Municipal heating system modelling towards urban energy transition : integration of spatial dimension based on a participatory approach

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Abstract

Urban spatial data such as building information and its distribution within districts are often less emphasized in energy system modelling studies even though they are the main end-users in urban energy systems. This is partly due to the fact that that data collection on a local scale for characterizing the urban energy system is not a straightforward process. In this respect, municipal urban/energy planners' roles in energy planning becomes critical since they can provide the necessary data and local-specific knowledge as well as their preferences and visions of their future energy system through participating the energy systems modelling process: from the identification of the spatial dimension to scenario development. This study applies an integrative modelling methodology based on a participatory approach to a case municipality in Denmark exploring how the spatial dimension is implemented in energy systems model and the implication of a participatory modelling approach. It is found this type of model can improve the possibility for the model outcomes being more useful as decision support.

Keywords: Energy systems modelling, Municipal heat planning, Long-term transition pathways, Urban energy transition, Spatial dimension, Participatory approach

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1. Introduction

The expectations imposed on urban authorities to play an important role in urban energy transitions have been growing. This derives from the fact that urban areas consume the vast fraction of global primary energy supply emitting more than 70% of world's CO_2 emissions (Johansson et al., 2012; Seto et al., 2014) and that the urban stakeholders are able to impact the urban energy system planning with their local-specific knowledge (Dias et al., 2019; Fichera et al., 2018; Morvaj et al., 2016; Scheller et al., 2018; Selvakkumaran & Ahlgren, 2017).

Energy transitions in urban areas should be addressed with long-term visions and appropriate planning. Here, energy systems models are important tools that are widely chosen to support the decision-making process in energy planning to achieve the user's objective, e.g., minimizing the total system cost, the total emissions, etc. While various approaches and methodologies for modelling energy systems have been developed and applied at the national level, methods and approaches for making and evaluating energy plans and policies at the urban level have been less studied (Muñoz et al., 2020).

Traditionally, urban energy systems modelling focuses solely on techno-economic data and cost-based assumptions without taking the urban stakeholders' preferences into consideration in the process of model development (Pfenninger et al., 2014). Unfortunately, this approach does not capture the opportunity of the model being used in reality through assisting the decision makers in actual urban energy planning processes. One of the advantages of including stakeholders' participation in energy systems modelling processes is that the modeller is given not only the incumbents' preferences and visions of their system development but also detailed local-specific information that could impact model outcomes if considered. Such detailed local-specific information includes spatial plans and building information. Urban spatial data such as building type, floor area, construction date, or envelope's characteristics, building energy demand, and division of districts are necessary and valuable information as buildings are the main energy end-users in urban energy systems. However, this aspect is often omitted in energy system studies (Allegrini et al., 2015).

Energy supply decisions in general, and heat supply in particular (due to high cost of heat distribution), should be based on knowledge of the spatial placement of energy demands and details about the location or distribution of the building types and construction years within the spatial boundary. However, this dimension is not represented well enough in many energy models studies (Langevin et al., 2020; Nielsen & Möller, 2013). To assess the impact of future urban energy transition scenarios and support the development of urban energy strategies and plans, accurate modelling which takes the spatial dimension into account is essential as it relates to building and district design and planning (Allegrini et al., 2015). Such modelling can help determining the potential and calculating the performance of energy technologies which is important to plan the desired energy system in urban areas.

In this regard, a participatory approach could benefit the modelling development process in provision of such information and creating model outcomes more useful for the stakeholders' needs in their urban energy transition.

In light of the importance of the spatial dimension and a participatory approach in the energy system modelling process, this study aims to explore values of implementing the spatial dimension in energy systems models under different urban energy transition scenarios developed through a participatory process. To reach the study aim, this paper answers the following research questions: How can district/building level spatial dimension/representation be implemented in an optimizing energy system model to support municipal energy transition?; How can a participatory approach be implemented in municipal energy systems modelling to improve the possibility for using model outcomes as decision support? Further, it would be important also to evaluate the impact of the implementation of the spatial dimension in an urban energy systems model but this part of the study is not included here.

