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Solar heat strategies for Vienna: identifying regions with highly reliable and affordable potential

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ABSTRACT
A techno-economic heating energy system model for Vienna (Austria) is developed. Based on an existing solar potential map, different solar heat strategies can be evaluated economically and ecologically. The resulting share of installed solar heat units for every building is displayed in a 3D city model. This 3D model allows city planners to study the spatial impact of these strategies. Results are reported for three different scenarios, which differ in the assumptions regarding policy frameworks.

1. Introduction

1.1. Motivation

The heat sector causes a huge share of a city's energy demand: in Vienna 41 % of the final energy demand is used for heat and domestic hot water demand (Stadtvermessung Wien (41), 2013). Actually, less than one percent of this demand is supplied by solar heat - a negligible share of the theoretical potential of 27.2 TWh (Haas et al., 2013). To exploit this theoretical potential for solar heat, investments in buildings heating technologies are necessary. These investments have to be done by the building owners and therefore subsidies and political strategies can be helpful to influence these decisions and the share of renewable heating technologies.

For a sustainable long-term planning of a city's energy system, the strategies have to be analyzed from an economic and social point of view too. The increase of decentralized solar heating technologies can worsen the economic feasibility of centralized supply by district heating due to a decrease in demand. The interdependencies between the centralized and decentralized heat supply as well as the interdependencies between the investment decision of the building owners, the government and strategies of district heating operator require an interdisciplinary analysis.
Such an interdisciplinary analysis aims to indicate the reduction of the total costs for heat supply, the reduction of the CO2 emissions and the share of each technology for different strategies. In addition, it is necessary to provide the results for scenarios differing in subsidies and strategies in a decision support tool to analyze the long-term effects.

This approach addresses the following research question:
"How do solar heat strategies influence the energy system and the spatial footprint of a city and which consequences arise for its total costs, the CO_2 emissions and the share of renewables?"

1.2. State of Art

In recent years many different 3D city models have been developed for computing the theoretical potential for solar energy in urban areas (see for example (Hofierka and Kaňuk, 2009) and (Erdélyi et al., 2014)). However there has been little work on the economic viability for solar energy strategies that are trying to exploit these potentials. Up to now no simulation model exists for future heat demand and supply of all buildings in a city that includes an economic and ecological analysis of the impact of solar heat strategies, as well as the visualization spatial planning.

The well-established model Invert/EE-Lab considers the heating related investment decision of building owners due to legislatives, subsidies and obligations (for detailed description see (Müller, 2015), selection of projects and publications: (Kranzl et al., 2014a), (Müller and Kranzl, 2013), (Müller et al., 2010), (Kranzl et al., 2014b)),. It describes the future development of buildings heat demand and the share of the different heating technologies for the building stock. In particular it can be used for the analysis of the impact of solar heat strategies on the building owner's decisions. However when concerning the entire heating energy system the supply side sub-model for district heating, described in 2.2.2. Optimization model for district heating supply, is needed. Many other existing models like (Blesl, 2002), (Neuffer and Witterhold, 2001), (Hausladen and Hamacher, 2011), (Hensel, 2013) or (Nielsen and Möller, 2013) focus on the optimized expansion planning of existing district heating networks and also considers the heat supply. The development of the buildings' heat demand is not considered explicitly it's considered via endogenous scenarios.

3D city models in general support multilevel and procedural planning processes as cooperative planning instrument used in the "Model of Vienna" ((Freisitzer and Maurer, 1985)) or problem solving strategies in planning environments based on trainings formulated by Walther Schönwandt ((Schönwandt et al., 2011)). The aim to help city planners and policy makers is also included in a project of the ETH Zürich in collaboration with IBM, ESRI and the Imperial College London, named "Smart Urban Adapt". This project wants to support "european cities with next-generation decision tools, to design development paths for the 1-ton-CO2-society."(Weinstock, 2013, p.120-124) It comprises a scenario-based low carbon development path assessment. In 2011 Daniel Segraves and Adrian Smith dealt with the goal to reduce carbon too. They designed a "decarbonisation tool" for the city of Chicago. It is a comprehensive decision support tool within a 3D graphic environment, that incorporates carbon tracking, building energy analysis, design and planning optimization.(Weinstock, 2013, p.120-124).

1.3. Overview

To evaluate solar heat strategies economically and ecologically we introduce a techno-economic model of the entire heating energy system of a city with three different sub–models, described in section 2.2. However, it should be recognized that the areas of highest economic potential for solar heat is not necessarily the preferred optimal location. This is determined by the impact on the cityscape especially in the historic center. Thus simulations of visual axis for economic reliable solar heat units are needed for spatial planning. Therefore we build a 3D spatial simulation described in section *2.3 3D spatial simulation*.

