaller valuation areas, can also be valued, for example, assets, such as power plants, as already shown by Frayer and Uludere [58]. To this end, the business models under consideration are briefly presented. Here, the energy system is seen as a multilevel complex organization as presented by Barrera et al. [59]. In this context, the business models are categorized according to their level of organization. In this case, the resulting hierarchy also corresponds to the degree of aggregated flexibility.

The business models of an LFM are producer, district aggregator, and aggregator. The business models and their level of aggregated flexibility are shown in Figure 3. The first level is the micro level, shown in Figure 3a. These represent, for example, companies with several power plants that sell the energy at a stock market or directly to other companies (“over-the-counter”). On this level, the operation plan is fixed. Further flexible production capacity is not used. The second level is the aggregated level, shown in Figure 3b. In a district with a distributed energy supply, the power plant owners can sell their production capacity or produced energy to a district aggregator. On this level, the flexibility of production capacity is coordinated by the district aggregator in an LFM and may add value to the business model of the producers. The third level is the meso level, shown in Figure 3c. In case an LFM, as presented in the *USEF*, exists, the district aggregators can sell their flexibilities in a regional market. District aggregators, balance responsible parties, and distribution system operators can trade in this market. In exceptional situations, where the market overloads the system, the grid operator has the right to prioritize and stabilize the grid.



**Figure 3.** Business models in an local flexibility markets (LFM) and the level of aggregated flexibility (a) producer (micro), (b) district aggregator (aggregated), and (c) aggregator (meso).

In the following, the status quo will be examined to determine whether conventional valuation methods take flexibility into account when determining the value of energy assets.

## 5.2. Valuation of Flexibility in the Energy Market

In economics, valuation deals with the methodology for calculating the current value of investments. Typically, the valuations of options are compared before investment decisions are made in order to make the best possible choice. A comprehensive approach is the discounted cash flow method (DCF). This method totals the future cash flows discounted to the valuation key date. It can be applied to companies, projects, or individual properties to determine the net present value. One problem arising from the initial investment decision is whether the market role of the aggregator is of interest for

a company or not. Although the analysis of operational optimization and the evaluation of flexibility as a product already allow conclusions to be drawn about the value of a company, this information basis is usually not sufficient for an investment decision. Therefore, it is necessary to develop a methodology that supports the decision function from the field of company valuation [60].

Fraye and Uludere [58] had already taken up the problem in 2001 and illustrated it using the example of an investment decision between a gas-fired and a coal-fired power plant. Parts of the DCF and the real option theory (RO theory) were used. Frayer and Uludere [58] criticize the existing valuation methods for using the future prices of the European Energy Exchange as a basis for calculating revenues. This would not be appropriate for flexible power plants, as they receive the value of their flexibility through spot market trading. The RO theory is based on Black and Scholes [61] from 1973. In the last two decades, the RO theory has been used for various generation technologies to illustrate the applicability of the approach. Ceseña et al. [62] examined the existing literature on adding value to projects taking real options into account. The focus was on electricity generation projects and renewable energy projects. As a result, Ceseña et al. [62] point out that there is a lack of understanding and expertise of the RO approach make it unsuitable for widespread use in the field of management. In addition, there is a lack of breadth in the literature in this field.

In 2016, criticism of the RO theory as an appropriate methodology was expressed. Schachter and Mancarella [63], as well as Godinho [64], pointed out that the transfer of financial pricing options was not appropriate in most cases. Based on the studies presented, the use of RO in practice is often flawed due to a lack of specialist knowledge. Kim et al. [65] examined the added value of using RO in investment decisions, specifically in developing countries. In addition to the review of existing literature in this area, a separate approach is presented. A current literature review of Kozlova [66] from the year 2017, which is also the most comprehensive so far, highlights the research focus, trends and different designs within the literature for evaluation using RO. The literature mainly deals with RO, which represents the investment decision as such and the time of the investment decision. Here, a lack of research for the evaluation of operational flexibility options was determined. Kozlova [66] recognizes a particular need for RO, which evaluates demand-side-management and supporting measures at the policy level.

