Geo-Referenced Modeling of an Urban Quarter for the Assessment of Refurbishment Potentials and Energy Supply Strategies

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Keywords: Building stock; refurbishment strategies; energy transition; simulation model; energy supply; model-based optimization

Extended Abstract

The necessary rearrangements of our energy system are numerous and affect energy supply and energy demand alike. Various studies [1] show the existing extensive potential for emission reductions. The change and optimization of our energy system is a crucial challenge of the coming years, which can only be done on the basis of verified knowledge about the details inherent to the system.

The number of interdependencies and variables included illustrates the high requirements for the description of the system in simulation models, which should become increasingly detailed by zooming into the system. Depending on the purpose of the investigation, the level of detail varies strongly.

Concerning the building stock of an urban quarter, accuracy is often limited in using available statistical data for the modeling of energy demand. This data includes information about building size and building age classes. Especially site-specific information, like arrangement and alignment of the buildings, cannot be considered in this way. Geo-referenced data include this information; therefore their integration provides two important possibilities: The potential in energy efficiency of a city quarter can be assessed with respect to the special characteristics thereof, and the data resolution in time can be increased in order to deliver the demand to the optimization algorithm of the further energy supply structure.

In contrast to the residential buildings, for the non-residential buildings no data are collected by the statistics agency. Thus, the data about the existing non-residential buildings and their use had to be collected by site inspections in the quarter “Nuremberg West”. Furthermore, only rough typologies offer data about the quality of the building components and the typical issues of the building age. Therefore site-inspections provided information like the building age and the energetic quality of the components and the dimension of the building envelope. Because of the high share of conditioned space in non-residential buildings - about 50% - they had to be considered in the same way as the residential buildings.

Only once this is done, the impacts of different refurbishment strategies can be assessed and a negotiation over contributions of different strategies can begin. Particularly in respect to district heating in combination with basic fabrics from before 1948, the assessment of the impact to the energy supply is a fundamental precondition for the negotiation over the necessary extent of refurbishment.

A special characteristic of the quarter Nuremberg West is the high share of residential buildings which were built before 1948. These buildings, which predominantly have decorative facades, form the character of the quarter even though large-scale commercial space exists as well. The improvement of the thermal protection of these buildings is a technically demanding task which can only be succeeded by careful planning and construction.

In contrast to modeling the building stock of an urban quarter, a higher scale-level is used for the investigation of the electricity system. The interaction between optimization on a supra-level and local data aggregation has always been a bottleneck. But alongside with intense methodical research in the area of energy systems optimization over the past decades, drastic gains in accurate modeling of aggregated systems arose. This allows for increasing degrees of detail in the modeling of local circumstances.

This paper describes approaches in modeling to design the energy structures of an urban quarter sustainably. Therefore, the site-specific modeling of the energy demand was enhanced by the use of geo-referenced data to increase the level of detail and the resolution in time. Furthermore, the detailed data about the arrangement of the buildings was used to assess the site-specific potential in energy-efficiency regarding the careful handling of decorative façades. The higher resolution in time, which was achieved in the course of the project, provided the possibility to deliver time-dependent data for simulation and optimization of the energy supply. Thereby it is possible to optimize the energy system by the use of more site-specific information.

With regards to the energy supply the crucial question of the project was to find optimal strategies in different scenarios. To answer this question, the findings of the estimation of the energy demand were used in a linear energy systems optimization model (URBS). The model was adopted by the Institute for Energy Economics and Application Technology at the TUM in order to match all project targets. The requirements of the project are a more specific research focus on the structure of capacity built-up for thermal energy generation and the interaction with the surrounding electricity system with high shares of renewable energies.

To answer further questions about multi-level interactions in the energy system, the cooperation of the energy supply optimization side with the detailed energy demand calculation offers potential to do so, but also requires equivalent effort to develop the corresponding methodologies.