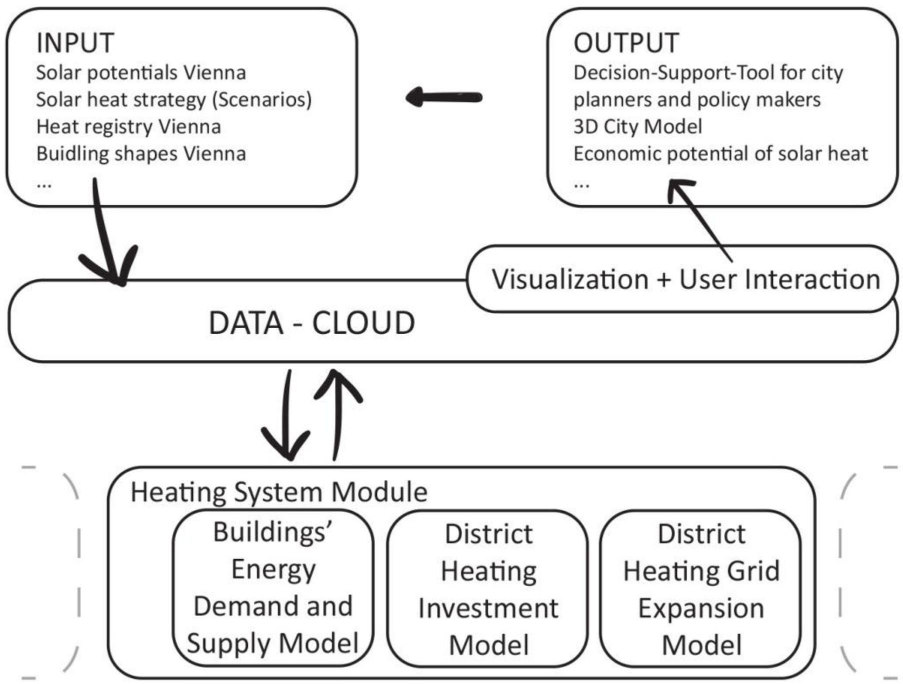

Figure 1: Overview of the evaluation platform environment

For our calculation we will use three different scenarios for subsidies until 2030, that can be found in section *3.2 Scenario Description and General Assumptions*. We will build our economic computations on the existing solar potentials computed by the Viennese municipal department 41 (Magistratsabteilung 41 der Stadt Wien), for an overview see *3.1 Data set* .The results of the economic and ecologic assessment can be found in section *4. Results* as well as in screenshots of the 3D spatial simulation.

2. Methodology

2.1 Methodological Framework

We use a techno-economic model for a city's heating energy system and a 3D spatial simulation in order to evaluate different solar heat strategies based on economic, ecological and spatial planning criteria. Based on a data cloud, the involved sub-models of the heating energy system model (see *2.2.*) are connected to this cloud enabling the data transfer. On top of the data cloud, a visualization environment is involved, displaying a 3D simulation of the installed solar heat and illustrating the considered scenarios with the predefined parameters. The visualization environment also enables user interaction and predefined parameter control. Figure 2 shows an overview of the visualization framework, including the sub-models.

2.2. Modelling heat demand, supply and related infrastructure

For evaluation of solar heat strategies by economic and ecological criteria we set up a techno-economic model for the entire heating energy system. Modelling only the building owners' investment decisions for different solar heat strategies is insufficient for city planning: rising capacities of decentralized heating technologies have a strong influence on the economic viability of district heating and subsequently on the overall CO_2 balance of a city's heating energy system. Many district heating systems rely on combined heat and power plants that have a thermodynamically highly efficient use of fuel. Thus a substitution by solar thermal heating may be undesirable in the short-run. On the other hand extending the existing district heating grid causes additional costs that have to be taken into account for investment decisions. Thus the heating energy system model for Vienna for evaluation of solar heat strategies consists of three parts:

a. a simulation model for the future development of the buildings' heat demand and supply. It considers the economically based investment decisions for increasing energy efficiency as well as heating technologies including solar heating.
b. an optimization model for the investments in district heating plants based on the buildings' district heat demand computed in (a). It will give a cost-minimal investment strategy for district heating based on the future demand.
c. an optimization model for the district heating grid expansion. It maximizes the heating network operator's profit with possible new connections of building blocks to the existing grid.

The results of the heating energy system models comprise the investment costs in heating systems, the share of all technologies as well as the corresponding CO_2 emissions. Figure 2 shows an overview about the methodological framework. Moreover we provide a more detailed description of the mathematical foundation in the following sections.