2. Methodology

This section presents a participatory approach in energy systems modelling and how this is applied to the current study. The case municipality is also introduced and the model building process representing the spatial dimension is described.

2.1. Participatory approach modelling process

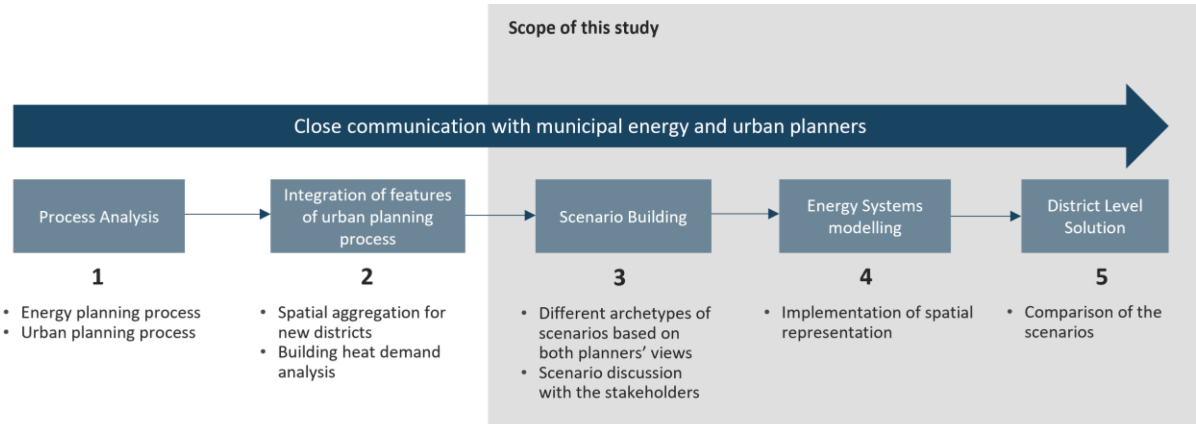

Figure 1. The whole process of the participatory modelling approach (Yu et al., 2021).

This paper reintroduces and applies a modelling methodology developed in Yu et al. (2021) and proceeds with further steps of that methodology. Yu et al. (2021) stressed stakeholder's participation in the energy systems modelling process with an emphasis on the need of integrating urban planning features into it. The motivation of such argument comes from the interconnectedness of urban energy systems and urban spatial plans which gives significant impact on how energy is being converted, distributed or/and could be consumed. The methodology consists of five steps. The first two steps are already addressed and presented in the mentioned study and this study continues to adopt Steps 3, 4, and 5 of the methodology.

In the first two steps, both energy and urban planning processes are analyzed and new districts are identified. 15 districts are identified based on the information and preferences from the interviewees: combinations of cadastral lines in their spatial planning, heating supply technologies, heat demand density and distances between districts. Specifically, the current and planned heating supply technologies are considered as three different categories (Yu et al., 2021). This process of identification of new districts takes its departure from urban plans with the aim of creating districts based on their energy characteristics, e.g., taking into account certain energy infrastructures as gas and/or natural gas grid distributions. In this, the new districts created are still representative of the urban planning but are integrating, through integration of spatial plans and building information, much more strongly the spatial dimensions of the local energy system as e.g., spatially disaggregated and detailed information of heat demand of different types of buildings. It should be noted that the entire modelling process is based on a participatory approach.

2.1.1. Step 3: Scenario building

After the first two steps, the modeler has become familiar with the energy and urban planning processes. In addition, the modeler is given the necessary data and knowledge to map out the new energy districts with different archetype of buildings and their energy demands. In the third step, municipality energy scenarios are formulated together with the stakeholders based on the spatial dimension which was addressed in the previous steps.