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Summary

For the implementation of the German energy transition, it is essential to develop strategies for the reformation of the energy system. Numerous studies prove the feasibility of the national targets formulated to decrease the greenhouse-gas emissions.
The integration of renewable energy and simultaneously the large reduction of energy demand are preconditions for the optimization of the energy system and can only be implemented on the basis of verified knowledge about the details inherent to the system. It is a major challenge to improve collaboration at the interface between the supra- and local-level-models to optimize the system and investigate their effects.
Hence, in the research project “Stadtlabor Nürnberger Weststadt”, which was initiated to develop a sustainable urban transition, various steps towards a site-specific modeling were done. Through the use of geo-referenced data, special characteristics of the quarter are included in the calculation of the energy demand and the site-specific potential for energy efficiency of the buildings can be estimated. Furthermore, a higher resolution in time of the energy demand in delivering these data to the optimization algorithm of the energy supply is achieved. The goal of optimizing the energy supply is the assessment of the interactions between the local and the global levels, taking into account the existing thermal energy supply infrastructure.

Keywords: Building stock; refurbishment strategies; energy transition; simulation model; energy supply; model-based optimization

1. Introduction

The necessary rearrangements of our energy system are numerous and affect energy supply and energy demand alike. Various studies show the existing extensive potential for emission reductions. The change and optimization of our energy system is a crucial challenge of the coming years, which can only be done on the basis of verified knowledge about the details inherent to the system.

The number of interdependencies and variables included illustrates the high requirements for the description of the system in simulation models, which should become increasingly detailed by

zooming into the system. Depending on the purpose of the investigation, the level of detail varies strongly. In modeling the energy system on a supra-level, details are averaged to keep the simulation accessible to get insight into the overarching system.
Concerning the building stock of an urban quarter, accuracy is often limited in using available statistical data for the modeling of energy demand. Especially site-specific information, like arrangement and alignment of the buildings, cannot be considered in this way. Geo-referenced data include this information; therefore their integration provides two important possibilities: The potential in energy efficiency of a city quarter can be assessed with respect to the special characteristics thereof, and the data resolution in time can be increased in order to deliver the demand to the optimization algorithm of the further energy supply structure.
Only once this is done, the impacts of different refurbishment strategies can be assessed and a negotiation over contributions of different strategies can begin. Particularly in respect to district heating in combination with basic fabrics from before 1948, the assessment of the impact to the energy supply is a fundamental precondition for the negotiation over the necessary extent of refurbishment.
In contrast to modeling the building stock of an urban quarter, a higher scale-level is used for the investigation of the electricity system. The interaction between optimization on a supra-level and local data aggregation has always been a bottleneck. But alongside with intense methodical research in the area of energy systems optimization over the past decades, drastic gains in accurate modeling of aggregated systems arose. This allows for increasing degrees of detail in the modeling of local circumstances. However, the progress achieved did not yet lead to more integrated approaches of combined local and national optimization. So far, data structures are more or less adapted to the investigated level, making it hard to exchange valuable information.
However, by zooming into the system, the importance of individual pieces of information increases. Singularities arise and generally have high influence on the robustness of the results. Within the scope of the research project "Stadtlabor Nürnberger Weststadt", the task of designing a sustainable urban development strategy by 2050 required the design of sustainable structures in energy demand and energy supply. Hence, the key questions were the following: How can the residential and the non-residential buildings and their use be recorded with sufficient accuracy? What contributions to energy and emissions savings could be achieved by a distinct city quarter with restrictions due to decorative façades? What impact could optimization exert onto the overall structures? What singularities exist within the area and how do they impose restrictions on the optimization of the system?

This paper describes approaches in modeling to design the energy structures of an urban quarter sustainably. Therefore, the site-specific modeling of the energy demand was enhanced by the use of geo-referenced data to increase the level of detail and the resolution in time. Furthermore, the detailed data about the arrangement of the buildings was used to assess the site-specific potential in energy-efficiency regarding the careful handling of decorative façades. The higher resolution in time provided the possibility to deliver time-dependent data for simulation and optimization of the energy supply. Thereby it is possible to optimize the system by the use of more site-specific information.
The content of the paper is organized as follows: In Section 2 we describe the scope of the project as the basis for the interdisciplinary work. Section 3 outlines the steps taken to improve the site-specific modeling necessary to consider singularities. In addition, this section shows the approach to attain a higher resolution in time of the whole energy demand in order to pass the data onto the optimization of the energy supply. The factors influencing energy demand caused by different levels of quality in the refurbishment and different arrangements of all buildings built in the quarter before 1948 are discussed in Section 4. Thereby, the importance of the distribution of problems in the system is discussed. A short description of the intra-scale modeling of heat and power supply as well as their interdependencies can be found in Section 5. Finally, Section 6 finishes the paper with conclusions and a summary of findings from this study.

