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# Effect of apartment building energy renovation on hourly power demand

Janne Hirvonen[a]*, Juha Jokisalo[a], Juhani Heljo[b], Risto Kosonen[a,c]

[a]*Department of Mechanical Engineering, Aalto University, Espoo, Finland;*
[b]*Department of Civil Engineering, Tampere University of Technology, Tampere, Finland*
[c]*College of Urban Construction, Nanjing Tech University, Nanjing, P.R. China*

* Department of Mechanical Engineering, Aalto University, PO Box 14400, FI-00076 AALTO, janne.p.hirvonen@aalto.fi, +35850 431 5780

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# Effect of apartment building energy renovation on hourly power demand

Optimal energy renovations of apartment buildings in Finland have a great impact on annual energy demand. However, reduction of energy demand does not necessarily translate into similar changes in peak power demand. Four different types of apartment buildings, representing the Finnish apartment building stock, were examined after optimal energy retrofits to see the influence of retrofitting on hourly power demand. Switching from district heating to ground-source heat pumps reduced emissions significantly under current energy mix. However, the use of ground-source heat pumps increased hourly peak electricity demand by 46 to 153%, compared to district heated apartment buildings. The corresponding increase in electrical energy demand was 30 to 108% in the peak month of January. This could increase the use of high emission peak power plants and negate some of the emission benefits. Solar thermal collectors and heat recovery systems could reduce purchased heating energy to zero in summer. Solar electricity could reduce median power demand in summer, but had only a little effect on peak power demand. The reduction in peak power demand after energy retrofits was less than the reduction in energy demand.

Keywords: Energy retrofits, District heating, Power demand, Energy performance, Greenhouse gas emissions, Apartment building

## 1. Introduction

Energy consumption in buildings is a significant source of carbon dioxide emissions in Finland and in Europe. This is why new buildings in EU need to be built according to nearly zero energy building requirements by the end of the year 2020, as decreed by the Energy Performance of Buildings Directive, EPBD (EU Parliament 2010). Most existing buildings have been built long before this kind of strict energy standards (Holopainen, et al. 2016) and renovation of old buildings is needed to reduce the total energy consumption in the building stock. With this in mind, the European Parliament has updated the EPBD so that the EU member states are also required to provide clear guidelines on how to achieve deep renovation and energy performance improvements in existing buildings (EU Parliament 2018). According to the EU Commission, an annual renovation rate of 3% is needed to achieve EU's energy efficiency targets.

Various energy efficiency measures can be used to reduce energy consumption and studies on energy retrofits of apartment buildings have shown the importance of heat pumps in reducing primary energy consumption (Niemelä, Kosonen and Jokisalo 2017). However, with an increasing amount of electrified heating and variable renewable energy sources it is also important to know when energy is being used. For example, (Howard, et al. 2012) examines the energy consumption of various different types of buildings in New York City, separating annual demand by type of use, but not by time. Similarly, various retrofit scenarios were analysed in Brisbane conditions to find the average annual energy performance reduction, but no information was provided on the variability of energy demand (Matthew and Leardini 2017). The effect of building energy conservation measures and climate change on the instantaneous power consumption in San Francisco and Philadelphia was visualized in (Sehar, Pipattanasomporn and Rahman 2016). In Northern Italy, energy retrofits for old office buildings of different sizes were examined (Luddeni, et al. 2018). Primary energy consumption could be reduced by 54% and the reduction in energy use correlated almost one-to-one with reduction in peak power demand. In the hot climate of Dubai, energy demand during peak season was reduced by 40% after performing energy retrofits in residential buildings (Rakhshan and Friess 2017).

