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Power requirements of ground source heat pumps in a residential area

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HIGHLIGHTS

- Calculations of power requirements for heat pumps were conducted.
- The factors affecting power requirements were investigated.
- Peak power requirements for heat pumps are not affected by room temperature reduction.
- Total peak electric power for heat pumps may reach 49–63 GW in the UK.

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ABSTRACT

A study was undertaken to investigate the energy demand for space heating and domestic hot water systems as well as the electrical power requirement for heat pumps in residential dwellings. A residential area of 96 two, three and four bedrooms houses was considered. Energy demand and power requirements in old poorly insulated buildings and in new, well insulated buildings were investigated. The requirement for electrical power for the heat pumps in the whole residential area was computed. The effect of room temperature settings, hot water use, heat pump thermal capacity and building insulation on the power requirements in the residential area was considered.

It was found that hot water consumption has a significant effect on energy demand and power requirements. The energy demand for hot water systems may be up to 3.5 times higher than that for space heating for small, well insulated buildings.

A reduction of the room temperature setpoint and hot water consumption reduces average energy consumption. However, the peak power requirements are not significantly affected. Therefore a different control strategy, such as energy demand shifting, is needed in order to reduce electrical power peaks.

1. Introduction

Growing concerns over increased carbon dioxide emissions are encouraging the use of alternative heat sources for space heating and domestic hot water systems in buildings. If the UK 2050 targets to reduce greenhouse gases (which are mirrored in many countries) are to be met, traditional heating using natural gas boilers may not be sustainable in the long term due to the large quantities of carbon dioxide emitted during combustion.

Heat pumps have been identified as one of the available technologies allowing the reduction of carbon emissions from the domestic heating sector [1]. The UK Renewable Heat Incentive scheme [2] has been established in order to speed up the transition from existing heating technologies towards lower carbon emission alternatives. This policy encourages the use of heat pumps.

A number of research studies related to heat pumps can be found in the literature [3–12]. Recently the role of heat pumps and energy storage in balancing an electrical network has been analysed by Hewitt [3]. A discrete demand side control algorithm integrated within a building simulation platform has been applied by Hong et al. [4] to analyse space heating systems in light- and heavy-weight construction buildings using a heat pump powered from a wind turbine.

Comprehensive exergy analysis of ground source heat pumps has been conducted by Bi et al. [5]. That study showed that the largest exergy destruction occurs in the compressor and the ground heat exchanger has the lowest exergy efficiency. Therefore, these heat pump components require special attention when designing heat pumps. Dynamic performance of ground source heat pumps fitted with frequency inverters was studied by Lee [6]. It has been found that the energy consumption of the compressor of the heat pump can be reduced by 27–31% in a sub-tropical climate, when a heat pump operates in cooling mode.

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An experimental study of ground source heat pumps in a cold climate has been performed by Ozyurt and Ekinci [7]. The coefficient of performance of heat pump has been found to be in the range of 2.43–3.55.

A comparative study comparing the design and actual energy performance of ground source heat pump system in cooling and heating operation has been conducted by Magraner et al. [8]. They used TRNSYS software to model a heat pump system. They reported that the simulated energy performance factor of the heat pump system was around 4.2–4.3. The measured energy performance factor was around 3.4–3.5 during the heating season.

Man et al. [10] have studied the operation of ground source heat pump. Experimental results showed that operating performance of GCHP system depends on its operation mode. When a HP operates in intermittent mode the COP of the heat pump can be up to 10% higher compared with constant operation mode for the same unit.

When a small number of heat pumps are connected to an electrical network, their impact on the electrical power system is limited. However, if the number and geographical concentration, of heat pumps increases, problems may arise due to the limited capacity of the electrical systems. A concentration of heat pumps in small geographical areas will have an impact on the electrical distribution network while large numbers will affect the transmission and generation systems.

The study reported here investigated energy demand for space heating and domestic hot water (DHW) systems and the resulting electric power requirements for ground source heat pumps in a residential area in Wales (UK). Energy demand and power requirements in old poorly insulated buildings and in new, well insulated buildings were considered. Using simulation results of individual houses, the power requirement for heat pumps in the whole residential area was computed. The effect of room temperature settings, domestic hot water regime, heat pump thermal capacity and building insulation on the power requirement in the residential area was investigated.