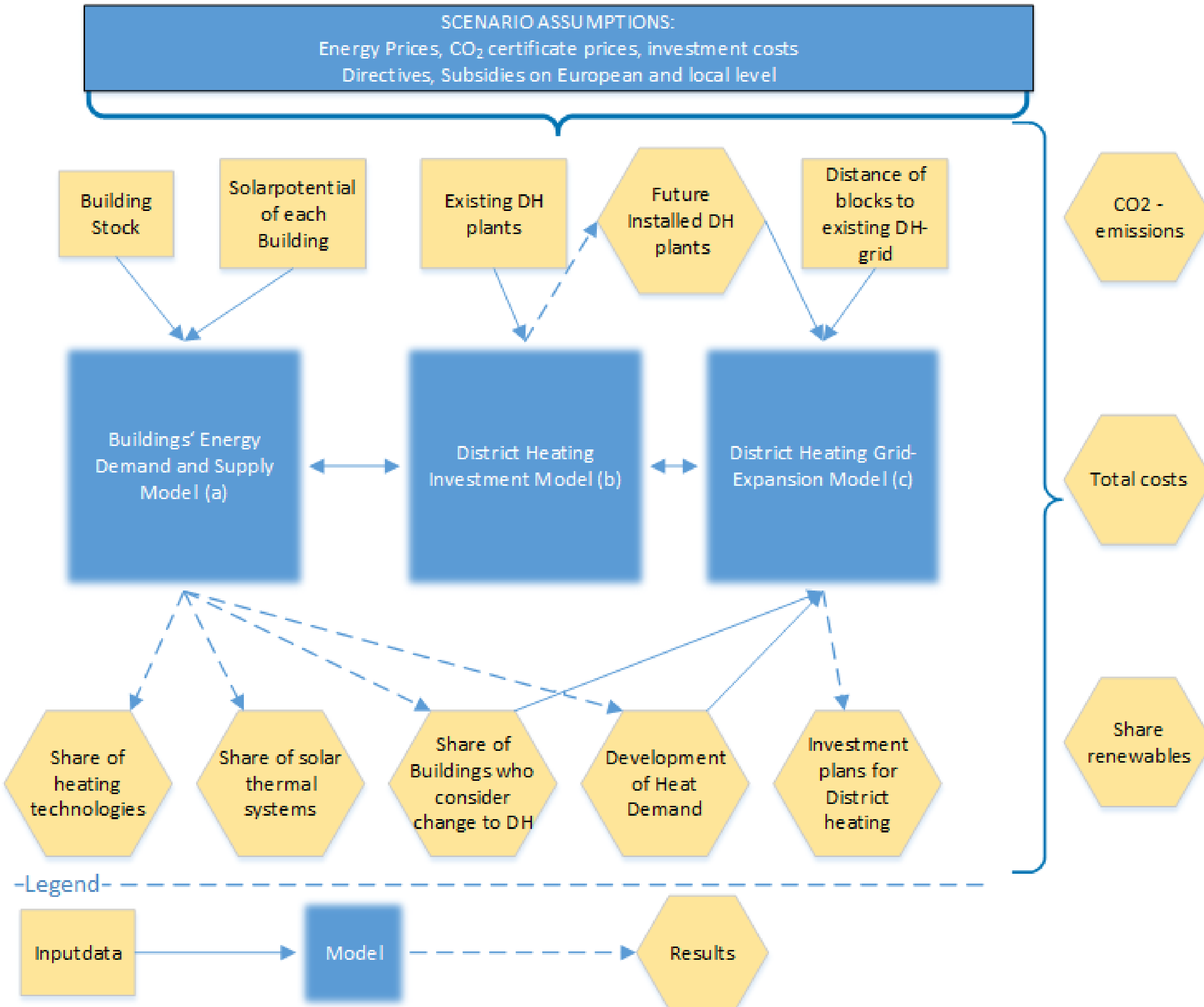

Figure 2: Overview of the methodological framework

2.2.1. Simulation model for buildings' heat demand and supply

For the simulation of the buildings' heating demand up to 2030, the share of solar heat, district heating and other heating technologies, the existing techno-socio-economic bottom-up modelling tool Invert/EE-Lab is used (for detailed description see (Müller, 2015)). The model uses a cost based logit approach to describe potential future paths assuming the consumer's decisions strongly depend on the costs of technology. These costs cover energy prices, connection costs for grid-bounded heating systems as well as obligations or subsidies. The buildings are grouped by their area of settlement, usage of building, building size, construction period, quality of thermal insulation and installed heating system. With the usage of areas of settlement the building can be located within the city and a distinction for different connection costs to the existing district heating network is possible.