In cold climates, the focus of energy retrofit measures is on reducing energy demand during the heating season. A Swedish study was completed to find out the most economical solutions out of various retrofit packages for single-family houses (Ekström, Bernardo and Blomsterberg 2018). Primary energy demand could be reduced by 65 to 95%, assuming that energy improvements were completed as part of other mandatory renovations. Cost-effective retrofit solutions for apartment buildings were found in Estonia and over 60% energy demand reduction was possible, but availability of funding was a problem (Kuusk and Kalamees 2016). An optimization study revealed that primary energy consumption in existing Finnish apartment buildings could be reduced cost-effectively by 20-50%, but the study did not present the change in peak power demand (Niemelä, Kosonen and Jokisalo 2017).

Knowing the peak power levels is important when considering what types of flexibility services or storage systems should be used. In liberalized energy markets, the hourly energy prices are determined by the balance between the most expensive energy source and the maximum price the consumers are willing to pay (Nord Pool 2018). During demand peaks, the cheapest baseload power generation capacity is often not enough and energy prices tend to rise as more expensive to operate power plants are brought online. As demand rises, investments into new power plants need to be considered according to their capacity-based fixed costs and the market-based variable energy prices (Grimm and Zoettl, 2013). Other options to combat increasing peak demand are expansion of energy transmission lines to bring in power from other areas (Grimm et al. 2016), or demand response services which try to shift power demand away from the peak moments (Chen, et al. 2018).

Peak power savings of cooling were examined in Virginia, USA (Sehar, Pipattanasomporn and Rahman 2016). Solar photovoltaic (PV) systems and ice storage were successfully utilized to cut peak electricity demand by almost 50%. In Northern Italy, price tracking algorithms and PV panels were used to run heat pumps and store heat in building thermal mass and water storage tanks, reducing total imported and exported electricity by up to 22% (Schibuola, Scarpa and Tambani 2015). In the Nordic heating-dominated climates, peak shaving and energy saving based on solar energy is challenging, because availability of solar energy (in summer) is inversely correlated with maximum energy demand (in winter). Demand response with water-based thermal storage controlled by electricity price trends has been studied in Finnish conditions. DR with both direct electric heating (Alimohammadisagvand et al. 2017) and heat pumps (Alimohammadisagvand et al. 2016) was used to reduce electricity demand and cost by 10%. However, while the cost savings were based on reducing power consumption during peak hours, the actual change in peak and average power consumption was not analysed.

Momentary power consumption in a building can also be controlled by energy management systems connected with an electric vehicle in a bi-directional manner (Doroudchi, et al. 2018). Power consumption levels in a house with a micro-CHP system were analysed in (Alahäivälä, et al. 2015). Availability of cheap intermittent power enabled a higher power consumption as low cost electricity was converted to heat.

As more electrified heating is added to the system, the effects to the whole power generation infrastructure need to be accounted for. The changes in electrical loads after widespread adoption of heat pumps were analysed in annual, daily and hourly timescale in a study of Geneva (Fraga, et al. 2018).in Calculating building energy balances in a daily level can provide overly optimistic results, as self-consumption of solar electricity in a heat pump system was found to be 50% less when demand/generation matching was calculated on an hourly level instead of daily. In Finland, electricity demand during winter is typically between 10 and 14 GW (Fingrid

2018). However, the estimated available capacity of emission-free power generation (nuclear, wind and hydro power) during demand peak is only 5.4 GW on average (Jääskeläinen, et al. 2018). Thus, the effect of energy saving measures on not only total energy demand, but instantaneous power demand must be considered. It is also important to consider the balance between district heating and electricity demand, because widespread electrification of heating reduces the need for the existing system of combined heat and power (CHP) production in Finland (Helin et. al 2018a). In the future, peak loads might be met through CHP plants and intermittent renewable energy sources connected to thermal storages (Wang, et al. 2015).