The following assumptions were made in this study:

– The residential area in this study was composed of 96 two, three and four bedrooms old poorly insulated and new well insulated houses.
– Old houses were modelled using the requirements of Building Regulations 1991 (U_{wall} = 0.45 W/(m^2 K)), and new houses were modelled using the requirements of Building Regulations 2010 (U_{wall} = 0.25 W/(m^2 K)). An air leakage rate of 1 h^{-1} for all old buildings and 0.25 h^{-1} for all new buildings was used.
– Commercial single speed compressor ground source heat pump (GSHP) connected to a vertical ground heat exchanger was used in this study. Constant fluid return temperature from the ground loop heat exchanger was assumed.
– Two types of GSHP with thermal capacity of 6 kW and 10 kW were used. All heat pumps were equipped with hot water tanks with auxiliary immersion electric heaters.
– Three different room temperature regimes were investigated: high room temperature regime (room temperature setpoint +20 °C), normal room temperature regime (day temperature setpoint +20 °C, night temperature setpoint +16 °C) and low room temperature regime (day temperature setpoint +20 °C, night temperature setpoint +10 °C).
– Two domestic hot water (DHW) temperature setpoints: normal (+55°) and reduced (+45°), were used in the simulation.

2. System description

2.1. Residential area

A small residential area consisting of two bedroom terraced, and three and four bedroom detached houses was considered. Two extreme cases were addressed. First it was assumed that all buildings were old poorly insulated houses. Then a simulation was undertaken of well insulated low energy demand. In both cases the same size and type buildings were modelled.

The residential area was composed of 60 two bedroom houses, 21 three bedroom houses and 15 four bedroom houses. The total living floor area was 8370 m^2. The yearly energy demand for heating at constant room temperature +20 °C was calculated for all old and new buildings. Weather data representing Wales (UK) climate was used. Results are shown in Table 1.

2.2. Heating system

It was assumed that ground source heat pumps (GSHPs) coupled with vertical ground loop heat exchangers were installed in each building. Constant fluid return temperature from the ground loop heat exchanger of +5 °C was assumed. The size of the ground heat exchanger was estimated using the recommendations of Microgeneration Installation Standard 3005 [14]. Single U-tube type ground loop heat exchanger was used. The diameter of the pipe was 32 mm; shank spacing between the pipe centres was 52 mm. Two 130 mm diameter and 90 m depth boreholes were required for the installation of the ground loop heat exchanger.

Heat pumps were used to supply heat for space heating system and for domestic hot water (DHW). Two types of commercially GSHP were considered with a nominal heat output of 6 kW and 10 kW.

Conventionally heat pumps are equipped with hot water tanks for DHW. Hot water in the tank has to be heated to +55–60 °C in order to avoid the risk of legionella. However GSHP are not always capable of delivering a sufficiently high water temperature, therefore additional electric heaters are used. In this study it was assumed that each heat pump had a 180 l hot water tank. The tanks were equipped with 3 kW immersion electric heaters. In the heat pump unit electrical energy was consumed by the compressor and electric heater.

The heat pumps were assumed to operate in three regimes: heating regime, hot water regime and standby regime.

In the heating regime, the supply water temperature to the radiator system was controlled depending on the outside air temperature. The supply water temperature varied between +55 °C and +35 °C depending on the outside temperature. The maximum water temperature (+55 °C) was set when the outdoor air temperature was below −5 °C. The minimum water temperature (+35 °C) was set when the outdoor air temperature was above +12 °C. The supply water temperature varied linearly between +35° and +55° with the outside air temperature between +12 °C and −5 °C.

The hot water regime was the highest priority. The hot water regime was activated when domestic hot water was used and the temperature in the hot water tank started to drop. When the temperature in the hot water tank dropped below +53 °C the electric heater was switched on. If the water temperature dropped below +50 °C the heat pump was automatically switched from standby or heating regime to hot water operating regime in order to maintain the temperature in the hot water tank. When the hot water demand ceased the temperature started to rise. When it reached +53 °C the heat pump was switched over to standby or heating regime. The remaining temperature increase from 53 °C to 57 °C was achieved using the electrical heater.

When the heat pump was in standby mode the compressor and electric heater were switched off, as there were neither heating nor hot water demand.

The hot water requirement in a house is difficult to predict, as it depends on the number, the age and the habits of occupiers. In this study the daily profile, based on field studies, presented by Spur et al. [15] was used. The total water consumption was 320 l per household per day.