To our knowledge, no approach exists in the literature for the evaluation of the business model of the aggregation of flexibility and the literature ends at the evaluation of power plants with flexibilities. In particular, it was found that none of the existing approaches takes into account different degrees of aggregated flexibility in the valuation of energy assets. Thus, a further research gap could be identified, which will be further investigated in the ENaQ project. Classical valuation models are examined to determine whether they can depict the value of a company or business model participating in an LFM similar to Figure 3c. Based on this, a method needs to be developed, which is adapted to the USEF market design. Further districts will be modeled for the evaluation. Real case studies, as well as fictitious districts with different framework conditions, can be created. These framework conditions can, for example, affect the district type (i.e., industry), existing building stock, building specifications or the resident, and owner structure. Once the individual districts and associated plant parks have been determined, an option to sell flexibility outside of the district, similar to the spot market, will be added. In this way, the business model of the district aggregator and the aggregator presented by the USEF can be assessed and evaluated. These models are then to be simulated with a selected plant park. By doing this, the value of flexibility of existing power plants or demand side flexibility can be determined. This may be compared to the same districts where access to LFM was already taken into account during design optimization in order to determine the added value of this consideration. The size and number of the models should be chosen in such a way that partial participation in an LFM, as presented by Blik et al. [52], is possible.

## 6. Dynamic Valuation of the Environmental Impact of District Energy System

In addition to the evaluation of financial aspects of an energy supply concept, as presented in Section 5, ecological aspects play an increasingly important role due to growing sensitivity to climate change and sustainability. As part of the KPIs set in the first planning phase (Section 1), the stakeholders therefore agreed that the minimal environmental impact of the district's energy supply should play a central role. In order to ensure a transparent and comprehensible review of this objective, it is necessary to find a methodology that makes it quantifiable. There are various approaches and procedures for the ecological assessment of individual technologies, as well as for overall supply concepts, all of which have certain advantages and disadvantages.

The scientific literature in particular has been dealing with the topic of ecological assessment of distributed and holistic energy supply concepts for many years. Reference [67] choose a very simplified approach. They burden energy imports and exports with annually constant CO<sub>2</sub> emission factors and use the results for the multi-criteria optimization of an industrial area. A similar approach is taken, for example, by Ren et al. [68] and Li et al. [69] and can also be found in the quantification of greenhouse gas reduction potential in research projects funded by the German Federal Ministry of Economic Affairs and Energy in the field of energy-optimized buildings and districts [70]. This method is inspired by DIN EN ISO 14064-1 [71]. A similar approach is proposed by the German Building Energy Law (Gebäudeenergiegesetz—GEG), which is still to be adopted. Mancarella and Chicco [72] are developing an assessment approach that specifically quantifies the local and global emission impact of natural gas use in cogeneration plants. The electricity and heat generation in these plants is compared with the separate energy generation in power plants and boilers. This methodology is used, for example, by Reference [73]. Koutra et al. [74] compare different software solutions for planning net-zero energy districts against the background of the EU climate strategies & targets. They find a variety of tools that could be used for the assessment and present one they developed themselves that is evaluated based on various case studies. However, many tools are often very specific and not very transferable and comparable. A different approach frequently found in the current literature on the subject of ecological assessment of technologies is Life Cycle Assessment (LCA). Ristimäki et al. [75] describe a methodology for combining LCA with life cycle costs at the neighborhood level and thus find systems that are particularly environmentally friendly despite their low costs. Walker et al. [76] develop a simulation-based methodology to evaluate the life-cycle performance of neighborhoods. The methodology is specifically aimed at decision-makers and uses Monte Carlo simulation for sensitivity analysis. Here, too, not only ecological but also other key performance indicators over the lifetime of the neighborhood are examined. [77] use an LCA based on ISO 14044 to determine the effect of different fuels for use in a district-heating combined heat and power plant. They place a special focus on the future availability of these fuels and develop substitution strategies. Carvalho et al. [8] use the Eco-indicator 99 methodology, a modified form of LCA, and on this basis, calculate static values per energy flow, with which these are then burdened. They use this calculation for multi-criteria optimization of a hospital.

In the ENaQ project, the resulting ecological impact is taken into account at various interfaces as can be seen in Figure 1. On the one hand, the project objectives should be evaluated and communicated in a transparent and comprehensible way. On the other hand, the results will also be incorporated into the design and operational phase. For example, a multi-criteria optimization is used for the optimal sizing, with CO<sub>2</sub> emissions as one objective. Similarly, the *oemof*-based scheduling optimization can not only calculate the economically optimal operating mode at any given time, but can also take ecological aspects into account. In addition, the project is also considering incentives to encourage the inhabitants to behave in the interest of the energy system at all times. In order to find out at which times such incentives make sense, information on the current environmental impact of the overall energy system must be available.

