Building heat demand characteristics in a planned city district with low-temperature district heating supply

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Abstract

Due to desirable emission reductions and population growth, increasing energy demand is identified as a dire issue for energy systems. The introduction of low-energy building districts enables increased energy system efficiency. This study's aim is twofold. Firstly, an extensive urban building energy model is used to simulate the hourly use and geographic distribution of the heat demand for residential and commercial buildings that are to be supplied by a low-temperature district heating system. The simulated buildings are a part of a planned city district, located in Gävle, Sweden. Two building energy performance cases are studied; one where all buildings are assumed to be of Passive House standard, and one where the building energy performance is in line with conventional new-building regulations in Sweden. Secondly, one specific building is modeled in detail and simulated in the building energy simulation software IDA ICE to investigate what building heating system is best suited for low-temperature heat supply. The temperature demands of floor heating and ventilation with heat recovery are investigated and compared to conventional water-based radiators. The building's temperature demand results can be used when designing a low-tempered district heating system which will provide the supply temperature to identify a compatible heating system technique. Varying supply temperature demand will enable optimization for choosing building heating systems and consequently, possible cost reductions. The results could be used as an example for future city district planning as well as presenting relevant heating systems for low-temperature district heating.

1 Introduction

Energy demand is increasing at a problematic rate for regional and global systems due to increasing population and the desire to reduce greenhouse gas (GHG) emission (Energimyndigheten, 2022a). The Swedish housing sector utilized roughly 34% of the total energy use in Sweden in the year 2022, where the majority of energy was used for space heating (SH) and domestic hot water (DHW) (Boverket, 2023). With an increasing construction rate, the energy systems tend to be further burdened with higher energy demands (Naturvårdsverket, 2022). Studies, such as the one carried out by (Abu Bakar et al., 2015), have found that it is possible to reduce energy systems by implementing energy-efficient buildings. District heating (DH) is the most common heat source (>50%) for residential and commercial buildings in Sweden (Energimyndigheten, 2022b). To comply with the EU's climate goal of lowered energy use, studies have been conducted to explore the possibility of implementing low-temperature district heating systems, where the supply and return temperatures are lowered (Lund et al., 2014). Low-temperature district heating has two distinct advantages: the ability to incorporate lower temperature sources that would otherwise be wasted and the reduction of distribution losses. These in turn can lead to a reduction in GHG emissions. This would imply lower energy use as well as distribution losses and higher demand on the building envelope. Johari et al. (2023) and Reinhart & Cerezo Davila (2016), among others, developed and investigated urban building energy models (UBEMs) in the interest of facilitating planning of city districts. To enable the implementation of low-temperature DH, further studies have been conducted to investigate suitable heating systems for buildings. Hasan et al. (2009) found low-temperature water heating systems, radiators, and floor heating, to be applicable to such a heat source while maintaining comfortable indoor air temperature.

The work in this paper is part of a larger work where the aim is to use the 3D plans for a coming city district and simulate the energy use on a building level. Then simulate losses and mass flows in different low-temperature DH-systems and finally, simulate supply and return temperatures in a building with different heating systems using water as distribution media. This paper focuses on simulating the heating demand on a building level from 3D plans of an upcoming city district and simulating different heating systems inside a building connected to a DH system. A planned city district located in the northern parts of Gävle, Sweden, will be used as a case study to investigate the importance of building energy performance and heating system temperature demands for applying low-temperature DH. The first will be investigated by simulating varying building energy performances to later be used for planning a DH. The second will simulate inlet temperatures to space heaters to determine the best-suited technique for low-temperature DH supply.

2 Background

The planned city district (Näringen) is located north of Gävle, Sweden, and will be used as a reference case for this study. The district intends to be one of Europe's most sustainable city districts with roughly 6000 residential apartments and 450000 m^2 commercial space (Gävle kommun, 2021). The buildings are to be supplied with low-temperature DH, further addressed as 4th generation DH (4GDH), generally defined by supply and return temperatures of $55/30°C$ (Lund et al., 2014). 4GDH has been proposed as a method to reduce energy losses and incorporate waste heat to decarbonize heating needs (Connolly et al., 2014). One advantage is that once established there is flexibility to incorporate carbon-neutral thermal energy sources. This paper focuses on the requirements of the shell and indoor heat delivery, i.e. radiators, required for 4GDH. District heating is considered a favorable heat source when an area's heat density is at least $40-50\ kWh/m^2$ (Frederiksen & Werner, 2014). Below this threshold, thermal losses in the pipes leading to and within the area are too high. Lower energy demands can also be uneconomic to justify the infrastructure investment of district heating. A shell with a higher U-value leads to lower energy demand but may push the heat density below the recommended for district heating network integration. Both heat density and heat delivery inside the apartments are identified as research gaps in the field of 4GDH.