Prior studies have shown the value of controlling peak power demand and how retrofitting of the energy systems in existing building stock can reduce total energy consumption and emissions. Building energy retrofits reduce both average and peak energy consumption. This study shows what kind of effects these retrofits have on hourly power demand. Such information is important to take into account if widespread adoption of electrified heating is planned to support or replace existing district heating systems. If average or peak power consumption changes drastically, the current average energy generation mix may not be able to match the demand and increased use of high emission marginal generation could follow. In this study, the electricity and district heating power demand of Finnish apartment buildings before and after optimal energy retrofits are shown. The novelty of this paper is to show the effect of the cost-optimal deep-renovation on hourly power demand of district heating and electricity in apartment buildings of different ages. The paper gives insight on how energy retrofits that are optimized according to the economics of individual buildings might affect the power demand in the grid as a whole.

## 2. Methods

This study analyses the effects of cost-optimal deep renovation on peak power demand in Finnish apartment buildings. User power profiles for household equipment, lighting (Degefa 2012) and domestic hot water (DHW) (Koivuniemi 2005) were obtained from measured data of past studies. The space heating and ventilation energy demand profiles were generated using the IDA-ICE building performance simulation software (EQUA Simulation AB 2018), which is validated in several studies, such as (Moinard and Guyon 1999), (Travesi, et al. 2001), (Achermann and Zweifel 2003) and (Loutzenhiser, Manz and Maxwell 2007). The hourly net heating and electricity demand profiles were taken from a previous optimization study (Hirvonen et al. 2018). The optimization of the renovation measures was performed with the genetic algorithm NSGA-II, using the MOBO optimization tool (Palonen, Hamdy and Hasan 2013). A genetic algorithm is a heuristic method, where design variable values of good solutions are combined with each other over several iterations to find nearly-optimal solutions.

The hourly energy consumption of the buildings was simulated using the hourly weather data of Southern Finland (TRY2012), where 75% of Finnish building stock is located. The annual average air temperature is 5.6 °C and the annual solar insolation on a horizontal surface is 970 kWh/m$^2$ (Kalamees, et al. 2012). The heating degree day value for the studied climate zones (at indoor temperature of 17 °C) is 3952 Kd (Finnish Meteorological Institute 2018). Cooling demand in Finland is so low that cooling degree days are not reported. The specific monthly heating demands (spaces, ventilation and hot water) for the different apartment buildings are shown in Figure 1.

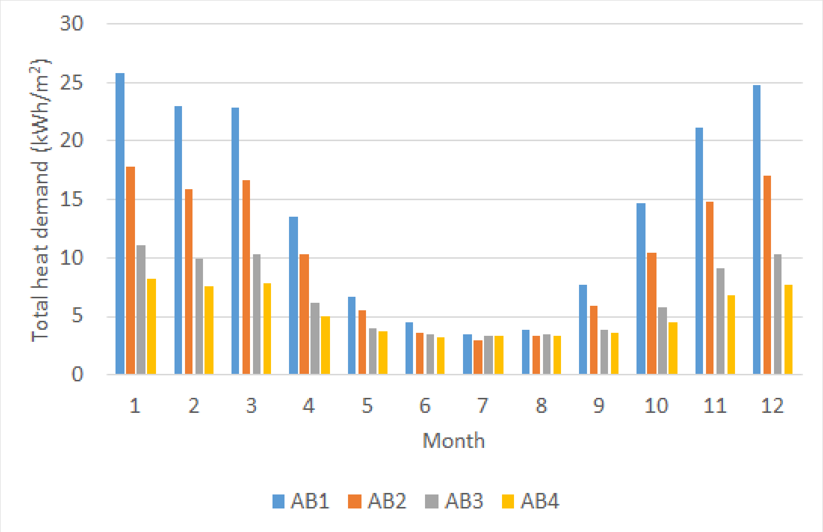


*Figure 1. Monthly heating demand in the studied apartment buildings.*

## 3. Studied cases

Four Finnish apartment buildings from different periods were analysed: AB1 represents buildings built before building energy performance requirements were codified in 1976, AB2 represents buildings built between 1976-2002 when only small changes to the energy performance requirements happened, AB3 represents buildings from a period of tighter regulations in 2002-2009 and AB4 represents the newest buildings built according to the efficiency standards of 2010. The reference case for all buildings utilized district heating (DH). Variable capacity exhaust air heat pumps (EAHP) and ground-source heat pumps (GSHP) were used as energy retrofit options. The heat pump part-load power was adjusted according to hourly demand. The backup system for EAHP was district heating and the backup system for GSHP was an electric boiler. Solar thermal systems were equipped with one day's worth of energy storage.

