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Renewable-based heat supply of multi-apartment buildings with varied heat demands

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ABSTRACT

This study investigates the cost and primary energy use to heat an existing multi-apartment building in Sweden, before and after deep energy efficiency renovation, with different types of renewable-based systems. District heating systems of different scales as well as local heat production based on bioelectric boilers, ground-source bioelectric heat pumps and wood pellet boilers with or without solar heating are considered. The annual energy demand of the building, calculated hour by hour, with and without energy efficiency improvements, are matched against the renewable-based heat supply options by techno-economic modeling to minimize cost for each considered heat supply option. The results show that the availability of heating technologies at the building site and the scale of the building's heat demand influence the cost and the primary energy efficiency of the heating options. District heat from large-scale systems is cost efficient for the building without energy-efficiency improvement, whereas electric heat pumps and wood pellet boilers are more cost efficient when implementing energy-efficiency improvement. However, the cost difference is small between these alternatives and sensitive to the size of building. Large-scale district heating with cogeneration of power is most primary energy efficient while heat pumps and medium-scale district heating are nearly as efficient.

1. Introduction

The demand for space heating of buildings located in regions with cold climates is significant, typically representing the single largest end-use of energy in households. In the European Union, approximately 33% of the total energy use is for space heating of buildings [1]. Furthermore, space and domestic water heating are provided at low temperatures [1,2] and can be satisfied by various means and energy sources [1,3].

The space heating demand of a building during cold climates varies during the year, with the climate conditions and the technical performance of the building provided by its initial technical design. The construction of energy-efficient buildings, an important strategy for reducing energy use in the building sector [4], influences the yearly variation of the heat demand. The energy-efficient buildings could influence the cost and the primary energy efficiency of different heat supply options due to the reduced need of production capacity and less yearly variation of the heat load. These parameters could alter the cost-efficiency ranking of the energy supply system.

Energy renovation of the existing building stock coupled with an efficient energy supply is a key part of the EU's climate and energy strategy [5]. Several studies (e.g., [6–10]) demonstrate that large space heating reductions may be achieved by implementing energy efficiency measures, such as improved building thermal envelope insulation and airtightness, efficient windows and ventilation heat recovery systems. The Intergovernmental Panel on Climate Change [11] summarized key recent research on the energy renovations of buildings and noted that space heating reductions of 80–90% have been achieved in several multi-apartment deep energy renovation projects. Furthermore, studies (e.g., [12] and [13]) indicate that the energy use for heating tap water may be reduced considerably by switching from standard to resource-efficient taps. Jensen [12] explored the energy savings potential for domestic hot water in Sweden and reported that energy savings of 30–60% are achieved when pre-2000 taps and showerheads are replaced with state-of-the-art alternatives.

Various technologies based on renewable resources can be used for heat production, including different alternatives for

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Nomenclature

BIGCC	biomass integrated gasification combined cycle
BIGGE	biomass integrated gasification with gas engine
BORC	biomass-based organic Rankine cycle
BST	biomass-based steam turbine
CHP	combined heat and power
DHS	district heat production system
EHP	electric heat pump
ERH	electric resistance heating
O&M	operation and maintenance
SWH	solar water heating
WPB	wood pellet boiler
WST	water storage tank

district heating and local heating [14]. District heating is widely used in urban areas in Europe [15], with approximately 6000 systems currently in operation supplying approximately 13% of the heat to the residential and service sectors in Europe [1]. In Sweden, district heat supplies more than 91% of the heat to multi-apartment buildings [16]. District heat is considered to be an effective mean for reducing the use of fossil fuels because low-grade fuels and low temperature heat sources, such as municipal solid waste and industrial waste heat, are suitable to use in district heating systems [17]. Moreover, a wide range of renewable resource-based technologies can be mobilized for district heat production, including solar energy, fuel-based heat-only boilers and CHP (combined heat and power) units of various technologies, such as a BIGCC (biomass integrated gasification combined cycle), BIGGE (biomass integrated gasification with gas engine), BST (biomass-based steam turbine), and BORC (biomass-based organic Rankine cycle). The minimum-cost heat supply option for a building depends on the scale of the buildings' heat demand and its variation as well as the location-based conditions. For buildings in low-heat density areas, the distribution cost and heat losses of a district heat system may cause a high overall heat cost. Examples of local heat supply options are small heating boilers and EHPs (electric heat pumps), which are commonly used for water and space heating purposes. In Sweden, the installation of EHPs in detached houses has increased steadily from the 1990s, and 46% of Swedish detached houses used these heat pumps for heating purposes in 2011 [16]. Solar and wind power are expected to have a substantial share in future electricity combinations [18], thus increasing the possibilities for electric-based heat production.