As the participatory approach contributed to acquiring the spatial information, it plays an important role in the discussion of scenarios development as well. The municipality actors can have a chance to express what it is they need to observe to utilize the model outcomes for their energy plans. The input that stakeholders can feed into the scenario building includes different level of municipal climate goals, prioritization of technologies and actions for the energy transition. For the quantification of specific actions, the modeler can also share and analyze the city's urban plans to determine the number of new and refurbished planned buildings, budgeted subsidies, and to estimate a number of privately refurbished buildings and generation systems replaced, or other data sources such as surveys, stakeholders' workshops, or the municipality's technical staff (Muñoz et al., 2020).

This scenario building contributes to the first research question of how spatial dimensions are represented in the energy model. The spatial dimensions are explicitly accounted for in the model, and each scenario thus developed takes into account the urban plans.

2.1.2. Step 4: Energy systems modelling

The spatial dimensions addressed in the previous steps can be represented and implemented into an energy systems model in this step. Each district, and its distribution of building types and energy demands, is considered and represented as different regions in the model in the same manner as it would be in a regionalized model. In other words, the districts are implemented in the model as independent regions but understood as the spatial division within the municipality boundary.

From urban plans, the modeler can obtain cadastral information depicted on maps. However, often energy systems models do not portray this spatial dimension of the outcomes unless making use of a certain geographical software such as GIS (Geographic Information System) or GeoNode. Implementing the spatial dimension by representing each district and the accordant data, i.e., spatially disaggregated energy demands, allows the model to be spatially explicit and thus the model outcomes add a layer of detail such as different investment cost depending on distances from central plants.

The different building types and their energy demands are implemented in each district which enables the model to produce not only district level but also building level solution. In this way, the energy systems model can explicitly represent the spatial dimension. Six different building types are categorized: Residential 1 (detached, farmhouse); Residential 2 (terraced, semi-detached house); Residential 3 (multi-dwelling building); Residential 4 (student housing and residential buildings for community); Residential 5 (others); and Commercial buildings.

This study uses TIMES (The Integrated MARKAL-EFOM System) energy modelling framework developed by the International Energy Agency (ETSAP, 2022) for municipality energy system modelling. TIMES is a cost optimization model finding the lowest total system cost over the chosen time horizon. The energy demands which need to be supplied by enough energy generation are exogenously given by the modeler. Techno-economic data such as investment cost, fuel costs, operation and maintenance (O&M) costs, and efficiency of different type of technologies are also exogenously given by the modeler and the model calculates the optimal solution meeting all the demands and specific goals and constraints, e.g., emission caps, share of a certain type of technology, policy measures, etc. The municipality energy system model used is a further development of a municipal heating system model (Vilén et al., 2021).

2.1.3. Step 5: District level solution

In the final step of the methodology, the model outcomes under the different scenarios formulated based on stakeholder participation in Step 3 are analyzed. As the spatially explicit energy systems model produces a district/building level solution in this final step, the optimal technology mix of each building type in each district can be visually depicted on a map. In addition, the result can be used to communicate with the municipality planners for either modifying/iterating the model or assisting the employment of the model in their decision-making process.

2.2. Case municipality

Lyngby-Taarbæk municipality, with around 56,000 inhabitants, is located near Copenhagen on the eastern coast of the island of Zealand in Denmark and is part of the Greater Copenhagen area. Most of the municipalities in Denmark voluntarily prepare their energy plans as a basis for achieving the locally set climate goals as well as the national climate goals.

The heating system of the municipality consists of two different supply and distribution systems. Lyngby-Taarbæk municipality receives heat mostly from a large scale of waste incineration plant and gas combined heat and power (CHP) plants outside and within the municipality through the district heating network. There is a natural gas grid which delivers natural gas to individual gas boilers to heat the buildings (this is of particular interest to the municipal planners and for the green energy transition in the municipality). There are also small number of individual oil boilers and heat pumps (oil boiler owners can get subsidies for switching to individual heat pumps or more economical biomass boilers).

The municipalities and utility companies are the key players in the collective heat supply. The municipality carries out the heat planning and is responsible for expanding grids and for the demarcation of the different forms of collective heating: the district heating network and the natural gas grid. The municipality also ensure that this is done in accordance with the Heat Supply Act. Figure 2. shows the heat demand in each district. The demand estimation was conducted in the previous study (Yu et al., 2021).