2. The Frame of the Investigation: “Stadtlabor Nürnberg West”

In the past, Nuremberg West (NW) has been exposed to dramatic changes. Bankruptcy and

closure of many long-standing local companies have led to massive job losses and greatly changed the appearance of the quarter. In the research project "Stadtlabor Nürnberger Weststadt" initiated by the Center for Sustainable Building, an interdisciplinary team integrating six different disciplines – civil engineering, architecture, landscape architecture, electrical engineering, geography and economic sciences – took on the issue of long-term sustainable development of the urban quarter. With input from different disciplinary perspectives, suggestions for a sustainable urban transition of the city quarter were to be developed.
The framework for the sustainable development was given by three future alternatives, which were designed during the process by the Department of Spatial Development of the Technische Universität München (TUM). These three future alternatives are based on current trends and on the district and its integration into the metropolitan region. They represent positive, desirable and attainable images for the development of the city quarter. As these visions for the future contain important information for the development of the boundary conditions, they provide an important basis for the analysis of the further development of energy demand and supply.
The city quarter Nuremberg West contains different singularities, which had to be considered for the modeling of the quarter: More than 60% of the space is located in non-residential buildings and an overwhelming majority of the residential buildings were built before the year 1948 and have decorative façades. In total, the city quarter comprises about 3,500 buildings and more than 13,500 inhabitants. In the following figure, the city quarter Nuremberg West is shown as a part of the city of Nuremberg.

Figure 1: The city quarter Nuremberg West as a part of Nuremberg

The project time comprised only one year, therefore it was clear already from the beginning that all arising questions couldn't be answered entirely. However, a lot of steps were done to improve the handling of the given questions.

3. Modeling the Energy Demand: Increasing the Level of Detail

As mentioned above, the importance of individual pieces of information increases by zooming into the system. Singularities arise and their mapping is crucial to reach a sufficient level of accuracy. Regarding the city quarter Nuremberg West, compared to the building typology of the city of Nuremberg, singularities are given by the arrangement of the buildings and their homogenous building age. The share of Multi-Family-Houses (MFH) with connected walls is quite high and the share of buildings built before 1948 is about 60%. If the information given by the German building typology and the mixed building structure of the whole city were transferred to the city quarter, the special characteristics would be negligible.
For modeling the building stock, the main data about building size and building age class of groups of buildings is given by statistical data for rural districts and cities. These data are based on the 1989 census and the on-going building completion statistics. In the research project 'Stadtlabor Nürnberger Weststadt' additional data about the rough position of the building was given by its assignment to a special building block. In contrast to the residential buildings, for the non-residential buildings no data are collected by the statistics agency. Thus, for the city quarter

Nuremberg West, the data about the existing non-residential buildings and their use had to be collected by site inspections. Furthermore, only rough typologies offer data about the quality of the building components and the typical issues of the building age. Therefore site-inspections provided information like the building age and the energetic quality of the components and the dimension of the building envelope. Because of the high share of conditioned space in non-residential buildings - about 50% - they had to be considered in the same way as the residential buildings.
So far the statistical data include no information about the arrangement and the alignment of the buildings, which is necessary to calculate the solar gains of the buildings and to further calculate results with higher resolution in time. Therefore, a method was developed to combine the information of the digital cadastral map with the statistical information, which is described in the following chapter.