2.2.2. Optimization model for district heating supply

The model for district heating plant investments assumes that investments are based on aiming minimal generation costs. The optimization program for the district heating system is based on a generation expansion planning model (GEP), a well-established linear program (De Jonghe et al., 2011). A simple model for short-term CHP planning of (Lahdelma and Hakonen, 2003) will be used to adapt the standard GEP formulation for district heating investments.

For every year $t \in T$ the district heating plants $i \in I$ are associated with fixed costs F_i (in Euro/kW). Heat generation is optimized for every hour. For every plant $i \in I$ we consider the sets of extreme points of the (convex) feasible generation region J_i.For the j_{th} extreme point then we have corresponding variable costs of cogeneration $V_{i,h,j}^{h}$ (in Euro) with generation of $g_{i,h,j}^{h}$ kWh$_{th}$ heat and $g_{i,h,j}^{el}$ kWh$_{el}$ electricity for every hour $h \in H_t$. The optimal generation can be displayed as convex combinations with weights $\lambda_{i,h,j}$ with $j \in J$. (see (Lahdelma and Hakonen, 2003) for details)

Investment decisions are modelled via the binary variables

$$n_{i,t} \coloneqq \begin{cases} 1 \; opening\ plant\ i\ in\ period\ t, \\ 0 \; else. \end{cases}$$

If the plant already exists $n_{i,t}$ can be set to 1, i.e. $n_{i,t} \coloneqq 1$ for all $t \in T$. Further we need to include the spot electricity market with spot price s_h (in Euro/kWh$_{el}$) for every hour $h \in H_t$. Note that all monetary values are discounted and all decision variables are non-negative.

In such a two-stage formulation, $n_{i,t}$ are the first-stage decision variables, $\lambda_{i,h,j}$ the second stage decision variables. Thus we have the program:

$$\begin{aligned} \min_{n} \coloneqq \sum_{t \in T} \sum_{i \in I} \sum_{s=1}^{t} F_{i,t} \eta_{i,s} + \sum_{t \in T} \sum_{h} O_h(\eta_{i,t}), \\ O_{h(\eta_{i,t})} \coloneqq \min_{\lambda} \sum_{i \in I} \sum_{j \in J_i} V_{i,h,j} - g_{(i,h,j)}^{el} s_h \lambda_{i,h,j} \end{aligned}$$

To ensure that heat and power generation is within the feasible operation region of every power plant and only proceeded in already built plants, suitable constraints are included. Moreover heat generation has to meet district heating demand for every hour. Additionally technical linear operation constraints for district heating plants can be added, e.g. temperature requirements for the district heating system.

2.2.3. Optimization model for district heating grid expansion

The investment optimization for the district heating grid expansion is based on the results of the module (a), shown in Figure 2, grouped by building blocks. The objective of the mixed-integer linear program model with several investment periods is to maximize the heating network operators profit P_i, under consideration, that already connected blocks can't be disconnected as long as there is heat demand for district heating. The costs for the grid extension/expansion c_{inv} and the costs for heat generation c_g are considered, as well as the capital costs c_{cap} and operation costs c_{op}. The revenues R_{tot} respect the base price p_{base} dependent on the blocks heat load in MW and the demand charge p_{dc}, which arise from the heat demand in MWh. The objective function is to maximize the profit Π, where r is the interest rate, T the considered horizon, P_b the connected heating load in MW of the building block and $D_{b,t}$ the heat demand in MWh per block.

$$\max_{x_{b,t,}} \Pi = \sum_{t=1}^{T} \frac{R_{tot,t} - c_{tot,t}}{(1+r)^t}$$

$$R_{tot,t} = \sum_{b \in B} \left(p_{base,t} + p_{dc,t} D_{b,t} + p_{base,t} P_b\right) x_{b,t}$$

$$c_{tot,t} = c_{cap,t} + c_{op,t} + c_{Inv,t} + \sum_{m=1}^{12} c_{g,m,t}$$

Due to cost variations within the year for the heat generation costs c_g, these costs are calculated on monthly base. The decision, whether a block is connected to the district heating network or not is formulated as a binary variable $x_{b,t}$.

$$x_{b,t} \coloneqq \begin{cases} 1 \; if \; block \; b \; is \; connected \; in \; period \; t, \\ 0 \; else. \end{cases}$$

This binary variable also indicates blocks, which are already connected to the existing heating network and influences the capital costs c_{cap}, the operation costs c_{op} and the costs for the grid extension/expansion c_{Inv}.

2.3 3D spatial simulation

For further evaluation of the economically and ecologically reliable solar heat strategies by means of their spatial footprints, we propose a 3D spatial simulation. It serves as a decision support tool and is based on the output data of the heating energy system model, in particular the future installed solar heat units per building. It allows spatial analysis in a three-dimensional virtual space.