The renovation measures used in the optimized buildings were the installation of exhaust air or ground-source heat pump, solar thermal and solar electricity systems, DHW and ventilation heat recovery (HR) systems, as well as improving the thermal insulation level of the walls and roof, changing the windows to energy-efficient ones and the installation of demand-based ventilation systems (Figure 2). Multi-objective optimization of energy retrofits was performed in an earlier study (Hirvonen et al. 2018) and a few of the retrofitted building configurations were chosen for further analysis in this study. Two solutions were chosen from each set of Pareto optimal solutions: 1) a cost-effective solution that had no net change in life cycle cost (LCC) compared to the reference case (situation before renovation), 2) a higher cost solution with a life cycle cost halfway between the cost-optimal and most expensive solutions. The latter solution always had lower emissions due to more investment into energy saving measures. While costs were considered during the optimization phase, this study focuses only on the power analysis.

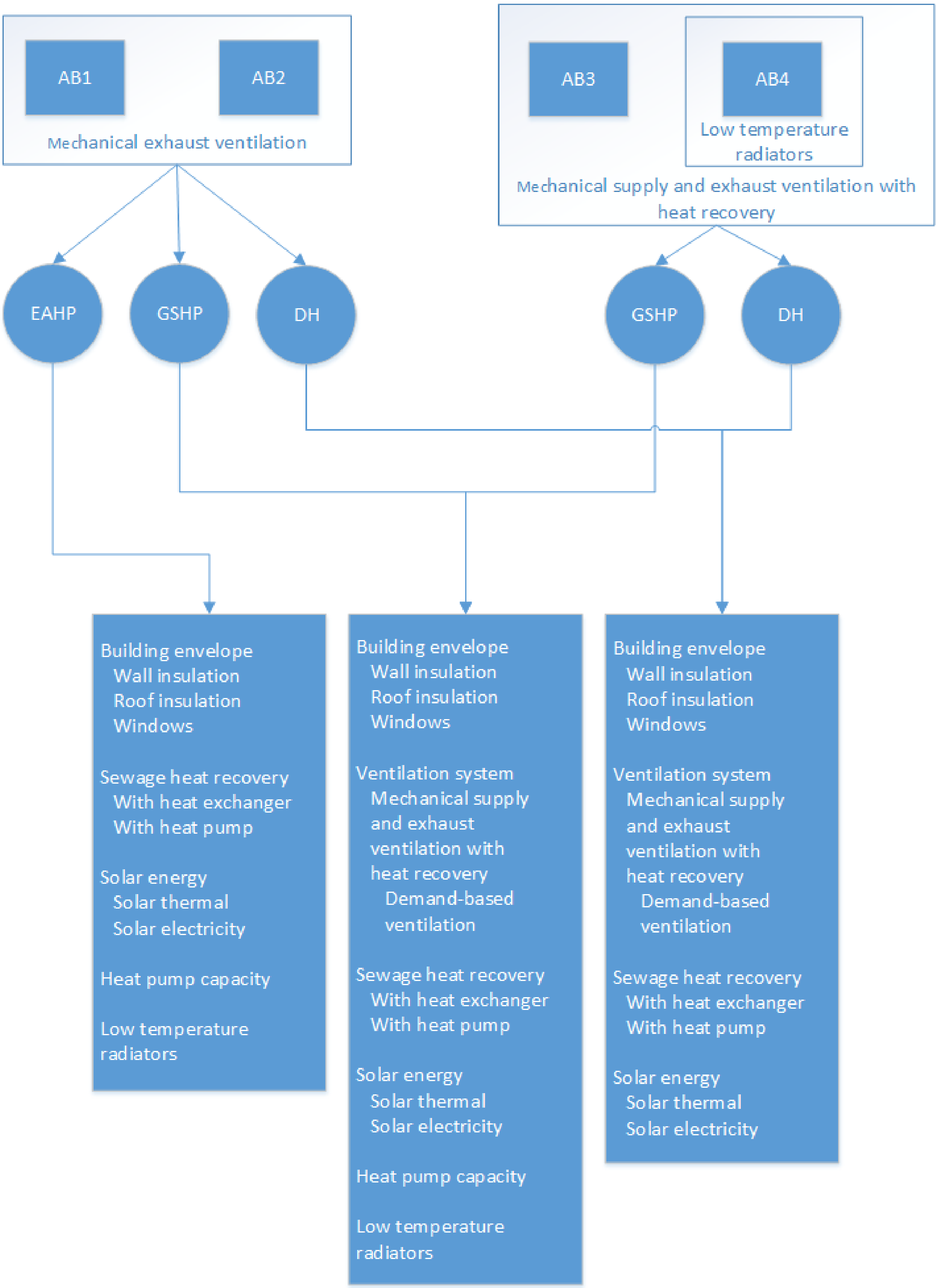


Figure 2. The four building types, their technical systems and the design variables for optimization.

Table 1 shows the emissions, costs and properties of the reference buildings and the optimized configurations defined in (Hirvonen et al. 2018). The chosen configurations marked with *c* represent lightly retrofitted systems that have the same LCC as the reference cases, while configurations marked with *b* are more heavily renovated cases with somewhat higher costs, but also lower emissions. Changes to U-value or power generation capacity have a straightforward effect on the power demand. The ventilation system could be changed to utilize demand-based ventilation (DBV), where ventilation rates are adjusted according to occupancy ratio, down to a minimum of 40% for not occupied spaces that still fulfils the requirements of the Finnish building code (Ministry of the Environment 2017). Two levels of sewage heat recovery (HR) were also considered: basic HR with only a heat exchanger, which reduced DHW demand by 30% and the HR with additional heat pump capacity, which reduced DHW demand by 70%, but also increased electricity consumption.