Non-fuel based technologies, such as SWH (solar water heating), can be mobilized for district heating and local heating. Solar heating is a matured technology, and it is expected to be one of the most important energy sources for space heating of buildings by 2030 in Europe [19]. The integration of SWH reduces the use of fuel based systems; furthermore, SWH is a supplement to fuel heating and can reduce the fuel use and heat production costs [20]. In Sweden, even though solar radiation intensity varies strongly throughout the year, roof-mounted solar water heating has been installed to supplement space and water heating [21,22].

In this study, we investigated different options for supplying heat to a multi-apartment building located in Växjö, Sweden before and after implementing energy efficiency measures. We considered renewable-based alternatives for both district heating and local heating. The local heating options are based on ground-source EHP, ERH (electric resistance heating) and WPB (wood pellet boilers), with and without solar heating systems. We evaluated the influence of the varying heat demand due to energy efficiency measures on the heat cost and the primary energy usage of the different heating options.

2. Methods and assumptions

Our analysis has three sections: i) dynamic energy balance modeling of a case-study building with and without energy efficiency improvements; ii) techno-economic modeling of different minimum cost renewable-based heat supply options; and iii) analyses of primary energy use and heat cost for the case-study building with and without improvements when using different minimum cost heat supply options.

2.1. Case-study building and analysis

The case study is based on an existing multi-apartment building constructed in the mid-1990s in Växjö (latitude 56°87′37″N; longitude 14°48′33″E), Sweden. The building consists of a light-wood structural framework and a total heated floor area of 1190 m^2, and 16 apartments are distributed over four-floor levels. The building is connected to the municipal district heating network and is equipped with a mechanical ventilation system for exhaust air. To explore the impact of the building energy density on the performance of the different heat supply options, an extensive energy renovation is modeled for the building to achieve a second building configuration with significantly improved energy efficiency. The measures applied to achieve the energy-efficient version of the case-study building are described in detail by Truong et al. [23] and include an improved thermal envelope insulation for the exterior walls and roof, new energy-efficient windows and doors, efficient water taps and electric appliances, and balanced ventilation system with heat recovery. Table 1 presents the key thermal characteristics of the existing and energy-efficient building configurations.

The hourly energy balance calculations of the building configurations are performed using the VIP + program and the climate data for Växjö in 2013. VIP + supports multi-zone calculations and simulates the energy balance of buildings by considering the interactions between outdoor climate variables, indoor air temperatures, building thermal envelope characteristics, occupancy and operational schedules as well as heating, ventilation and air conditioning systems installed in a building. The space heating demand is simulated for each building configuration with two zones: the living area, with an assumed indoor air temperature of 22 °C; and the common area, with an assumed indoor air temperature of 18 °C. For domestic hot water, VIP+ assumes a constant use profile over the entire year. To accurately design the systems for the hot water supply, the hourly and seasonal variations of demand need to be considered. We adapted the annual hot water demand calculated using VIP+ to account for the seasonal and hourly variations using data from Widen et al. [24] and Bernado [25].

2.2. Heat supply options

We considered different options for supplying heat to the building configurations. All of the heat supply options are assumed to provide heat for a water-based heat distribution system inside the building configurations. Therefore, the costs of the indoor heat distribution system and the end-use radiators are the same and not included in the analysis.

2.2.1. District heating

District heat production costs and primary energy use vary with the district heat production scales [26]. We considered three