Buildings' energy demand modelling for sustainable decision support

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Abstract

The City of Vienna (Austria) follows a long-term initiative to be sustainable and affordable. Therefore the interdisciplinary fields of energy, buildings and infrastructure have to be analysed and connected in a virtual planning and decision support tool for stakeholders. In this context, this paper focuses on the development of the buildings energy demand and the interaction to the investments in the extension or expansion of existing district heating networks as district heating represents an energy efficient way to supply the cities heat demand. The extension of these networks and the increase of its share in heat supply allows replacing ecological inefficient heating technologies. Besides the ecological issues, also the economic feasibility is necessary to contribute to a sustainable city. Since the development of the buildings heat demand depends on the building owners investment decision, the methodological approach is divided in two parts: A simulation model, which brings out possible paths for the development of the buildings' heat demand for various scenarios up to 2030 and an optimization model to determine investment plans for existing district heating networks, considering the development of the heat demand explicitly. The focus of this paper is on demonstrating the developed model. Therefore an analysis of the effects of subsidies regarding renovations and investments for decentralized usage of solar heat on the heating energy system is conducted. The result of the approach displays the optimal investments in the grid and the resulting effects on the whole heat market, i.e. the effects on the CO_2-emissions, costs and share of all technologies, for different scenarios. The results can be visualized in a spatial simulation environment to support stakeholders in their decision process (URBEM-platform).

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1 Introduction

1.1 Motivation

The building sector is responsible for 40% of energy consumption and 36% CO_2 emissions in the European Union [1]. In addition, about 35% of the buildings in the EU are older than 50 years. Due to the worse thermal quality of the envelope of these buildings, renovations are meaningful to improve their energy efficiency and reduce their energy demand. In addition, the directive on the promotion of the use of energy from renewable sources demand from the member states to establish national targets, which are consistent with a 20% share of energy from renewable sources [2]. Therefore it could e.g. be ecologically worthwhile to try to increase the share of decentralized solar heat for the buildings' heat demand. In combination with the European directive on energy efficiency [3], where it's stated that high-efficiency of cogeneration and district heating and cooling has significant potential for saving primary energy it could also be reasonable to aim the promotion of district heating. For the operators of district heating networks the reduction of the buildings' heat demand and the usage of decentralized solar heat can cause a challenge for an economic feasible supply with district heat. This problem is strengthen by the fact, that there is no obligation for building owner to connect to district heating in many regions. Therefore an extension of an existing district heating network can help to improve the feasibility, whereas an expansion frequently is to expensive due to long distances, which have to be covered.

To analyse and compare different strategies to reach the mentioned targets a methodological framework for an integrated analysis of the development of the buildings' heat demand and the resulting consequences on the economy of an existing district heating network is formulated. This analysis considers the investment decisions of building owners in renovations and their choice of heating systems, when a replacement is necessary. Based on the possible developments for the used heating systems in buildings and the chosen energy carriers to supply it, the future investment plans for district heating operators and the evaluation of their economic feasibility is considered. The methodological framework is then used for an exemplary case study for the city of Vienna.

1.2 Research question

The methodological framework and the case study, presented in this paper, addresses the following research questions:

- How develops the buildings heat demand under different scenarios for policy frameworks and how do subsidies influence the mix of the chosen energy carriers to supply this demand, whereas a special focus is on decentralized solar heat and district heating?

- How do these policy frameworks influence the investment plans of existing district heating networks and what are the effects on the economic feasibility of the network?

1.3 State of the art

This section outlines shortly the already existing models and methods to answer the formulated research questions or parts of it. There are some models which focus either on the development of the buildings' heat demand or on the optimization of the expansion of an existing district heating network. The model described by Blesl [4] analyses the expansion and extension in grid-bounded energy supply for low-temperature heat demand. The author formulates a time-discrete, mixed-integer optimization model to determine the optimal investment strategy in heat generation technologies, distribution and buildings' heating technology. The spatial information is displayed similar to a network flow model. The model uses different types of settlement to determine the costs of a change of the energy carrier and the required connection length to the existing grids. The types of settlement are determined by the urbanistic appearance of regions. This method is also used in various other works [5, 6], since interdependencies between the type of settlement and the heat supply exists [7]. Hensel [8] compares three different optimization models to examine the expansion of the existing district heating network for each single street of houses, whereas the existing grid for gas supply is considered as well. This method provides results in reasonable time for parts of cities. These approaches are suitable for expansion planning of areas like districts of cities. The last years a lot of GIS-based model frameworks are developed to determine the potential for district heating. Finney *et al.* [9] use heat maps to identify the expansion potential for district heating. Another approach is described by Nielsen and Möller [10], where the future potential for district heating in Denmark is considered. The methodology is based on the Danish heat atlas with all the buildings and their heat demand. The economic feasibility of a connection to the existing district heating network considers costs for heat generation, transmission and distribution costs. Persson and Werner [11] use the plot ratio to determine the costs for the expansion of the district heating network, whereas Nielsen [12] uses a high resolution planning, where the required lengths for expansion/extension are calculated based on the geographic properties of regions.