The computed installed solar heat units data is joined with the building shape data via an ID number defined by the GIS data source for buildings of Vienna. These GIS based data can include several parts of a building complex with the same ID. We dissolve all building complexes via their IDs and the maximum height of all parts will be assigned to the building complex. Thus a two dimensional map can be designed with the solar heat units for the considered scenarios in specific city quarters over time as well as the distribution of solar heat units in the whole city.

Based on this 2D city map, areas of particular interest, determined by the city planner can be displayed in bigger scale and transformed in a 3D city model with a rule based procedural 3D modeling software

(ESRI City Engine). The two dimensional building shapes are extruded to three dimensional objects, roofs and front buildings. A 3D city model is evolved which enables the possibility to change single object's appearance via defined color intervals corresponding to the data it represents. The underlying data determine the visual design of the spatial objects.

To enable interactive user control and multi-scalar viewing options, the use of a web viewer (ESRI) is beneficial. Especially the possibility of implemented features like sun altitude simulation within diurnal variations offers advantages for the user.

3. Data and Case Studies

3.1 Data set

Two main data sets are used for this case study: the "Solar potential registry of Vienna" (Wiener Solarpotential Kataster) provided by the municipal department 41 and the "Heat registry of Vienna" (Wärmekataster Wien) provided by municipal department 39. The Solar potential registry of Vienna (GIS data set) is a land register for the solar potential in Vienna and includes the area suitable for solar thermal and photovoltaic potential for every single building. The Heat registry of Vienna (table data set) contains every single building from Vienna with the construction year, actual heat demand and its geometry like total gross floor area, ground area, number of floors, etc... The theoretical potential for solar thermal is the basis for the actual used potential up to 2030, determined with the simulation model.

To match the data structure for the used models (see chapter *2.2.1. Simulation model for buildings' heat demand and supply* for detailed description) some modifications and pre-calculations are necessary: In a first step, the data for the solar potential has to be matched to the building stock database and as the potential for the simulation model depends on the available roof area and the algorithm of simulation model is for segments and not for every single building, the roof area as well as the area for the theoretical potential has to be averaged. For visualization purposes GIS data sets representing streets, parks, etc. of the Open Government Data[1] Platform are used.

3.2 Scenario Description and General Assumptions

Three exemplary scenarios, based on those described in (Müller and Kranzl, 2013), are considered. These scenarios are adapted for the situation in Vienna, since the scenarios in (Müller and Kranzl, 2013) represent the situation for policy instruments for whole Austria. It's necessary to mention here, that the considered scenarios don't represent the actual situation in Vienna, they just should point out potential developments dependent on different policy frameworks.

[1] https://open.wien.gv.at/site/open-data/

- Scenario 1 - WEM (With existing measures): This scenarios represent roughly the existing policy frameworks implemented in spring 2012 in Austria. The Scenario considers investment subsidies for heating systems and for refurbishments up to 2030. (see detailed description in (Müller and Kranzl, 2013))
- Scenario 2 - WEMpluSol (Additional Solar thermal subsidies): In addition to the policy frameworks from Scenario 1 the investment subsidies for solar thermal are increased.
- Scenario 3 - WAM (with advanced measures): In addition to the WEM Scenario additional budget for renovations is available and the renovation quality increases within the simulation horizon. (see detailed description in (Müller and Kranzl, 2013))

The focus of the analysis of all scenarios is on the actual building stock. New buildings due to the increase in population are neglected. However, buildings newly constructed due to demolition are included in the case study. In addition, the competition between photovoltaic and solar heat isn't the focus of this study either.

The yearly price increase varies in average during the simulation period between 1.02% for gas and 0.76 % for district heating, the two mainly used energy carriers for heating and domestic hot water in Vienna. (In 2013, share of gas in final energy consumption: 42.3 %, share of district heating: 40.6 % (Statistik Austria, 2014)) For climate data, the hourly averaged temperature values for the years 2012-2014 are used (Source: Wien Energie).
We assume constant losses for district heat distribution amounting to 7.5 %[2].

4. Results

To compare the results for the different scenarios, the following indicators are used:

- Average CO_2 Emissions (kg/GWh) for heat and domestic hot water supply.
- Cumulative costs for the building's heat and domestic hot water demand from 2015 until 2030. These costs 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.
- Share of solar heat and district heating in the final heat consumption in 2030.
- Additional average generation costs for district heating in 2030. These costs include future annualized investment costs for new heat plants as well as fuel costs in 2030. They do not include investment costs for already existing plants.