This results in the following requirements for the ecological valuation: The method must be easy to understand and calculate, it must be based on freely available live data and yet model the

environmental effects as closely as possible. Besides, it should not only create incentives for the project and its inhabitants but also create macro- and microeconomically meaningful incentives to minimize emissions on a bigger level, be open to technology, and transferable to other applications.

Many methods found in the literature shown above are too specific, too difficult to understand, are not able to produce live data, or require too much effort to be used within the ENaQ project. Often, only a limited choice of technology or energy forms is examined, data are used that are not usually freely available, and the requirements for comprehensibility are neglected. For this reason, a novel methodology was developed that combines various existing approaches to achieve the previously set requirements.

The methodology developed is based on the first of the above-mentioned valuation options, in which energy flows are assigned CO<sub>2</sub> emissions across balancing boundaries. All energy flows into and out of the district are accounted for, which are then assigned specific emissions at that time. Imports are assessed positively, whereas exports are assessed negatively. The result is, thus, the indebted emission within the balancing boundaries. Such a result offers the advantage that it is relatively easy to understand and apply without being too far removed from the reality of the operation.

For the district under investigation, five energy flows are to be considered, whereby four are energy imports and one is energy export:

- Electricity Import (EL, IM)
- Natural Gas Import (NG)
- Wood Pellets Import (WP)
- Biomethane Import (BM)
- Electricity Export (EL, EX)

Directly used forms of environmental energy, such as solar radiation, wind, or geothermal energy, are neglected, as they do not cause direct CO<sub>2</sub> emissions, at least in the first step. The same applies to non carbon based energy carriers such as hydrogen. If, on the other hand, these primary energy carriers are converted into electricity which is then exported, this is added back to the balance. In the later operating phase of the energy system, depending on the specific use case, it may happen that not all the energy flows mentioned here occur. For an application in the design phase that is open to technology and independent of the project, it must be possible to map all these energy flows.

The annual emission  $E$  resp. current emission  $E(t)$  can then be calculated as follows, where  $A_{XX}(t)$  is the amount of energy in time step  $t$ , and  $s_{XX}(t)$  is the specific emission at this time step:

$$E = \sum_{t=0}^{1a} E(t) = \sum_{t=0}^{1a} \left( A_{NG}(t) \cdot s_{NG}(t) + A_{WP}(t) \cdot s_{WP}(t) + A_{BM}(t) \cdot s_{BM}(t) + A_{EL,IM}(t) \cdot s_{EL,IM}(t) - A_{EL,EX}(t) \cdot s_{EL,EX}(t) \right). \quad (1)$$

### 6.1. Valuation of CO<sub>2</sub> Emission for Import of Carbon Based Primary Energy Carriers

For carbon based primary energy carriers, such as natural gas or biomass, energy and carbon content, and thus also the CO<sub>2</sub> emissions released during use, are assumed to be constant. Although regional differences or fluctuating qualities are neglected, errors can be kept small by sensible selection of the data source. Since the application for the case study is in Germany, figures of the German Federal Office for Economic Affairs and Export Control are used [78] (Table 1).

**Table 1.** Specific CO<sub>2</sub> emissions of the relevant primary energy sources according to Reference [78].

Primary Energy Carrier		Spec. CO <sub>2</sub> Factor t <sub>CO<sub>2</sub></sub> /MWh
Natural Gas Import	$s_{NG}$	0.202
Wood Pellets Import	$s_{WP}$	0.023
Biomethane Import	$s_{BM}$	0.148

This shows the great advantage of solid biomass over gaseous energy sources. Oil and coal are neglected at this point, as they no longer play a role in Germany, at least in new construction.

### 6.2. Valuation of CO<sub>2</sub> Emissions for Import and Export of Electricity

In contrast to the primary energy carriers, the secondary energy carrier electricity must be dynamically calculated, since it does not always originate from the same primary energy sources at any one time and the specific CO<sub>2</sub> emissions therefore change dynamically.

The simplest method to calculate the specific CO<sub>2</sub> emissions caused by electricity ( $s_{EL,IM}(t)/s_{EL,EX}(t)$ ) would be to look at the electricity tariff booked by the residents and derive from this the electricity mix purchased by the energy utility and then to adopt it. However, this would completely neglect the technical-physical, as well as the macro- and microeconomic, reality, so that a different approach is chosen.

