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Low-energy district heating in energy-efficient building areas

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ABSTRACT

This paper presents an innovative low-energy district heating (DH) concept based on low-temperature operation. The decreased heating demand from low-energy buildings affects the cost-effectiveness of traditionally-designed DH systems, so we carried out a case study of the annual energy performance of a low-energy network for low-energy houses in Denmark. We took into account the effect of human behaviour on energy demand, the effect of the number of buildings connected to the network, a socio-economic comparison with ground source heat pumps, and opportunities for the optimization of the network design, and operational temperature and pressure. In the north-European climate, we found that human behaviour can lead to 50% higher heating demand and 60% higher heating power than those anticipated in the reference values in the standard calculations for energy demand patterns in energy-efficient buildings. This considerable impact of human behaviour should clearly be included in energy simulations. We also showed that low-energy DH systems are robust systems that ensure security of supply for each customer in a cost-effective and environmentally friendly way in areas with linear heat density down to 0.20 MWh/(m year), and that the levelized cost of energy in low-energy DH supply is competitive with a scenario based on ground source heat pumps. The investment costs represent up to three quarters of the overall expenditure, over a time horizon of 30 years; so, the implementation of an energy system that fully relies on renewable energy needs substantial capital investment, but in the long term this is sustainable from the environmental and socio-economic points of view. Having demonstrated the value of the low-energy DH concept, we evaluated various possible designs with the aim of finding the optimal solution with regard to economic and energy efficiency issues. Here we showed the advantage of low supply and return temperatures, their effect on energy efficiency and that a DH design that relies on low-temperature operation is superior to a design based on low-flow operation. The total primary energy use in the best design was 14.3% lower than the primary energy use for standard, recently designed networks, and distribution heat losses were halved. Moreover, the exploitation of the entire available pressure by means of careful network design decreased the average pipe size required, which slightly lowers the investment costs for purchasing and laying the pipelines in the ground. This low-temperature DH concept fits the vision of the future energy-sustainable society.

1. Introduction

1.1. *The low-energy concept applied to district heating*

District Heating (DH) covers 60% of the heating demand in Denmark and has a large influence on the rest of the energy system [1,2]. DH will also play a central role in the future Danish energy system based on Renewable Energy (RE) [3]. Many local authorities therefore have plans for preparing the energy system to implement the vision of a society that achieves dramatic energy savings and fully relies on RE [4–6]. The potential to satisfy the energy demand in communities with DH is high, not only in cold climate countries, but also significant in other countries [7–9]. Nevertheless, the cost-efficiency of DH supply in energy-efficient building areas may be critical. In fact, DH can become uneconomic, especially due to the fixed costs that derive from capital-intensive investments. Furthermore, current Danish Building Regulations do not require low-energy buildings to be connected to DH. Finally, traditionally-designed networks often have sub-optimal energy performance, because of over-dimensioned design and unnecessarily high operational temperatures. The application of the low-energy concept to DH technology has three main targets. The first one is to guarantee comfort with regard to Domestic Hot Water (DHW) and Space Heating (SH) requirements, by exploiting low-grade energy sources

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Nomenclature

d	Diameter [mm]
e	Hourly energy use [kWh]
A	Heated area [m^2]
DH	District Heating
DHW	Domestic Hot Water
E	Specific annual energy use [kWh/(m year)]
GSHP	Ground Source Heat Pumps
LF	Load factor [-]
RE	Renewable energy
SH	Space Heating
T	Temperature [°C]
Subscripts	
by-pass	By-pass in the substation
ground	Ground
i	Hour of the day [-]
j	Day of the month [-]
n	Number of days in a specific month [-]
return	Return pipe
supply	Supply pipe

and RE. The second objective is to match the exergy demand of such applications with the exergy available in the supply system, by bringing the temperature levels of the supply and the demand closer to each other. Thirdly, it aims at reducing the heat loss in the distribution network. The main design concepts are:

a) Low-size media pipes. This is achieved by allowing a high pressure gradient in the pipelines, above all in the branch pipes connected to the unit with instantaneous DHW preparation [10], or by installing units with storage of DH water [11]. The latter consist of a heat exchanger coupled to a water storage tank on the primary side, which ensures low continuous water flow from the DH network and therefore low-size media pipes in house connections.
b) Low temperatures: down to 50–55 °C in the supply line and 20–25 °C in the return line. The technical and economic feasibility of such systems have been investigated from the theoretical point of view in [12,13] and applied in [14,15]. Lowering the supply and return temperatures increases the final energy efficiency of the systems [16] and decreases the distribution heat losses [17].
c) Using twin plastic pipes rather than a pair of single steel pipes. This leads to both lower investment costs for the civil works connected to the laying of the pipelines and lower heat loss.

1.2. Objectives of the study

The investigation described in this paper was aimed at developing and demonstrating a proposal on how best to apply the low-energy DH concept for low-energy buildings. We evaluated the annual energy performance and the socio-economics of a demonstration network, based on realistic energy loads that derived from a model of human behaviour with reference to the indoor environment. Next, we discussed a reasonable lower limit for the linear heat density for which connection to low-energy DH networks is cost-effective and energy-efficient. The linear heat density is defined as the ratio between the heating annually sold to the customers and the trench length of the DH network [9]. Finally, after demonstrating the value of the low-energy DH concept, we evaluated various possible designs with the aim of finding the optimal solution with regard to economic and energy efficiency issues. The focus was the assessment of proposals for effectively designing low-energy DH networks, that supply heat to energy-efficient buildings. The investigations dealt mainly with the design and operation of the network, and the impact of operational parameters on its energy performance. This represents a step towards a complete holistic view, which must comprehend the building installations and the heat sources as well.

2. Methods

2.1. Simulation of the energy use in low-energy buildings

Dynamic energy simulations were carried out using the software IDA-ICE [18]. A special module, which was developed in [19], was used to evaluate the realistic human behaviour and its effects on the energy use. The model is based on measurements in 10 apartments and 5 detached houses, in which the following factors were measured every 10 min for an 8-month period: indoor-environment factors (operative temperature, relative humidity, CO_2 concentration), outdoor-environment factors (air temperature, relative humidity, wind speed, solar radiation), human behaviour (window state open/closed, opening angles, temperature set point of thermostatic valves in radiators). These factors were used to create a standardized human behaviour model for energy simulations in IDA-ICE; the model takes into account the window opening angles and the heating set point. A linear regression was used to calculate the relationship between the heating set point and environmental factors. Moreover, a realistic occupancy schedule was set by adopting the model of [20]. Finally, using the tools just mentioned, we determined the expected energy use and peak loads in two typical types of low-energy buildings: a terraced house with a floor area of 114 m^2 and a detached house with a floor area of 196 m^2. The terraced house complies with the definition of Low-Energy Class 1 in the Danish Building Regulations 2008, while it slightly exceeds the maximum annual specific primary energy use which is set by the Low-Energy “Class 2015” in the Danish Building Regulations 2010 [21]. The detached house complies with the requirements of the low-energy building “Class 2015”. The formulas for calculating the maximum annual specific primary energy use for SH, DHW and ventilation in residential buildings are:

$$E = 35 + 1100/A\left[\mathrm{kWh/m^2year}\right] \quad (\mathrm{Low-Energy\ class\ 1}) \tag{1}$$

$$E = 30 + 1000/A\left[\mathrm{kWh/m^2year}\right] \quad (\mathrm{Low-Energy\ class\ 2015}) \tag{2}$$

where E is the specific annual energy use and A is the heated floor area. A complete description of the two reference houses and the design parameters is available in [22,23]. We considered 5 different cases for the reference terraced house and 3 cases for the reference detached house. The cases were chosen with the aim of comparing the influence of human behaviour on energy use with the effect of various system control strategies and environmental parameters (see Table 1). The cases were:

1. The input data as required by the software Be06 [24]. Be06 (updated in 2011 with the new version Be10) is the official Danish software for energy certification of low-energy buildings.
2. The lighting and equipment were set with a schedule. The total electrical energy use in Case 2 was the same as in Case 1, but the constant loads were replaced by variable loads.