3.1 More Site-Specific Modeling by the Use of Geo-Referenced Data

In the last years, apart from the statistical data, geo-referenced models of the building stock were created and made available for the public. These models contain a lot of site-specific information about buildings, which is a meaningful addition to the available statistical data. In fact, the Bavarian land surveying office provides two types of models, which differ by the level of detail included. *Level of Detail 1* (LoD1) includes data about the outlines and an average height of each building while *Level of Detail 2* (LoD2) additionally contains roof shapes of all building.
For the investigation of the city quarter Nuremberg West, models of both scales were submitted. As mentioned above, statistical data include neither site-specific data nor information about the shape of the buildings. Hence, the aim of using the data was to include these details, which enhance our ability to identify special building characteristics. Therefore, a method was developed that uses information about the building age and the living space on the one hand and information about site-specific building characteristics on the other.
The site-specific characteristics, which were generated by the use of LoD1 data, include the connected walls and also walls which can include windows. This first aspect is important as a parameter to estimate the building component surfaces; the second one is necessary to realistically estimate the solar gains by using the orientation of the windows.
The first step of the identification of the connected walls is the division into single lines of the outlines of the buildings in the LoD1 data. If there is a connection to other buildings, in the second step, these lines are divided at the meeting point with the other buildings, and as result every single line of the building outline is classified into lines that are either free or otherwise connected to other buildings. On this basis, for each building block a distribution is calculated of how many walls in each orientation are connected and how many are free. This distribution is used to count the different number of buildings that are free-standing, have three free walls and one connected wall or have two or less free walls and two or more connected walls. The following figure shows the classification of buildings within one building block.

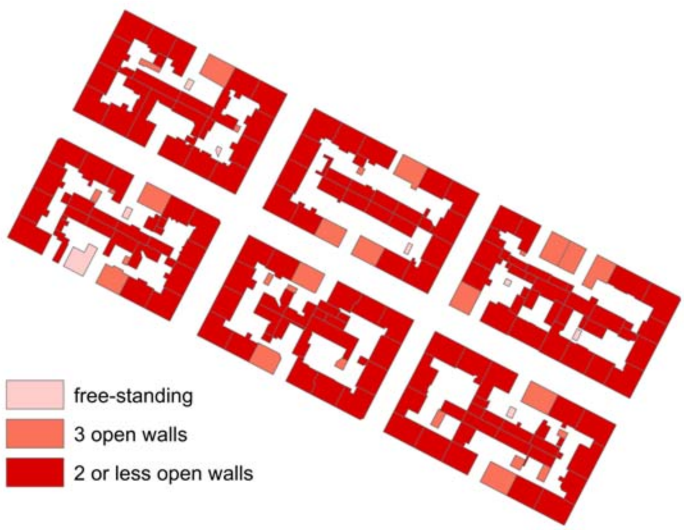

Figure 1: Example of building blocks with free-standing and embedded buildings

As the number of buildings with only one free wall is small they were assigned to the group of buildings with two free walls and handled like these in the area approximation algorithm.
The information about connecting provides the possibility to distinguish between walls which adjoin to free air and those who adjoin rooms with a similar temperature. Though, the transmission lost can be estimated in a more realistic way.
A constraint of the accuracy is given by the lack of information about non-residential buildings inside the blocks. By the site-inspections only the rough classification of a non-residential building could be done and information about the special use of each non-residential building was not available. Except the specific buildings like schools, the former “Quelle” logistics center or the “AEG” production buildings or similar buildings can be classified by their use. But, predominantly the non-residential buildings that are embedded in building blocks, are mainly used as shops or offices. So the indoor temperature is comparable to that of residential buildings and the the inaccuracy of this missing information is marginal.
By above-mentioned process the connected walls could enable us to identify the distribution of walls available for window areas. This was done by calculating a distribution of free walls and their orientation for each block. Then the window areas given by the area approximation algorithm [2] were placed in the orientations corresponding to the calculated distribution. Generally, only a limited free wall area is available for windows in compact and dense urban quarters, so all these areas have to be used to maximize the utilization of daylight.