For a physically and technically correct model, an extremely complex calculation would have to be carried out to determine exactly which generation plant generated the electrical energy that would then arrive at the district's grid connection point. This would presuppose that all system characteristics are fully known at all times and for the entire electrical network. These include, for example, the operating mode, technical properties, and connection mode of the generation plants, the design, and capacity utilization of the electricity grids for extremely large regions, as well as the positions, connection configurations, and energy requirements of all consumers. Although such an approach seems to be technically feasible, it will fail in practice due to a lack of data availability and its too high complexity. Moreover, such an approach would completely neglect the energy-economic and macroeconomic effects. In order to create a functional method, certain assumptions must be made.

Due to the lack of free data on the utilization of the network, not to mention the official course of it, a copper plate must be assumed, which represents certain grid zones, e.g., cities, regions, or whole countries. This means that electricity can flow between producer and consumer in this grid zone without physical and technical restrictions. As a result, grid bottlenecks, such as those often caused by the integration of renewable energies, particularly in Germany, are partly neglected. Based on this assumption, producers and consumers in this zone can also be aggregated, as their position in the grid no longer plays a role. All that is relevant for the producers is the primary energy source from which they generate electricity.

In general, there are now two different quantities that are used in the literature to value energy flows based on grid zones: The average electricity mix and the marginal power plant [79,80]. The average mix describes, as the name suggests, the average composition of an energy unit in the grid zone under investigation. This can consist of a proportion of both generation in this region and imported electricity from other zones. A distinction must be made between the production technology (e.g., coal, gas, solar) both for one's own region and for all other regions in order to be able to allocate the correct specific emissions. The second frequently found assessment methodology is the marginal power plant. This does not imply a mix of generation technologies, but rather a power plant that changes its output in the event of a marginally changing demand. It does not have to be located in the same zone but can be located anywhere in the network as long as the interconnection capacities are sufficient.

There are already well-proven calculation methods for the average mix: Using the flow-tracing method, energy flows are allocated by rather simple vector-based mathematics. For each zone,



the composition of a unit of energy from the generation technologies of its own and all other zones can thus be calculated. This method was postulated in the context of the allocation of energy flows by Kirschen et al. [81] and Bialek [82] and modified by Hörsch et al. [83] to an approach applicable to the present problem. The application of this methodology to the topic of CO<sub>2</sub> assessment on a European level has already been shown by Tranberg et al. [84]. By burdening each generation technology at each zone with its individual specific emissions, the emissions can be calculated for each grid zone.

The approach is more complicated for the marginal power plant: Often the operational priority of the national power plants and thus also the marginal power plant relevant here is described with the merit order. This is a microeconomic model that orders the power plants of a marketplace according to rising marginal costs and then finds the point of intersection with current demand. All power plants with lower marginal costs are then allowed to produce, and all others are switched off [85]. The interconnection of all European electricity grids makes it possible to exchange electricity between all the associated energy markets. A modeling of all these markets to find the marginal power plant according to the merit order approach seems hardly feasible. Moreover, the merit order approach is only a simplified economic model [86,87], and the long-term techno-economic market effects actually observed are thus only partially described. Therefore, a machine learning approach based on historical data seems to be much more appropriate. Such an approach is postulated e.g., by Wang et al. [88], but, up to now, there is relatively little application-oriented work and few publications on this topic.

Which of these valuation methods is actually used depends strongly on the question to be investigated, and there is no silver bullet [79]. Most frequently, e.g., in Reference [67,89,90], the mean emission is used for import and export, but in contrast to what is postulated here, it is often used as an annual mean value. Literature can also be found, e.g., Reference [91–93], which (statically) selects the marginal power plant as an assessment variable for import and export. There is also literature, e.g., Reference [94] or the previously mentioned German Building Energy Law, which uses an asymmetrical evaluation method. Here, for the import, the average mix and, for the export, especially of CHP systems, the marginal power plant is chosen. Within the framework of the ENaQ project, the asymmetric approach is therefore used, since it allows the legal framework applicable in Germany to be mapped as closely as possible.