| | Emissions ($kg\text{-}CO_2/m^2/a$) | Emission reduction ($kg\text{-}CO_2/m^2/a$) | Relative reduction (%) | Reduction cost (€-LCC/ $kg\text{-}CO_2/a$) | LCC (€/$m^2$/25a) | Walls ($W/m^2K$) | Roof ($W/m^2K$) | Doors ($W/m^2K$) | Windows ($W/m^2K$) | ST ($m^2$) | PV ($kW_p$) | HP ($kW_{th}$) | Ventilation | Radiators (°C/°C) | Sewage HR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AB1 Ref | 34.4 | - | - | - | 400 | 0.81 | 0.47 | 2.2 | 1.7 | 0 | 0 | 0 | No HR | 70/40 | No HR |
| DH c | 24.7 | 9.7 | 28 | 0.07 | 400 | 0.81 | 0.08 | 2.2 | 0.7 | 55 | 30 | 0 | No HR | 70/40 | HR with HP |
| DH b | 16.0 | 18.4 | 54 | 3.21 | 459 | 0.36 | 0.08 | 2.2 | 0.8 | 55 | 30 | 0 | HR + DBV | 70/40 | HR |
| EAHP c | 10.9 | 23.5 | 68 | 0.07 | 401 | 0.23 | 0.1 | 1 | 0.8 | 0 | 40 | 35 | No HR | 70/40 | HR with HP |
| EAHP b | 9.3 | 25.1 | 73 | 2.06 | 451 | 0.13 | 0.06 | 0.7 | 0.6 | 75 | 30 | 39 | No HR | 70/40 | HR with HP |
| GSHP c | 7.0 | 27.4 | 80 | -0.10 | 397 | 0.36 | 0.08 | 0.7 | 0.7 | 60 | 35 | 110 | No HR | 45/35 | HR with HP |
| GSHP b | 5.5 | 28.9 | 84 | 2.70 | 478 | 0.23 | 0.1 | 0.7 | 0.8 | 0 | 35 | 115 | HR + DBV | 45/35 | HR |
| | | | | | | | | | | | | | | | |
| AB2 Ref | 25.7 | - | - | - | 283 | 0.34 | 0.26 | 1.4 | 1.7 | 0 | 0 | 0 | No HR | 70/40 | No HR |
| DH c | 16.2 | 9.2 | 36 | -0.01 | 283 | 0.34 | 0.26 | 0.7 | 1 | 100 | 25 | 0 | No HR | 70/40 | HR |
| DH b | 7.3 | 18.1 | 71 | 4.99 | 373 | 0.34 | 0.1 | 0.7 | 0.7 | 100 | 25 | 0 | HR + DBV | 70/40 | HR with HP |
| EAHP c | 10.4 | 15.0 | 59 | -0.04 | 282 | 0.34 | 0.26 | 0.7 | 0.6 | 35 | 45 | 25 | No HR | 70/40 | HR with HP |