The model Invert/EE-Lab, described by Müller [13], which is integrated in this approach focuses on the development of the buildings heat demand explicitly under consideration of the building owners decision behaviour in heating related investments.

In contrast to the used methodological framework in this paper, the focus of the above mentioned works is either the detailed analysis of the development of the buildings heat demand or the economic expansion planning of gas and district heating grids. In addition, most of the works assume that the full determined heat load can be connected. Although Sperling and Möller [14] generate marginal costs curves for energy savings and district heating expansion, the explicit effects of different policy frameworks on the development of the buildings heat demand and the endogenously modelled consequences on the expansion/extension aren't considered. Also for the computing of the theoretical potential for solar energy in urban areas, some models have been developed [15, 16]. However, up to now there was little work on the calculation of the economic potential under explicit consideration of development of the buildings heat demand and the effects of subsidies for different heating systems. An additional visualization within the URBEM-Platform can support stakeholders in their decision process [17].

2 Methodological framework and case study

2.1 Methodological framework

The introduced methodological framework consists of two parts. First, a simulation module to determine the development of the buildings heat demand and the energy carrier to supply it under consideration of investment decisions of buildings owners. Additionally based on the decision of the building owners, an optimization module is used to determine investment plans for the expansions and/or expansion of district heating networks and the economic evaluation of it.

The existing bottom-up techno-socio-economic modelling tool Invert/EE-Lab is used for the simulation of the buildings heat demand and depicts possible paths for future development under various scenario assumptions, e.g. variation in energy prices, subsidies for renovations or heating systems. For a detailed description see Müller [13]. The time of investments in renovation of the building or the change of the heating system is determined by Weibull distributions [13, p. 82]. These distributions are used to define the lifetime of building and heating components. The decision for the quality of the refurbishment or the new heating systems depends on different owner types, assigned to building categories and is predicated with a cost-based algorithm: For this purpose a nested logic approach is used [13, p. 96], where the total heat generation costs are considered, consisting of the consumption-dependent costs, consumptions-independent annual operating costs and the levelized investment costs. This approach determines the market share of each technology.

Based on the results of INVERT/EE-Lab the optimization module can be used. The objective of the mixed-integer linear optimization module is to maximize the heating network operators profit under consideration of investments in the expansion/extension, costs for heat generation, reinvestment costs and operation and maintenance costs. The revenues rise from the district heating price paid by the costumers, depending on their heat load and heating demand. The level of detail is on building blocks. Therefore a binary variable indicates, whether a building block is connected or not. A description of the used data-sets and the model in more detail is given by Fritz [18].

2.2 Case study

An exemplary case study for the city of Vienna (Austria) is conducted to demonstrate the methodological framework. The considered time horizon for the development of the buildings heat demand is up to 2030. Investments in the expansion or extension of the existing district heating network in Vienna are determined every five years, starting with 2015. All the data regarding the building stock are calibrated to the year 2013. In the year 2011, Vienna had more than 164,000 buildings, of which 47% where older than 50 years [19]. The final energy consumption in the year 2013 for residential buildings and public as well as private service buildings was about 21,613 GWh. The share of district heating was about 6,313 GWh in the same year. The share of solar heat in the residential building and service sector is almost negligible: Just 60 GWh solar heat supply the final energy demand in these buildings [20].

The existing district heating network in Vienna is 1.192 km in 2013. The heat generation for district heating is mainly based on combined heat and power (CHP). The second largest share is from waste incineration plants, followed by industrial waste, alternative heat generation an heat from fossil heating plants [21].

The assumptions for the investment optimization model are depicted in Table 1. The cost allocation of fuel costs and CO_2-emissions to heat and power in CHP plants is done with the market based method [22, p. 617].