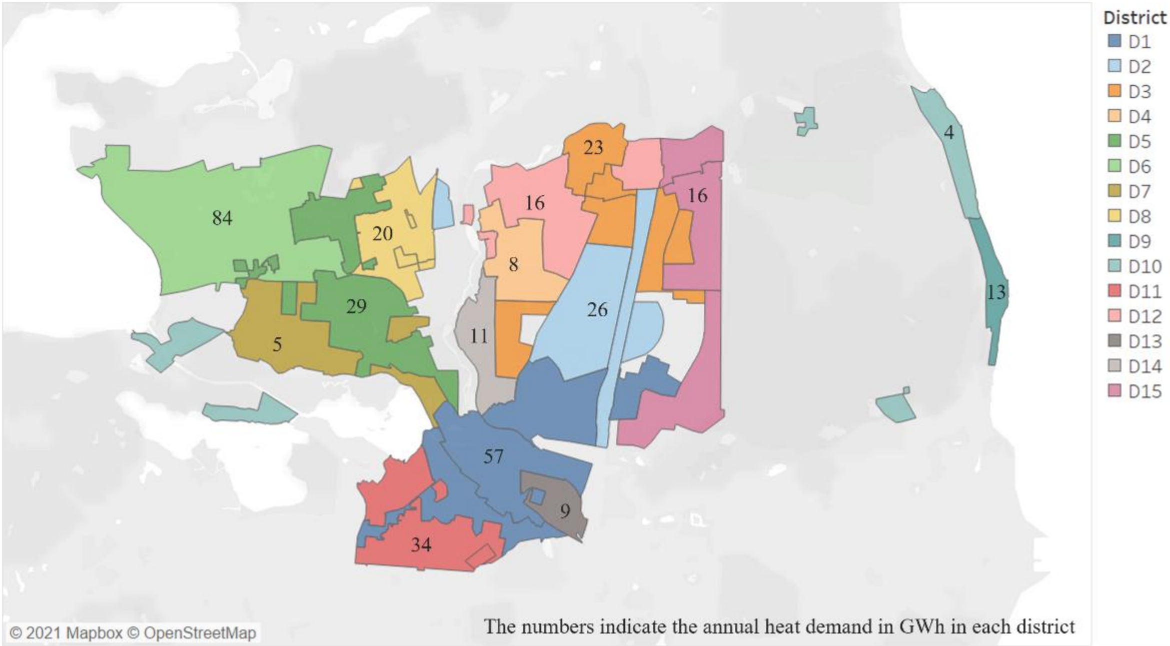

Figure 2. New districts identified. The map is based on longitude and latitude. Colors show the different districts (D1-D15) and its details are presented in 4.3.2. The numbers on the map indicate the annual heat demand of buildings in GWh in each district (Yu et al., 2021).

3. Application to participatory energy systems modelling

3.1. Step 3: Scenario building in the case municipality

Once the heating system of the municipality is characterized through the first two steps of the methodology, several energy transition scenarios can be developed to explore different transition pathways that may unfold in the municipality in the future. A participatory approach in the scenario building process was achieved through various forms such as stakeholders' workshop, on/off-line meetings, interviews and e-mail communications with the municipality planners. The modeler may analyze the municipality's proposed measures or raise new ones. In order to consider alternative energy scenarios which may include changes in investments in new technologies, in local-specific environmental conditions, the modeler need to know the future vision of the municipalities to develop accurate and tailored scenarios for their needs. For this task, a number of aspects were communicated with the municipal planners throughout the scenario development process and then incorporated in the model in an iterative manner. Such aspects include any preferences for specific technologies, locally set climate goals, upcoming investment plans, any structural changes expected in the municipality, and geographical and environmental limitations for such investments. Several municipality energy transition scenarios are formulated based on the planners plans and visions at different level of detail. However, here we focus on only three of these scenarios.

(1) Reference scenario
In the reference scenario, the municipality's heating system is allowed to invest in any new technology meeting the municipal climate goal. No policy measures are implemented to restrain or encourage investment in certain technologies and the fuel prices changes according to the projection.