In order to put this calculation method into practice, data of the technology-specific generation and consumption of network zones for the overall network in question must be found. The overall grid in question is the European synchronous grid and the synchronous grids directly connected to it, since, at least in theory, an unhindered exchange of energy can take place between them. Hourly data for these network regions, divided into countries, are freely available via the ENTSO-E Transparency Platform (<https://transparency.entsoe.eu/>). Both historical technology-specific generation and consumption data and the values forecast by the transmission system operators for the following day are available. Although the application of these data has some disadvantages, such as the extremely large grid zones and the sometimes rather mixed data quality, it seems to be the only reliable and freely available data source with the required data at this stage.

## 7. Conclusions

In this paper, selected aspects were presented that are relevant for a holistic planning process of innovative and distributed energy supply concepts using the example of a new development district. To this end, the case study of the ENaQ project was first presented in Section 2. The case study is to develop a multisectoral supply concept for a new district on a former airbase in Oldenburg in Northern Germany as part of a funded project. The most important results of the individual sections are highlighted below.

Section 3 shows that the use of building information in a *BIM* model can increase the accuracy and actuality of building data. The changes to the building design that take place during the planning process can be documented by a *BIM* model and made available to other specialist planning groups.

For this purpose, a retrievable API was created as an example, which initializes the export of certain data from a *BIM* model.

Section 4 presents a routine based on *TESPy*, that allows for automated data transfer from heat grids, that are preliminary designed in *GIS*, to a *Python* readable format. Based on this, a thermodynamic calculation of the heat grid and the losses at each time step is possible. Using these, the heat demand time series of the district, taking losses of a heat grid into account, can be computed. This time series is finally used as an input parameter of the energy system optimization. It allows a good estimate of local consumption and shares of renewable energies, which is an intended outcome of district energy system evaluations and part of the KPI in ENaQ. Oversizing can also be avoided, which would lead to high energy costs due to higher installation costs and possibly higher heat losses in oversized heat pipes.

Section 5 outlines the scope of the literature in flexibility markets and valuation methods regarding energy plants with flexibility options. There are existing regulatory energy frameworks for flexibility markets. The status quo of the literature on methods for the economic evaluation of companies and business models in the energy sector which trade distributed energy is presented. It was found that the European Energy Exchange future market is used as a basis for valuation. However, this is mainly relevant for inflexible, large power plants. The capacity of flexible plants, on the other hand, tends to be traded on the spot market. This valuation basis fails to adequately reflect the value of flexibility realized in short-term markets. It was also noted that new evaluation methods are being developed which take into account the value of flexibility. However, the current literature does not yet seem to consider decentralized neighborhood facilities and LFM. Many of the new approaches are developed on the basis of real options theory. The criticism of the scientific trend of applying real options theory is, besides the lack of practical applicability, that it leads to overvaluation and overinvestment. A scientific niche could be determined, which will be addressed in the context of future work within ENaQ.

Section 6 addresses the ecological evaluation of district energy systems and proposes a possible methodology based on the assessment of CO<sub>2</sub> emissions due to energy flows from and into the district. In order to achieve this, each energy flow is burdened with a specific emission. This specific emission is assumed to be constant for primary energy sources, such as natural gas, but must be calculated continuously for electricity—in contrast to approaches frequently used elsewhere. For this purpose, a method was described which uses the technology-specific production and consumption per grid zone to calculate the specific emissions as an average value and those of the marginal power plant. Europe-wide data from *ENTSO-E*, for example, could be used for this purpose.

All methods and tools presented are for flexible district systems with a high share of renewable energies. These can be used for future districts or for the redevelopment of existing districts. The development is therefore based on ENaQ, which also allows validation. However, the methods and tools are kept as generic as possible to ensure transferability.

**Author Contributions:** Conceptualization, Methodology, Software: S.W., L.S., L.V., F.R. and K.-L.W.; Writing—original draft, Writing—review & editing: S.W., L.S., L.V. and F.R. 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).

**Acknowledgments:** The authors thank all the other ENaQ project partners for support, inspiration and fruitful discussions. We thank Duncan Howson (Lecturer at Jade HS.) and Tobias Brandt (Researcher at OFFIS e.V.) for comments that greatly improved the manuscript.

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

## Abbreviations

The following abbreviations are used in this manuscript:

API	Application Programming Interface
BIM	Building Information Modeling
DCF	Discounted Cash Flow
ENaQ	Energetic Neighborhood District
GIS	Geographic Information System
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LFM	Local Flexibility Market
NIST	National Institute of Standards
PV	Photovoltaic
RO	Real Option
USEF	Universal Smart Energy Framework

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