Table 1: General assumptions.

interest rate	6 % per year	yearly price increase	2 % per year
Amortisation		Demand price customer	49.18 €/MWh
Horizon	15 years		
Biomass fuel	30 €/MWh	base price customer	69 437 €/MW
Gas price	22 €/MWh	CO_2-Emission factors	
		taken from	[23]
Electricity	32.91 €/MWh	CO_2-Emission costs	5.75 €/t

In the present work, the investment costs and capital costs for the investment in the extension/expansion of the existing district heating network are combined as distribution capital costs c_{dcap}. Based on the method of Persson and Werner [11] the distribution capital costs are formulated as shown in (1), where C_1 indicates the construction cost constant in €/m, C_2 is the construction cost coefficient in €/m^2, d_a the average pipe diameter in m and L the total trench length in m.

$$c_{dcap} = (C_1 + C_2 * d_a) * L \tag{1}$$

As the cost parameters C_1 and C_2 depend on the plot ratio within an area, a classification of areas of settlements is conducted. (This method is also used e.g. in [4, 24].) Therefore the 23 districts of Vienna are further divided in 250 registration districts. As all the buildings from the input data are assigned to an registration districts, the necessary information to characterise these areas of settlements is available. The settlement types differs in amount of buildings per m^2, main usage of buildings (e.g. single family houses, office buildings, mixed usage, . . .) or ground floor area. Then the ratio between built area and usable area (plot ratio) is assigned to each registration district. The classification is based on Blesl [4]. The classification for the registration districts in Vienna can be seen in Figure 1. The legend represents the different settlement types. The most frequent settlement type in Vienna is ST 2, settlements with single family houses in the periphery. ST 5b consists mainly of small and medium apartment buildings and can be found around the city centre, which is assigned to settlement type 9, the historic city centre.

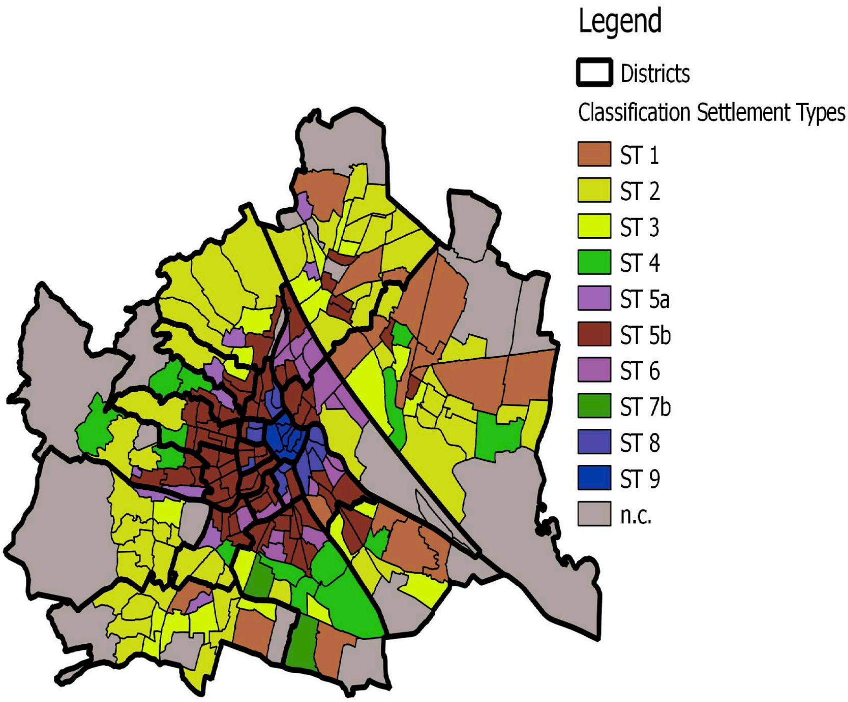

Figure 1: Classification in settlement types for Vienna. Source: own illustration.

An additional advantage of the classification in areas of settlement is the assignment of different costs for the house connection for the building owners, which differ for different plot ratios as well. These costs for the different settlement types are taken from Lutsch *et al.* [24] and are used in the simulation model.

The total trench length L in (1) is derived by summation of the individual buildings connection length l_b. Since every building is assigned to a specific energy carrier region the average connection length for the energy carrier region can be used. (Note: The distance of each single building to the existing district heating network is provided by Wien Energie).