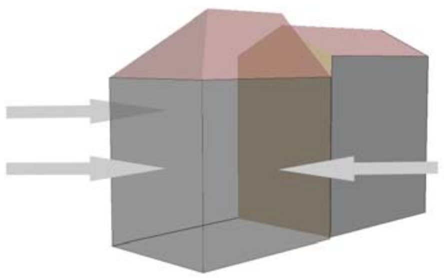

Figure 2: Example of free walls available for windows

Using the more detailed information about the roof in the LoD2 model enabled us to approximate the maximal available roof space for use with renewable energy sources like solar thermal collectors or photovoltaic cells. To do this, first of all, the sloped roofs facing east, south, and west were identified beside the flat roofs. For each of these surfaces the shortwave radiation from the sun was calculated in hourly time steps using a sun trajectory model given in [3] shading by other buildings was not calculated in this geometric model, but to get a realistic and not overestimated performance of the available solar potential, the calculated values were reduced by 50% according to [4]. This factor includes both, the shading by other buildings as well as self-shading of photovoltaic or thermal collectors on flat roofs, which exist to a great extent in this quarter. This hourly data was used to model the solar energy supply in the energy supply calculation described below.
While the geo-referenced data include information about single buildings, the statistical data concerning building age, building type and related living space are only given for a block of buildings. In order to refer the information to single buildings, they had to be broken down to this level. In order to minimize the inaccuracy of this assignment, a Monte Carlo approach was chosen. Multiple simulation runs were done with different distribution of block information to buildings; therefore, the result is an average of all these runs.

3.2 Steps of the Energy Demand Calculation

The above defined steps provide a site-specific calculation of solar energy gains in buildings. This is an important prerequisite for replacing the yearly to monthly balancing in order to take into account the actual alignment of the buildings in the quarter. Therefore, instead of the heating period balancing method now the monthly balance method can be used and so monthly demand values are determined.

To name the energy demand of the entire quarter (except the on for mobility) some further steps have to be taken. So, the total household electrical energy demand and the thermal and electrical energy demand of the service sector which is located in the non-residential buildings is calculated. But essential limitations are set by the missing data about local businesses in the quarter. The community trade office and the employment agency document both the kind of business and the number of staff employed, but due to data privacy, this data cannot be provided. Therefore, a lot of research was necessary to get the required information.

For the calculation of the energy demand of different types of business, the specific energy demand per employee from the research project [5] was used. In addition, the thermal energy demand of the non-residential buildings was calculated and compared to the results described above.

The calculation of the electrical energy demand of the households was done on the basis of the number of inhabitants, the living space and the number of different types of households. The specific demands of the different types of households are based on [6].

In order to convert the monthly thermal demand of the entire quarter to the hourly demand, a thermal load profile of a comparable quarter was used. It includes the demand from both residential and non-residential buildings and was scaled to the existing district size. For the distribution of the hourly electrical demand load profiles of residential and non-residential buildings were used **Fehler! Verweisquelle konnte nicht gefunden werden.**.

4. Assessment of Potentials: the Refurbishment of Decorative Façade?

A special characteristic of the quarter “Nuremberg West” is the high share of residential buildings which were built before 1948. These buildings, which predominantly have decorative façades, form the character of the quarter, even though large-scale commercial space exists as well. The improvement of the thermal protection of these buildings is a technically demanding task which can only be managed by careful planning and construction.

This peculiarity of the district shows that the objective to reduce the energy demand of the building stock can’t be applied to all sections of the system to the similar extent. The constraints of the technical feasibility and the demands for usability of the building after the refurbishment by each dweller should be taken into account.

The limitations in the utilization of the existing potential raise key questions: Can higher savings compensate lower savings of refurbishments, which are difficult to handle? Where in the system, can these additional savings be achieved and is it allowed to fall short of its potential? The energy concept of the federal government [8] requires an emission neutral building stock by covering the remaining energy demand from renewable energies. Therefore, is possible and correct to transfer a deficit in the decrease of the energy demand to the optimization of the energy supply? An answer to the above mentioned questions cannot easily be found if only a part of the system is investigated. Rather, analyzes of the sensitivity in the entire system are prerequisite for the design of strategies. The analysis of the entire system is a high challenge so far.

By the use of geo-referenced data, the existing potential and its constraints in energy efficiency of the building envelopes can be assessed for the district of “Nuremberg West”. Therefore, the building surfaces, which are orientated to the street (decorative façades) and those which are located at the back of the buildings, were recorded separately. For the façades, which are orientated to the courtyard, it is assumed, that they are less or not decorated and an improvement in the thermal insulation quality is possible. The façades were therefore treated separately and in case of refurbishment different qualities were assigned. In order to have a reference value, the efficiency gains without restrictions are calculated. To assess the influence of urban density to the energy savings the partly thermal protected buildings and those with complete thermal protection were calculated as free standing buildings. The following figure shows the results of the calculations including all residential buildings erected before 1948 in the quarter “Nürnberger Weststadt”.