(2) District Heating scenario
The municipality expressed the need of a scenario focusing on reaching a certain share (80%) of district heating supply by 2030. This scenario focuses on expanding the connection to the existing district heating network by either utilizing the current district heating plants or investing in additional capacity in new district heating plants. Fuel prices follow the projections as in the reference scenario and a policy measure of banning natural gas by 2035 is implemented.

(3) Heat Pump scenario
In this scenario, the municipality focuses on expanding heat pumps by subsidizing heat pump investments. 20% of the investment cost of heat pumps are subsidized by the government and the policy measure of natural gas ban by 2035 is implemented to facilitate the heat pump expansion. An additional electricity grid tariff is also implemented to represent the cost of higher electricity consumption due to the heat pump expansion.

3.2. Step 4: Energy systems modelling

Once the municipal energy transition scenarios are formulated and the necessary techno-economic data are set in terms of their spatial dimension, i.e., data on each district and building type, they can be implemented in the energy system model. Specifically, it is portrayed as if every district has their demands with different building type distributions so that the model computes the separate outcomes for each district. The spatial dimension is also reflected in the costs for a certain investment, e.g., district heating network, representing differences depending on its distances from the central plants.

4. Results

4.1. Step 5: District level solution

The spatial dimension is integrated in the energy systems model with cadastral data so that the final results can be presented for different building clusters which in turn can be split by building use in different districts. The modelling results are visually presented as in Figure 3. showing how the heating technology mixes of each building type in different districts develop over the selected target years under the different scenarios. For the purpose of presenting how the modelling outcomes can be depicted, two districts together with two target years are selected. Both districts mainly consist of the residential building type 1, detached houses, with small portions of residential building type 2, 3 (terraced, semi-detached house and multi-dwelling building respectively), and commercial buildings.

In the case of District 6, as an example of the modelling outcome, the residential building type 1 takes up most of the heat demand. In the district heating scenario, all the buildings in the district are already connected to the existing district heating network by 2030. Due to the natural gas ban policy and relatively low cost to utilize the existing district heating plants or solar heat district heating option, the system changes from natural gas based heat supply to district heating supply rather straightforwardly. On the other hand, the heat pump scenario shows a different and more diverse mix of technologies. The residential building type 1 is supplied by individual heat pumps with additional investment in biomass boilers in 2030. The biomass boilers are not used in 2050 and, instead, more heat pumps are used to fulfill the demand. It is likely that the heat pump subsidy has an impact on expanding the investment in heat pumps in the district.