| EAHP b | 9.1 | 16.3 | 64 | 4.54 | 357 | 0.34 | 0.1 | 0.7 | 0.6 | 125 | 30 | 25 | No HR | 45/35 | HR with HP |
| GSHP c | 4.7 | 20.7 | 82 | -0.04 | 282 | 0.34 | 0.26 | 1.4 | 0.7 | 25 | 35 | 35 | HR + DBV | 65/40 | HR with HP |
| GSHP b | 4.0 | 21.4 | 84 | 3.81 | 364 | 0.34 | 0.1 | 0.7 | 0.7 | 90 | 35 | 60 | HR + DBV | 45/35 | HR |
| | | | | | | | | | | | | | | | |
| AB3 Ref | 19.2 | - | - | - | 227 | 0.25 | 0.17 | 1.4 | 1.4 | 0 | 0 | 0 | HR | 70/40 | No HR |
| DH c | 11.3 | 7.7 | 41 | -0.25 | 225 | 0.25 | 0.07 | 1.4 | 1.4 | 50 | 15 | 0 | HR + DBV | 70/40 | HR |
| DH b | 9.1 | 10.0 | 52 | 8.20 | 308 | 0.25 | 0.06 | 0.7 | 1.4 | 95 | 15 | 0 | HR + DBV | 70/40 | HR with HP |
| GSHP c | 5.8 | 13.2 | 69 | 0.01 | 227 | 0.25 | 0.1 | 1.4 | 1.4 | 60 | 20 | 25 | HR + DBV | 70/40 | HR |
| GSHP b | 5.4 | 13.6 | 72 | 5.53 | 302 | 0.25 | 0.06 | 0.7 | 1.4 | 65 | 20 | 60 | HR + DBV | 45/35 | HR |
| | | | | | | | | | | | | | | | |
| AB4 Ref | 16.2 | - | - | - | 199 | 0.17 | 0.09 | 1 | 1 | 0 | 0 | 0 | HR | 45/35 | No HR |
| DH c | 9.4 | 6.8 | 42 | -0.05 | 199 | 0.17 | 0.09 | 1 | 1 | 45 | 15 | 0 | HR + DBV | 45/35 | HR |
| DH b | 7.3 | 8.9 | 55 | 9.88 | 287 | 0.17 | 0.06 | 0.7 | 1 | 95 | 15 | 0 | HR + DBV | 45/35 | HR with HP |
| GSHP c | 5.1 | 11.1 | 68 | -0.10 | 198 | 0.17 | 0.09 | 1 | 1 | 30 | 25 | 25 | HR + DBV | 45/35 | HR |
| GSHP b | 4.9 | 11.3 | 70 | 7.05 | 279 | 0.17 | 0.06 | 0.7 | 0.6 | 95 | 15 | 35 | HR + DBV | 45/35 | HR |

Table 1. The reference cases and optimized configurations (Hirvonen et al. 2018).

