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Spatial clustering for district heating integration in urban energy systems: Application to geothermal energy ☆

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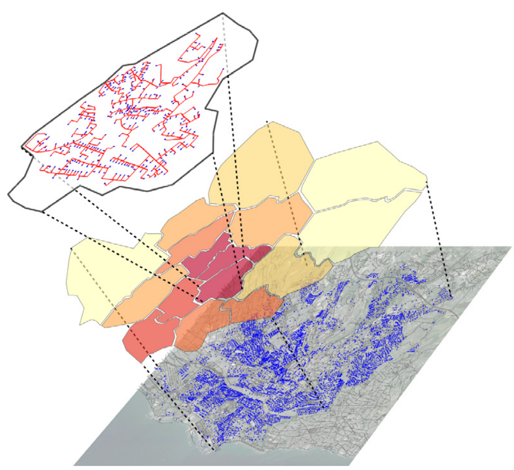
HIGHLIGHTS

- Methodology to integrate renewable energy-supplied district heating in cities.
- Integration of georeferenced data of buildings and resources in urban energy models.
- Rigorous optimization-based clustering approach to reduce model complexity.
- Realistic and optimized district heating network designed based on the road network.
- Case study: district heating integration assessed over the whole urban area.

GRAPHICAL ABSTRACT



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ABSTRACT

Given the challenges related to climate change and dependency from fossil fuels, modification of the energy systems infrastructure to increase the share of renewable energy is a priority in urban energy planning. The high heating density in cities makes it more economically competitive to deploy district heating (DH), which is essential for large-scale integration of renewable energy sources. Combining georeferenced data with district heating design methods allows to improve the quality of the system design. However, increasing the spatial resolution can lead to intractable model sizes.

This paper presents a methodology to spatially assess the integration of DH networks in urban energy systems. Given georeferenced data of buildings, resource availability and road networks, the methodology allows the identification of promising sites for DH deployment. First, an Integer Linear Programming (ILP) model divides the urban system into spatial clusters (of buildings). Graph theory and routing methods are then used to optimally design the DH configuration in each cluster considering the road network in the routing algorithm. A Mixed-Integer Linear Programming (MILP) model is formulated in order to economically evaluate the DH integration over the whole urban area.

☆ Electronic Supplementary Information (ESI) available.

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The proposed methodology is applied to an example case study, evaluating the use of geothermal energy (deep aquifer) for direct heat supply. The results of the optimization show the interest of deploying geothermal DH in some of the clusters. The profitability of DH integration is strongly affected by the spatial density of the heating demand.

1. Introduction

In Western Europe and North America, space heating (SH) and domestic hot water (DHW) are the main contributors to household energy demand. In European residential buildings, about 57% of the total final energy consumption is used for SH and 25% for DHW [1]. The European heat market for buildings is dominated by fossil fuels burned in decentralized boilers, accounting for two-thirds of the total domestic heat supply [2]. In the residential buildings of the United States (US), 93.5% of the energy used for space heating is provided by natural gas, fuel oil, liquefied petroleum gas, and kerosene [3]. Concerns related to greenhouse gas emissions, climate change and security of energy supply are gradually leading to modifications in the thermal energy supply chain. Local authorities are pushed to make strategic decisions for the planning of heat supply, encouraging the energy transition towards a low carbon future. In this framework, substitution of fossil fuels with renewable energy resources has been identified as a priority [4]. Thus, the optimal use of renewable energy resources and the sustainability of energy systems represent key issues in energy planning.

In 2010, approximately 73% of European Union (EU) residents lived in urban areas [2], where the highest share of the SH and DHW demand is concentrated. The high density of heat demand in cities makes the deployment of DH more competitive [5] as it leads to lower DH network lengths, lower thermal heat losses and therefore lower investment costs. Furthermore, DH offers the possibility of integrating heat resources that could otherwise not be used. These include excess heat from industrial processes, power plants or waste incineration. DH also allows to access large scale renewable energy resources such as geothermal, biomass or solar heat. DH penetration for heating of buildings in the EU was 13% in 2010 [2]. Nevertheless, the availability of resources reveals an important potential for DH expansion in some European countries [6]. As an example, in North-Eastern Europe more than 100 million people already depend on DH [7]. In Denmark, DH is the dominant heat carrier, accounting for 60% of total heat supply in 2009 [8]. As a comparison, in Switzerland DH provided only 2.8% of the heat demand in 2007 [9]. Many studies analyze the potential of DH related to specific case studies. For instance, Gebremedhin [10] studied the impact of DH in the city of Gjonik in Norway and concluded that DH can lead to a significant reduction in terms of CO_2 emissions.