[2] Source: http://www.nachhaltigkeit.wienerstadtwerke.at/oekologie/energieerzeugung-bereitstellung/energieeffizienz.html

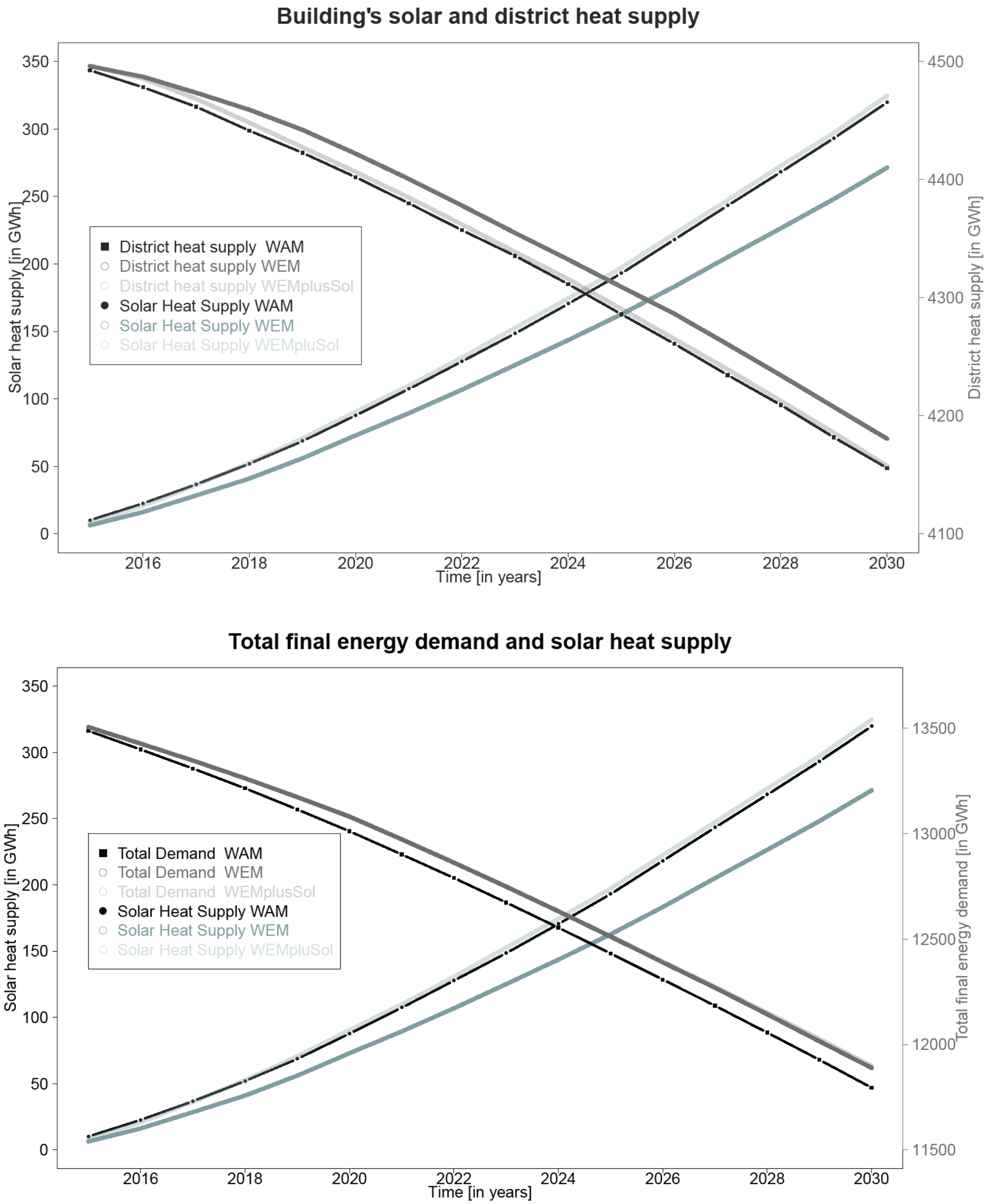

Figure 3: Development of the building stock's (Residential and office buildings) final energy demand for space heating and domestic hot water

In Figure 3 final energy demand (FED) for buildings in GWh in total and for district heating and solar heat is depicted from 2015 until 2030. The FED in total remains the same for the WEM and WEMpluSol scenario since the WEMpluSol scenario considers higher subsidies for solar heat with no additional incentives for the building owners to decrease their energy demand. The FED for the WAM scenarios decreases until 2030 by approximately 105 GWh. The impact of the additional solar heat subsidies is highlighted in the plot for the district heating demand and the solar demand: Here, the same change in demand for the WAM scenario and the WEMpluSol can be seen.