2.3 Scenario description

For the case study, three exemplary scenarios are considered, which are based on those in Müller and Kranzl [25]. As the scenarios are defined for whole Austria, they are adapted for the situation and in Vienna. It's important to mention, that these adapted scenarios for Vienna just cover some implemented and contemplated measures and don't describe the actual subsidies and policies in detail.

- Scenario 1 – WEM (With existing measures).
- Scenario 2 – WAM (With additional measures).
- Scenario 3 – WEMpluSol (With existing measures and additional subsidies for solar heat).

These scenario variations influence the development of the buildings heat demand and the selected energy carriers to supply it, as they differ in the budget for investment subsidies for renovations and heating systems. In contrast to scenario 1, scenario 2 considers more budget for renovations and the requirements for the renovation quality is higher. Scenario 3 has the same basic conditions as scenario 1, but additional investment subsidies for solar heat is considered. In the WEM scenario up to 25% of the required investment are raised, in the WEMpluSol up to 45% are raised. The case study just considers the existing building stock, new buildings due to the expected population growth in Vienna are not included in this analysis.

3 Results

For the comparison of the scenarios the results of the simulation module and the optimization module are used. The indicators defined for the comparison are the CO_2-emission for the buildings heat demand and domestic hot water, the overall costs and the share of district heating and decentralized solar heat per scenario as a part of the final energy demand. The costs are defined as the cumulative costs between 2015 and 2030 and include the annuity of investments in refurbishments, the annuity of constructions of new buildings and investments in heating systems as well as subsidies for refurbishments and heating systems and annual energy dependent consumption costs and operation and maintenance costs. In addition, the investment costs for the expansion/extension of the existing district heating network are included, as well as the operation and maintenance costs and the capital costs.

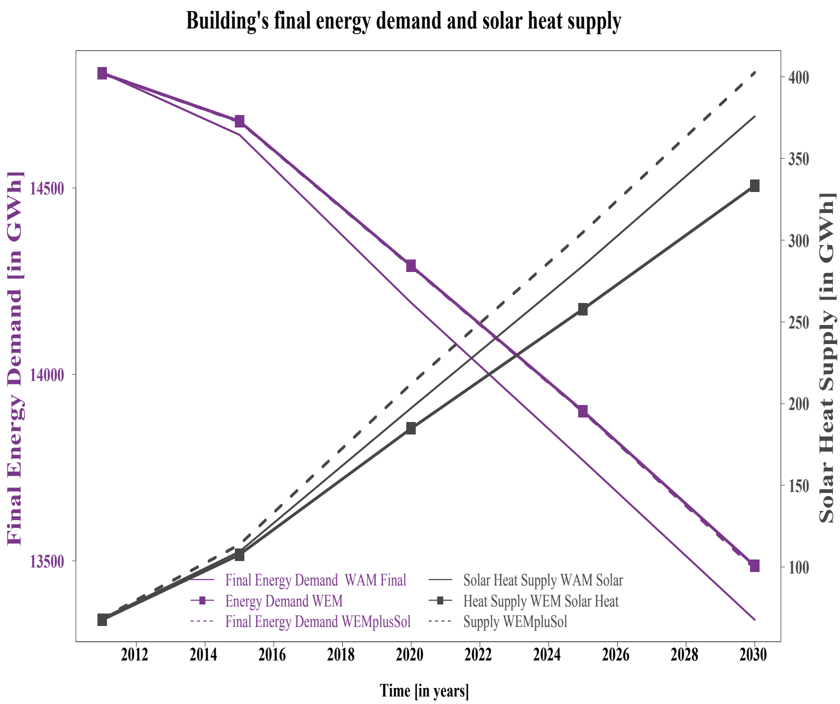

Figure 2: Comparison of scenarios: Final energy demand and solar heat supply. Source: own illustration.

In Figure 2 the development of the final energy demand of the existing building stock up to 2030 is depicted as well as the share of it supplied by decentralized solar heat for the scenarios. By definition, the decrease of the final energy demand is the same for the WEM and WEMpluSol scenario, since the subsidies for renovations and the required renovation quality are the same. It can be seen that the solar heat supply increases for the WAM and WEMpluSol scenario in comparison to the WEM scenario. Figure 3 shows the delivered final energy demand, i.e. excluding the demand supplied by solar heat, and the possible demand, which could be connected to district heating due to the building owners investment decisions. Here it can be seen that the final energy demand without solar heat for the WEM scenario is higher than the demand for the WEMpluSol scenario. This also results in an higher demand for district heating.