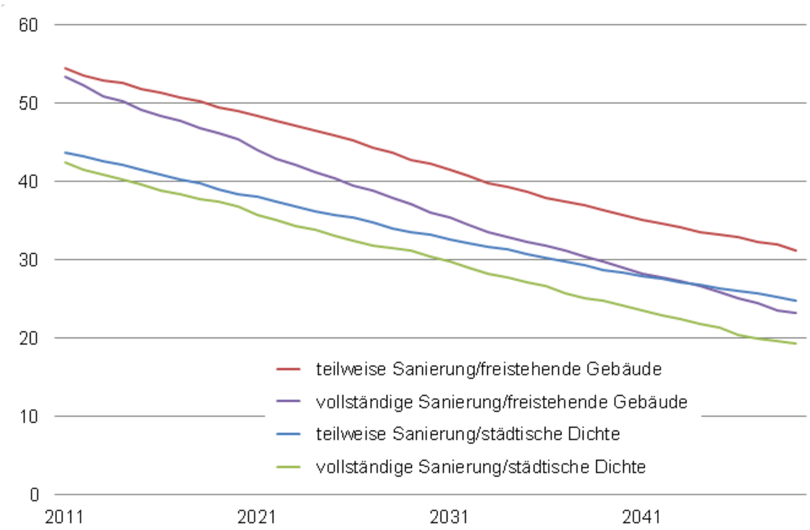

Figure 3: Heat demand of free-standing more-family-houses and connected more-family houses (7-12 dwelling units) with different thermal protection.

At present time, the energy demand of buildings with connected walls is more than 20 % lower than the energy demand of the free-standing buildings. In the following years the curves tend to approach each other. The demand of buildings with a complete thermal protection and no adjoining walls strongly decreases because of the high share of wall area in the building envelope. After about 30 years, the energy demand of these buildings decreases below the energy demand of the buildings in the urban set-up. The advantage caused by the arrangement of the buildings loses its influence in the further remediation progress. Comparing the curves of the complete refurbishment it is noticeable, that a rapprochement has been taking place, but the efficiency of the urban set-up cannot be caught up. It has to be mentioned, that the complete thermal protection of free-standing buildings is much more expensive than for buildings with connected walls.
In terms of the building stock of Nuremberg West it can be determined that the losses of the same group of free-standing buildings are higher than the losses of the buildings which are embedded. The advantage in efficiency can only be obtained by extensive thermal protection. Considering this being representative of different building sites, so slightly savings are compensated in other areas of the system. To assess the effect of different extents to the entire system, additional studies are required. It is particular important, if deficits in refurbishment are transferable to the optimization of the energy supply and what costs will be provoked by this.

5. Optimization on Different Scale-Levels: Considerations on Interaction the Energy Supply

The requirements of the project are on the one hand the interaction between Nuremberg West with the surrounding electricity system with high shares of renewable energies. On the other hand the structure of thermal energy generation capacity built-up is a specific research focus. Especially the second point is heavily influenced by existing capacities and the availability for district heating. In NW district heating is available from a commercial-scale power-plant nearby operating with CHP. Because of high investment and comparatively high efficiency/low operational costs it’s rational to operate, renew and potentially expand existing district heating infrastructure in future scenarios. In contrast small-scale heating systems need replacement over time, with changed conditions since built-in/last renewal. One option to replace small-scale heating systems is local CHP. This means there are two separate options to integrate CHP in NW.
With regards to the energy supply the crucial question of the project was to find optimal strategies in different scenarios. In order to answer this question the findings of the above described