# 4. Results

## *4.1. Old building (pre-1976) - AB1*

### *4.1.1. District heating system*

Figure 3 shows the duration curves of hourly district heat and electricity power demand for three configurations of the oldest building type AB1 (built before 1976). The hourly heating power was lower in the optimized building configurations compared to the reference case throughout the whole year. The peak heating power demand was 20% lower for the lightly renovated case c and 42% lower for the more deeply renovated case b. While case c had higher total emissions than case b (Table 1), district heating demand still remained longer at zero in case c. This was because case c included sewage HR integrated with a heat pump, while case b only utilized a heat exchanger. Thus in case c, a larger fraction of DHW was covered by the HR and solar energy was more often able to cover the remaining demand.

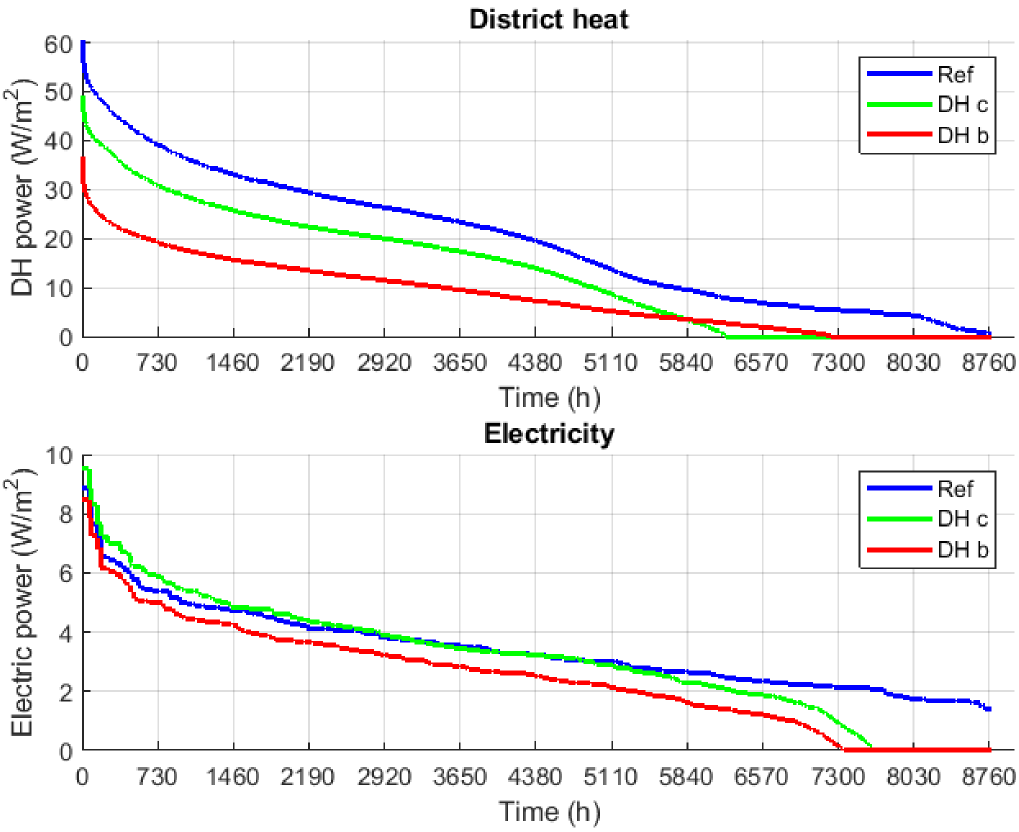


Figure 3. Duration curves of hourly district heating and electric power demand per heated net floor area for the three cases of the apartment building AB1 heated by district heating.