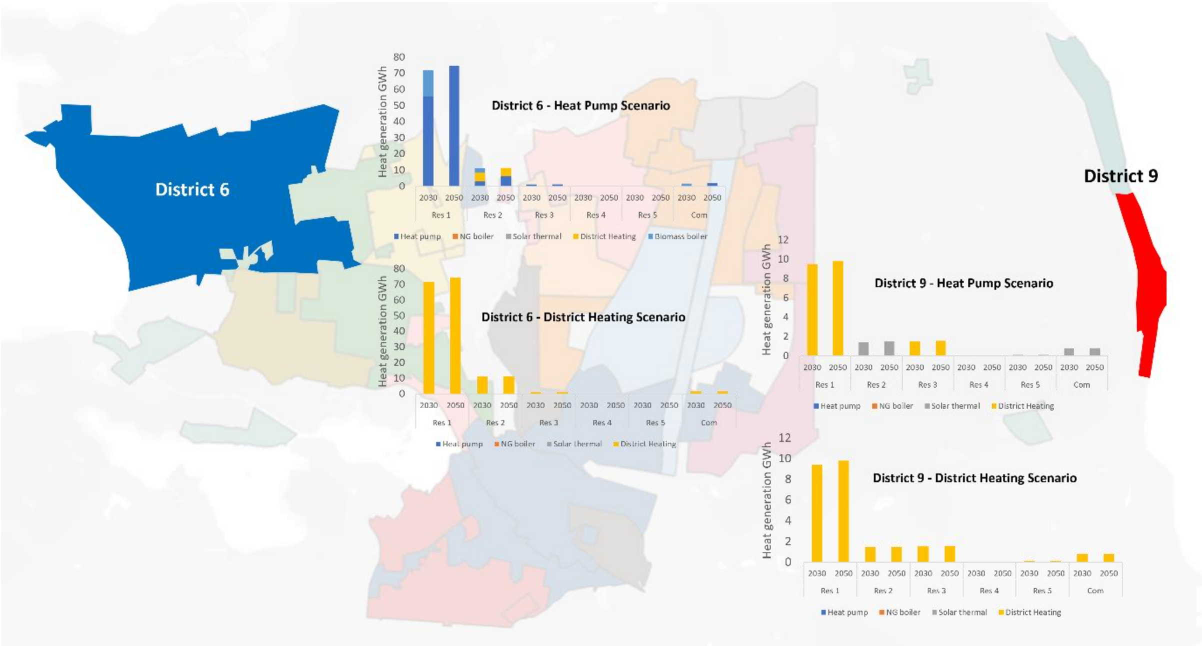

Figure 3. Visualized model outcomes.

5. Discussion

This study applied the integrative energy systems modelling methodology proposed by Yu et al. (2021) to a case municipality to develop a spatially explicit urban energy system model. The core idea of the methodology is that the entire modelling process is based on a participatory approach allowing the stakeholders to share not just the local-specific data and knowledge but also their preferences and visions for their urban energy system.

There are two major components that this modelling methodology of participatory approach contributed to this study. First, the stakeholders provided the necessary spatial information and preferences for identifying and designating the districts to be represented in the model. In addition to the input provisions, the stakeholder participation assisted setting the delimitation of the spatial and systemic boundaries of the modelling scope. As shown in *4. Results*, the model outcomes offer relatively detailed information, i.e., optimal technological choices for each building type in the districts. As the building heat demands and distributions are spatially disaggregated, the municipal planners can obtain district/building level solutions under the different scenarios.

Second, stakeholder participation in the scenario development allows the model to be more compatible and useful for the municipal planners' needs. Often, the responsible stakeholders of the municipality, i.e., energy planners and urban planners do not necessarily have the experiences or expertise to carry out energy systems modelling with advanced tools. However, if the municipality planners have experiences in participating in the development of energy systems models and scenarios themselves, they would be able to have better understanding and ownership of their energy plans and make it easier to include their local knowledge through a bottom-up approach. furthermore, it would be more easy to alter and test different scenarios for transition pathways with the greater ownership of such models (Johannsen et al., 2021).

The visualized model outcomes in 4. Results can be used to communicate with the municipality planners for either modifying/iterating the model or assisting the employment of the model in their decision-making process.

In a follow-up study, a comparison of the spatially explicit model developed in this study to an aggregated model, i.e., neither considering the spatial division of the municipality nor the different costs related to distribution distances and heat demand densities, will be carried out together with an analysis of the impact of the implementation of the spatial dimension in the energy systems model.

6. Findings

It has been shown how a district/building level spatial dimension can be implemented in an optimizing energy system model. It has also been shown how this implementation of the spatial dimension enables the model to produce the optimal solution for different types of buildings by representing the different costs dependent on other spatial characteristics such as distances and heat demand density. In this way, the model is able to provide information that the urban planners will need in their energy system planning processes and, thus, this spatially explicit urban energy systems modelling is also able to better support municipal energy transitions.

This study has a strong emphasis on its participatory approach throughout the entire modelling process. Through such an approach, reflecting stakeholders´ preferences and visions in the process, the outcomes become more useful for the decision makers, enabling an outcome that can be applied as actual decision support. Since the identification of the spatial dimension as well as the municipal energy scenarios are developed in cooperation with the stakeholders throughout the entire modelling process, the results offer what can be practically used and essential for the municipal energy planning work towards the desired energy transition. It implies that this type of model can improve the possibility for the model outcomes being more useful as decision support.

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