3 Methodology

To investigate the influence of energy performance of buildings and their space heating systems, in particular, water radiators, on low-temperature DH, two studies were made. In the first study, an UBEM method developed by Johari et al. (2023), was used for simulating the energy performance of buildings based on the criteria for Passive House standard and the latest Swedish building codes with and without heat recovery ventilation system. Second, to find the best-suited system for low-temperature DH supply, the inlet water temperature to conventional radiators, low-temperature radiators, and floor heating was determined using IDA ICE (AB, 2023).

As plans for the new city district are not yet final, assumptions were made when simulating in IDA ICE and UBEM. Information regarding the geographical position, number of floors, and building type was retrieved from a project description (Gävle kommun, 2021). Figure 1 shows the planned city district's buildings as well as the development phases 1-11.

Figure 1. Geographical positioning of the planned city district including development phases 1-11.

3.1 Weather data

Due to buildings' energy use's dependency on weather, both models utilize data for a typical meteorological year (TMY) for Gävle from the PVGIS Online Tool (European Commission, n.d.). The measured ambient temperature for 2022 was used when simulating the annual heat demand to use data consistent with the current temperature profile instead of the historical one. The data was collected from Gävle Energi's database, which is the company responsible for managing the DH system in Gävle. In IDA ICE, the wind profile was set to represent urban conditions.

3.2 Estimation of heat demand in the planned city district

To estimate the energy use of a large set of buildings located in the planned city district, a bottom-up physics-based UBEM developed in Johari et al. (2023) was used to estimate space heating (SH) and domestic hot water (DHW) use. The model was originally made for residential buildings. However, for the scope of this study, it was further extended to cover non-residential buildings, i.e., administrative and office buildings, as well. The key difference between residential and non-residential buildings was assumed to be centered around occupancy and load. Therefore, a new occupancy profile was attributed to non-residential buildings. Using the methodology suggested in Sandels et al. (2015), the occupancy profile for non-residential buildings was developed from a stochastic model for occupants' presence, use of electrical appliances, and lighting. As for the use of domestic hot water, it was set to zero (Sveby, 2010).

In this study, two types of building standards were used for modeling and simulation of buildings. The first was the latest Swedish building codes and minimum requirements for new constructions (in short, referred to as BBR) (Boverket, 2020). The second was the Passive House standard (in short, PH), which was proven to result in higher building energy performance than BBR. In the UBEM, the thermal properties of these standards were set according to the presented data in Table 1. In addition, for the case of PH, a mechanical heat recovery ventilation system with a minimum effect of 75 % was also considered in the model(FEBY, 2018). The window-to-wall ratio was assumed to be 20 % (Cerezo et al., 2017).

Table 1. U-values (W/m^{2}K) for PH and BBR.

Building	U_{wall}	U_{floor}	U_{roof}	U_{window}
PH	0.10	0.09	0.09	0.8
BBR	0.17	0.15	0.12	1.2

3.2.1 UBEM simulation scenarios

The importance of building energy performance when computing heat demand was simulated in three scenarios. First, all buildings were simulated based on BBR without ventilation heat recovery. Second, the energy performance was increased by implementing ventilation heat recovery. Third, all buildings were simulated as PH with ventilation heat recovery.

3.3 Estimation of the temperature demand

Urban scale models are rather simplified and therefore unable to represent a detailed low-temperature system (Johari et al., 2023). Therefore, it was chosen to use the building simulation tool IDA ICE to investigate the best-suited heating system for low-temperature DH supply. The supply temperature of water-based high-temperature radiators, low-temperature radiators, and floor heating were studied respectively. One three-story residential building with simple geometry was modeled in detail to represent BBR-building with ventilation heat recovery, $\eta_v = 75\%$. The floor area was estimated in the geographic information software QGIS to be 423.6 m^2 with interior and exterior ceiling heights at 2.5 and 3 m, respectively. A study by (Johari et al., 2022) has shown that simplified one-building modeling in IDA ICE results in limited errors. Hence, the building was assumed one zone per floor and evenly distributed windows with a window-to-wall ratio 20 % (Figure 2).

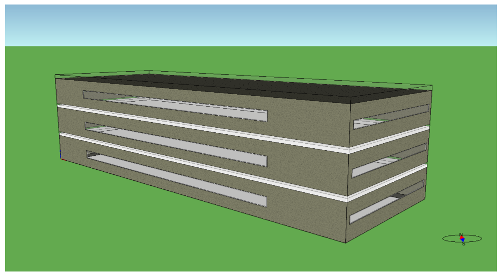


Figure 2. Building model in IDA ICE.