Among renewable energy sources for DH, some studies have highlighted the interest of geothermal energy integration. Hepbasli et al. [11] and Moret et al. [12] assessed that geothermal DH can provide heat at a lower cost than fossil fuel alternatives in the cities of Izmir, Turkey, and Lausanne, Switzerland, respectively. Globally, geothermal energy accounted for 0.1% of the energy supply in 2008 [4]. It is projected to cover 3.5% of the global electricity production and 3.9% of the final energy for heat by 2050 [13]. Fox et al. [14] showed that there is a large potential for utilizing low-temperature geothermal resources to meet the heating demand by direct heat use. Aquifers located under cities can naturally offer interesting thermal conditions for building heat supply. As an example, the DH of Riehen, Switzerland, is mainly supplied by an aquifer, from which around 25 kg/s of water at 65 °C are extracted [15].

Optimization models taking into account energy demand, energy resources and energy conversion technologies are often developed to support the understanding and planning of urban energy systems. Due to the spatial dimension of the problem, the use of georeferenced data is essential for assessing and preliminary designing DH solutions. In fact, the spatial configuration of the buildings connected to the DH network defines its length and, consequently, its investment cost. In large cities such as London [16] and Berlin [17], Geographic Information Systems (GIS) are used to analyze and visualize the heat demand distribution in the city. Finney et al. [18] used GIS in order to investigate the expansion possibilities of DH systems by identifying the existing and emerging heat sources and sinks. The methodology is solely based on heat mapping, i.e. the heat sources as well as the heat sinks in Sheffield, England, are identified and mapped. Nielsen et al. [19] developed a GIS model to examine the potential for expanding DH in Denmark. This is performed by determining the cost of deploying DH in urban areas that are not yet served. The output of the GIS-model consists of a map showing the economic potential of each area for DH integration compared with individual ground source heat pumps, which are assumed to be the cheapest decentralized heat supply alternative. In their study, the areas in which DH expansions are evaluated are taken from the Danish Common Public Geo-database [20]. Möller et al. [21] presented a geographical study of the potential to expand DH into areas supplied with natural gas. Their study uses a highly detailed spatial database of the built environment, its current and potential future energy demand, its supply technologies and its location relative to energy infrastructure. The cost of district heat expansion is evaluated as a function of the heat demand density in the areas, the number of buildings to be connected, as well as the straight line distance to the existing network. Cost-supply curves based on empirical methods are used to assess economic potential for district heat expansion. Girardin et al. [22] developed a GIS-based approach in order to evaluate the best zones to be covered by a DH system in a given geographical area. The geographical area is first divided into subsectors using the statistical sectors provided by the authorities. An algorithm is proposed to estimate the DH network length connecting a set of buildings. The length is computed based on the number of buildings, the area covered by the buildings and a topological factor. Based on the equidistance assumption, the model considers the calculated peak heat load to estimate the section of the pipes and the required investment. In his thesis, Girardin [23] extended the approach using a GIS-based Mixed-Integer Linear Programming (MILP) aggregation mechanism in order to evaluate the best zones to be covered by a DH system that has access to a limited but high quality resource such as a waste water treatment plant. As shown in [22], the evaluation of the length and the costs of future networks is an important issue in territorial energy planning. Reidhav et al. [24] evaluated the investment cost of new DH networks based on data relating to an existing DH network in Göteborg. The investment cost is empirically defined as a linear function of the district heat delivered per connected house. Persson et al. [5] proposed a method to estimate the distribution cost of a future DH system based on the concept of linear heat density, which corresponds to the ratio between the heat annually sold and the total trench length. The linear heat density is reformulated and estimated based on a set of parameters (such as the effective width initially introduced in 1997 in [25]) that are empirically defined. Falke et al. [26] developed a method to determine the optimal heating network design based on a heuristic approach that