estimation of the energy demand were used in a linear energy systems optimization model (URBS). The model was adopted by the Institute for Energy Economics and Application Technology at the TUM in order to match all project targets. The requirements of the project are a more specific research focus on the structure of capacity built-up for thermal energy generation and the interaction with the surrounding electricity system with high shares of renewable energies.
The interaction of these two different levels of energy systems optimization yields potential for improved efficiency of energy supply. For example combined generation of heat and power (CHP) is utile if both energies are demanded entirely and at the same time. Observations show, that demand for thermal and electric energy doesn't match. In energy systems with high shares of renewable capacities the interaction between thermal and electricity supply increases significantly, because at times of high feed-in from wind and/or solar the efficiency of CHP decreases drastically. In these cases a certain share of energy is wasted, if all demand is to be supplied by CHP. Therefore separate generation of heat or power can be more efficient but this is heavily dependent on surrounding system characteristics. In order to determine of the optimal mix of CHP, separate generation and energy imports from the surrounding system a mathematical model was applied, which was specifically adapted to handle these questions with high degrees of correlation. While these models are capable of determining optimal structures of energy supply, reliability of results heavily depends on the quality of parameters and demand input data available.
In order to investigate local scale consequences of the national transition strategy a linear optimization model with a social planner objective function was applied. This method seeks to minimize total system costs. Key bound is the satisfaction of an externally determined demand, while profit-ability of investment decisions is not an issue in this context. There are two key factors influencing the total system costs while complying with the constraints which define the characteristics of a given scenario/vision. First of all and representing the national strategy as well as a specific vision there are the constraints restricting potential solutions, e.g. stricter CO2 Emissions limitations require more renewable generation capacities to be installed. This incurs higher resulting costs; otherwise the model would have already expanded the renewable capacities to find the minimum of total system costs. The second group of key factors affecting the objective function is the value of the cost parameters associated with the dispatch and expansion of the energy system under investigation. These exogenously given values were received from external sources, e.g. different studies and research papers. Once again the cooperation within this project lead towards a higher rate of exchanging and iteratively validating these parameters.
To these ends local scale considerations contribute with their capability to handle the variety of different buildings. In contrast regional and higher-scale energy systems optimization has a strong background in the optimization of systems with many rival boundary conditions. Although having vast experience in urban energy systems optimization the improved data availability is beneficial. Consequently in this project high potential for mutual benefits was identified and first steps were taken for closer interaction in future. Still from a technical perspective there is a lot of effort needed to actually use all the potential. In order to successfully step forward the building side has to keep in mind the structure of data that is required for usage in the mathematical models, which starts way before a project is to be defined. On the other hand the system optimizations side's task is to develop models better suitable to the subject of research of the building side. E.g. development of interfaces to actually connect not only one subsystem with one system on the supra-regional level, but also allow for the interaction of many urban district style subsystem within the framework of a larger level in this project Bavaria.

6. Conclusion

In this paper, we describe the integration of site-specific data as an important basis for the simulation and optimization of the energy demand and energy supply structures of quarters in the context of the overall energy system. By the use of geo-referenced data, the alignment and arrangement of buildings in the urban context can be assessed and together with the information about the building age, the resulting savings and optimization potentials can be investigated. In this respect the impacts by the restrictions in the refurbishment of buildings with decorative façades are further investigated and the efficiency of the urban arrangement of buildings in contrast to free-standing buildings is compared.

Still, detailed data about the geometry of the buildings is not available and represents the restrictions in the simulation and optimization of the structures. Their improvement requires further steps in data collection and data management as well. By the described methodical steps, an approach to combine various data sources in order to include the specific monthly radiation on window surfaces was developed. Thus, the energy demand can be calculated in a higher resolution in time. Furthermore, the total energy demand of the quarter was calculated and has been handed over to the energy supply optimization.

In the process of energy supply optimization the core question focuses on the integration of local- and supra-level structures into the energy systems model.

This is aligned by the challenging integration of renewable energies to reduce greenhouse-gas emissions. Especially the thermal energy supply from CHP was taken into account. Thereby interactions between local and supra-level are caused by the simultaneous production of electrical and thermal energy. The use of data from the energy demand calculation, proved to be a fruitful initial step in the cooperation to investigate urban energy supply and demand. To answer further questions about multi-level interactions in the energy system, the cooperation offers potential to do so, but also requires equivalent effort to develop the corresponding methodologies.

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