According to BBR the air change was set to 0.35 L/s$\cdot m^2$ and DHW use 25 kWh/$m^2 \cdot A_{temp} \cdot y$ (Boverket, 2020). The average living space per person is 42 m^2/person in Sweden which was used to estimate occupancy of 10.09 people per floor with absence between 7 am to 5 pm and 80 W heat emission. This was further used to estimate heat emission from lighting and appliances 932.7 W/floor (Sveby, 2009).

A study by Hasan et al. (2009) was used to simulate low- and high-temperature profiles of the water supply (Figure 3). The study used design temperatures 21°C and -26°C for summer and winter, respectively, resembling the Swedish climate.

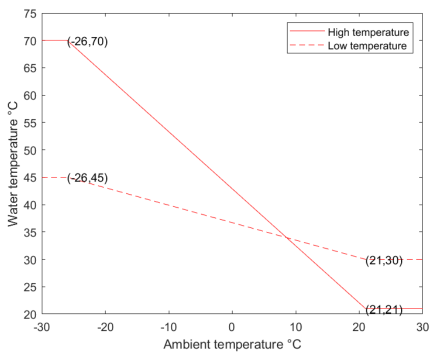


Figure 3. Water supply low- and high-temperature profiles to building heating system.

3.3.1 IDA ICE simulation scenarios

A 100 W/m^2 floor heated area radiator was placed under the window on the building's long side on each floor, generating a heat emissive area of 11.7 m^2. The design indoor temperature at maximum power was set to 21°C and ΔT at 10°C (Hasan et al., 2009). With the PI-regulator, IDA ICE estimated the water mass flow to be 1.0 kg/s. The supply water temperatures were then varied between high and low to simulate conventional high-temperature radiators and low-temperature radiators. Neither radiator system is supplemented with comfort floor heating. The supply temperature is determined by the outdoor temperature, and the mass flow varies depending on the heating demand.

35 circuits/floor at 12 m^2, placed 3 cm into the floor material, was used to simulate floor heating. Each circuit emitted 50 W/m^2 and had a design ΔT at $10°C$ as in Hasan et al. (2009). With temperature control and PI-regulator, a constant water mass flow of 0.014 kg/s was estimated in IDA ICE. The floor heating system was considered a low-temperature profile as in Figure 3. Three independent scenarios are tested:

- High-temperature radiators only
- Low-temperature radiators only
- Floor heating system only

4 Results

In this section, the results from the implementation of the methodology are presented in two parts. First, it is shown that PH has the lowest heat demand but an effective ventilation heat recovery has a large impact on the total heat demand. Implementation of varying building energy performances could be more beneficial to make DH possible, which in turn has a positive impact on the energy system. Floor heating showed to need the lowest supply temperatures of the investigated heating systems.

4.1 Area heat demand and heat density

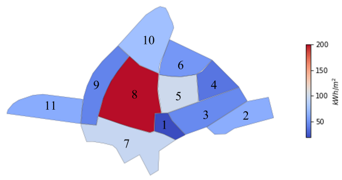
Results show that the total heat demand (DHW and SH) for the simulated area decreases from 130, 85, and 79 GWh/year with increasing building energy performance. Figure 4 shows the annual heat demand for each building of the district. A minor decrease (approximately 6%) in heat demand is seen when simulating buildings with PH standard compared to BBR-building when both include ventilation heat recovery. Heat recovery decreases the heat demand by approximately 34% when simulated on BBR-buildings. Thus, effective heat recovery has been shown to have a larger impact than materials with low U-values on a city district's heat demand. Further, Figure 4, also illustrates the buildings with the highest heat demand. This is due to its floor area and wall ratio and consequently inadequate solar heating. The building with the highest yearly heat demand decreases from 2980, 1930 to 1880 MWh for BBR-building without ventilation, BBR-building with ventilation, and PH.

Figure 5 shows each development phase's heat density. Phase 8 is well above the requirement (40 kWh/m^2) for DH for each simulated energy performance. Whereas phases 1 and 4 are always below this value. This result might be used to optimize the district for DH use.

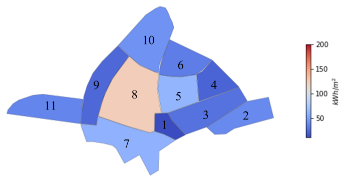
(a) BBR without ventilation heat recovery.

(b) PH with ventilation heat recovery.

Figure 4. Distributed total heat demand (MWh) for PH (with ventilation heat recovery) and BBR (without heat recovery).



(a) BBR-building without ventilation heat recovery.



(b) PH with ventilation heat recovery.

Figure 5. Heat density (kWh/m^2) for each development phase.