Due to the negligence of development areas, the expansion is very low in all the scenarios. Nonetheless the WEM-scenario has the highest expansion (42 building blocks in comparison to 31 in WEMpluSol-scenario and 29 in WAM-scenario).

These results combined provide the basis for the comparison of the indicators. The results for the CO_2-emissions and the Costs in Table 2 are relative to the

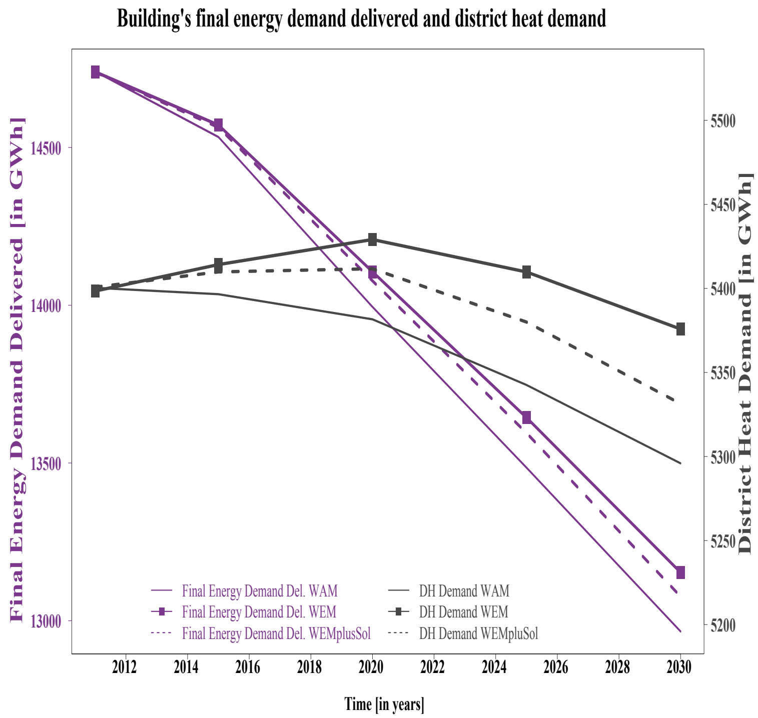

Figure 3: Comparison of scenarios: Final energy demand delivered and district heating demand. Source: own illustration.

WEM-scenario, the Share of district heating (DH) and the share of solar heat are absolute.

Table 2: Results: Indicators.

Scenario	Additional reduction CO_2-emissions [%]	Avg. share DH [%]	Avg. share solar heat [%]	Relative change costs [€]
WEM		38.02	3.52	
WAM	1.1	37.94	3.87	1.9%
WEMpluSol	0.39	37.89	4.10	−0.02%

4 Discussion and conclusion

The results for this exemplary case study of Vienna shows the effects of different scenarios. Based on a business-as-usual scenario (called WEM-scenario) two effects are analyses. One the one hand the effects of more budget for renovations and higher required renovation qualities are considered, on the other hand the effects of more subsidies for solar heat are analysed. The results, describes in Section 3 show, that from an ecological point of view it's preferable to raise the budget for renovations and introduce obligations for the renovation qualities. (The CO_2 emission can be reduced about 1.1% in comparison to the WEM-scenario) But this policy framework also result in higher costs for the heating energy system. (These costs include the investments in refurbishment, construction of new buildings due to demolition, investments in heating systems in buildings, subsidies for refurbishments and heating systems, annual energy dependent consumption costs in buildings, operation and maintenance costs of heating systems in buildings, investment costs for district heating network, operation and maintenance costs for district heating, investments in expansion/extension of district heating and capital costs for district heating.)

In contrast, the WEMpluSol-scenario reduces the CO_2 about 0.39%, but due to the higher share of solar heat and the resulting decrease in the delivered final energy demand this scenario has the lowest overall costs (0.02% reduction in comparison to WEM-scenario).

The developed framework allows to compare the impacts of different policy frameworks regarding the development of the heat demand and the future role of district heating. This integrated analysis combines the demand side as well as the supply side with district heat and tries to support decision makers to display the effects of different policy frameworks on the heating energy system in an ecological as well as economic sense.

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