Table 1: Overview economic and ecological assessment

Scenario	Avg. CO_2 emissions [$kgCO_2/kWh$][3]	Cumulative Costs demand side [Mio. €][4]	share solar in 2030 [%][5]	Share district heat in 2030 [%][5]	Generation Costs district heat 2030 [€/MWh][6]
WEM	0.2248	3031.7	2.20 %	35.16 %	19.87
WAM	0.2239	3028.3	2.70 %	35.23 %	19.81
WEMpluSol	0.2236	3034.7	2.73 %	34.94 %	19.80

In Table 1 the indicators for all three scenarios are shown. Due to the lowest final energy demand in the WAM scenario and the same demand for solar heat and district heat as in the WEMpluSol scenario, WAM scenario has the lowest CO2 emissions. In addition, because of the reduction in the energy demand, the additional costs in the WAM scenario are balanced and the lowest average costs for the considered simulation horizon can be seen. As the building's energy demand and supply model gives a similar decline in demand for all three scenarios there will be no difference in district heat generation costs and investment decisions computed by the district heating investment model. In all three cases a modest change of the generation portfolio by installing 50 MW of heat pumps is cost-optimal. Thus the district heat generation in Vienna would still be mainly based in these scenarios on CHP plants with heat-only boiler station for peak load and incineration plants for based load. As the generation portfolio remains widely unchanged the additional generation costs can mainly attributed to fuel costs (gas) and the gains/losses of electricity generation by CHP plants.

- 3 Calculations based on the following values for CO2-emission: Gas: 0.252 kg/kWh, Oil 0.299 kg/kWh, Coal: 0.34 kg/kWh, electricity: 0.157 kg/kWh, district heating: 0.211 kg/kWh, Wood: 0.025 kg/kWh, wood pellet: 0.052 kg/kWh
- 4 The Cumulative costs of the demand side 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.
- 5 The share is defined as the proportion of solar energy resp. district heating in the final energy consumption.
- 6 These costs include future annualized investment costs for new heat plants as well as fuel costs and gains/losses from electricity generation by CHP plants in 2030. They do not include investment costs for already existing plants.

Screen shots of the 3D spatial simulation are shown in Figure 4-Figure 6. In all three figures the probability of installing solar heat units until 2030 for different scenarios is displayed. In Figure 4, a 2D map of a city quartier in Vienna is displayed. This 2D map gives an overview of the impact of solar heat strategies. The City planner can choose some areas with particular interest that can be shown in a 3D partial simulation as shown in Figure 5. Here, two scenarios can be considered simultaneously. Moreover this 3D spatial simulation allows for more detailed street views too (see Figure 6).

Figure 4: 2D city map with the share of installed solar heat units in comparison to the theoretical potential until 2030 for WAM scenario