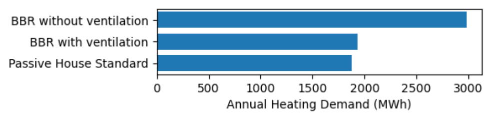


Figure 6. Results for the annual energy demand (MWh).

4.2 Individual building temperature demand

Figure 7 shows the temperature demand of the simulated space heaters and the hours the heaters are in use, i.e. the hours with heat demand in descending energy demand. Inlet and outlet temperature is set to the indoor temperature ($21°C$) when the heater power is $< 1\ W$. Floor heating is shown to require the lowest temperatures, maximum inlet/outlet temperature at $27/24°C$. The results showed a small ΔT of $1-3°C$. This is beneficial for maintaining comfort and even heat emissions. The two types of radiators require maximum inlet temperature of $41°C$ and $58°C$, low temperature and conventional, respectively. Almost identical outlet temperatures were simulated, following the indoor temperature, indicating effective heat emission regardless of the space heater.

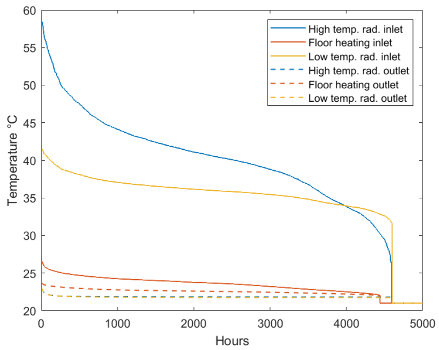


Figure 7. In- and outlet temperature to the heating system in BBR-building for winter.

Figure 7 shows that low-temperature radiators have a steady temperature curve to maintain the desired indoor temperature. However, high-temperature radiators enable fluctuations in the outlet temperature making it possible to use lower temperatures when possible as well as raising the heat when needed. After roughly 4000 h can the high-temperature radiators use lower temperatures than low-temperature radiators and still maintain an indoor temperature of $21°C$. Although counterintuitive, it reflects the assumption that the low-temperature radiator will require higher inlet temperatures at outdoor temperatures above $10°C$ which could reflect comfort floor heating in the cited paper (Hasan et al., 2009). At approximately 4500 h there is no longer a heat demand and the space heaters are therefore shut off. The principal results are however that the system is feasible to provide comfort even at lower inlet temperatures.

5 Discussion

The results from Figure 4 further the discussion and cost calculations on ventilation heat recovery versus low U-value constructions. As the results show heat recovery has a larger impact on reduction in heat demand of approximately 34% than possibly expensive PH construction of 6% compared to BBR-building without heat recovery. These gains need to be compared with the cost for each adjustment. A life cycle assessment (LCA) should also be conducted to understand the environmental impact. According to the current plans, a few residential buildings use a lot of energy when the majority have equivalent heat demand. These buildings should be evaluated and redrawn to e.g., minimize transmission losses through the building envelope and maximize solar gains.

When planning a city district supplied with DH, Figure 5 can be used to optimize the heat demand by varying building energy performance for different areas aiming at the threshold value at 40 kWh/m^2. By altering building energy performance in the different phases, the heat density can be made better suited for DH, allowing higher utilization of waste heat from e.g. industries. The result may also be used to identify issues in the current development plans such as the number of stories.

The low level of detail in buildings, both when simulating in IDA ICE as well as UBEM, results in simplified but sufficient calculations (Johari et al., 2022). Floor heating is shown to be the space heater best suited for low-temperature DH with a maximum temperature demand of $27°C$ and the lowest return temperature. When other aspects such as the initial installation cost of the heating system and slower response time to indoor or outdoor temperature changes are taken into account, other technologies can be favorable. One example can be the low-temperature radiator system that has a maximum supply temperature demand of $41°C$ which is still below the definition for 4GDH ($55/30°C$).

6 Conclusion

Improving efficiency can reduce the thermal energy demand of buildings but for DH systems to remain viable changes to heat delivery need to be made. To answer the questions of what impact a building's energy performance has on a city district's heat demand and which type of space heater is best suited for low-temperature DH, simulations in an UBEM and IDA ICE were conducted. Results showed PH has the lowest heat demand of 79 GWh/y compared to the reference case with BBR-building without ventilation heat recovery of 130 GWh/y. However, ventilation heat recovery seems to have a larger impact on a building's heat demand (34%) than construction with lower U-values (39%) compared to the reference case. Floor heating is the space heater best suited for low-temperature DH with a maximum inlet temperature of $27°C$ and the lowest return temperature of the investigated heating systems. Low-temperature radiators are also a good fit with 4GDH but demand a higher temperature of 41°C rather than floor heating's 27°C.

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