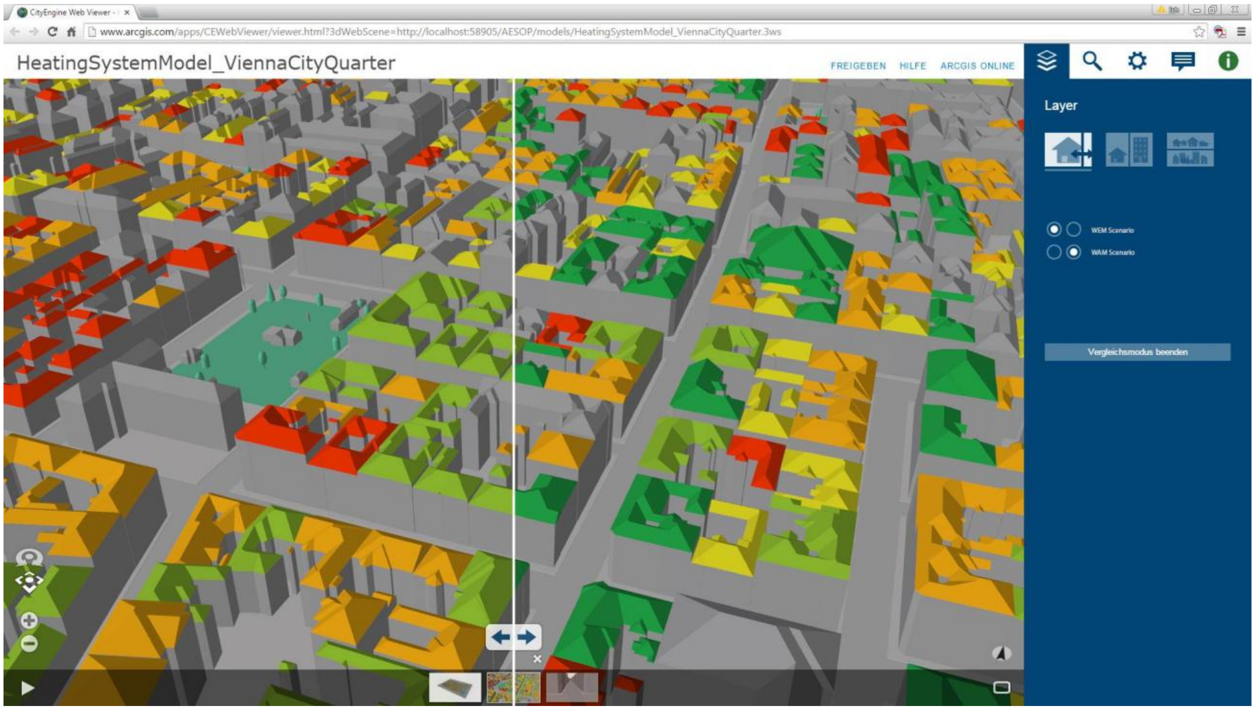

Figure 5: 3D Spatial simulation with the share of installed solar heat units in comparison to the theoretical potential of installing solar heat units until 2030 for WAM (right) and WEM (left) scenario

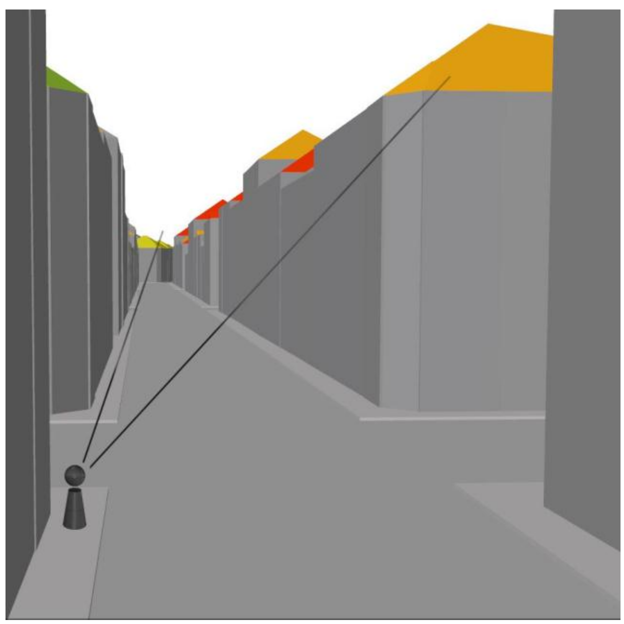

Figure 6: Street view within the 3D spatial simulation

The interactive (ESRI web viewer) version (see Figure 5) is available under: http://tinyurl.com/oebhcbl. It enables the comparison screen for two scenarios (WEM: Scenario 1; WEMpluSol: Scenario 2) for the year 2030. The Legend for the online tool is shown in Figure 4.

5. Conclusions

In this paper we developed a methodological framework for evaluating solar heat strategies based on economic and ecological indicators. Further we implemented a 3D spatial simulation of the probabilities of installing solar heat units for every building roof in Vienna. This allows an additional analysis of the possible spatial impact of economic and ecological reliable solar heat strategies. As seen in Figure 4 an economic assessment of theoretical solar heat potentials yields a quite different distribution of the most favored locations for solar heat. This can be attributed to the fact that many buildings with high theoretical solar heat potentials may already have economically or ecologically efficient heating systems installed. Thus we believe that such an analysis is essential for reliable city planning. Furthermore, we believe that using a 3D spatial simulation enhances city planning, since this is the easiest way for displaying spatial impacts.

Concerning the results for the city of Vienna, we want to raise several points: The theoretical solar heat potential differs severely from the economic potential. However solar heat subsidies don't have displacement effects on the usage of district heating in a city. In our computations mainly usage of gas for heat supply decreases by purely economic reasons. This is very satisfying from an ecological point of view and eases the implementation of solar heat strategies for city planners. Finally we have to emphasize that our 3D spatial simulation is designed as a decision support tool for city planners only. For detailed and reliable analysis, city planners need to define buildings, where installments of solar heat units (panels) are undesirable. Furthermore they have to define visual axes that have to be preserved due to historical or cultural reasons.

6. Acknowledgment

This project would have been impossible without the support of Wiener Stadtwerke Holding AG, Wien Energie and the PhD course URBEM. Further we would like to thank Stefan *Dürauer (MA 41) and Christian Pöhn* (MA 39) for providing us the data sets on building solar potential registry, GIS building data and heat registry.

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