With electricity, the opposite happened and case b had more zero power hours than case c, which in turn had more hours with zero power demand than the reference case. This is due to the solar electric panels, which during daytime in summer could often cover all electricity demand. Outside the peak solar times, the reference case and case c used roughly the same amount of power. On average, solar power compensated for the increased demand from the sewage HR system. However, the peak electricity demand was 8% higher in case c than in the reference case. In case b the duration of the peak demand was similar to the reference case, but 4% lower.

Figure 4 shows the seasonal variation of the daily peak heating power in district heated building AB1, using an hourly time resolution. It shows a clear reduction in the district heating power demand according to the level of retrofits done. The general shape of peaks is the same, but peak power demand is lowered, along with the average energy demand. Only case c had days when there was no district heating demand, due to sewage heat recovery. Even with solar thermal energy, case b always needed some district heating support to cover all DHW loads.

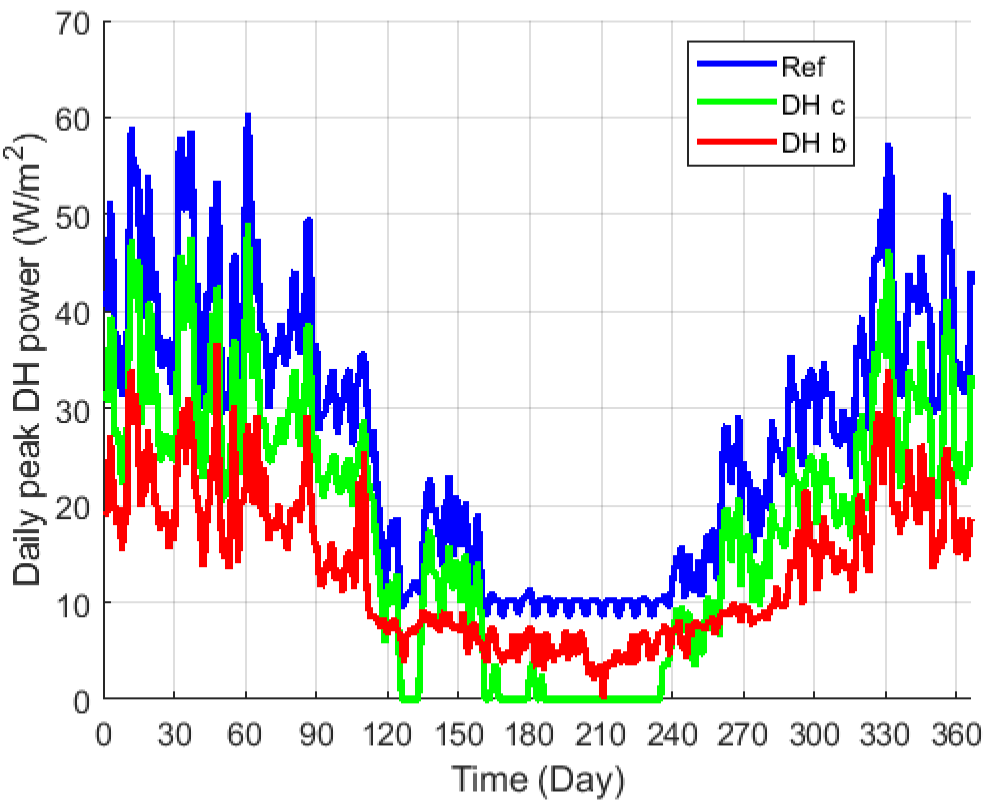


Figure 4. Daily peak hour district heating power per heated net floor area in the apartment building AB1.

Figure 5 shows electricity demand of the peak hour for each day in AB1. The hourly lighting and equipment profiles were determined separately for each of the four seasons, which explains the sudden changes in base power demand. The peak electricity demand was higher in case c than in the reference case because of the electricity needed by sewage HR with a heat pump. The peak values were lower for case b, which utilized demand based ventilation and thus had lower HVAC system electricity consumption.

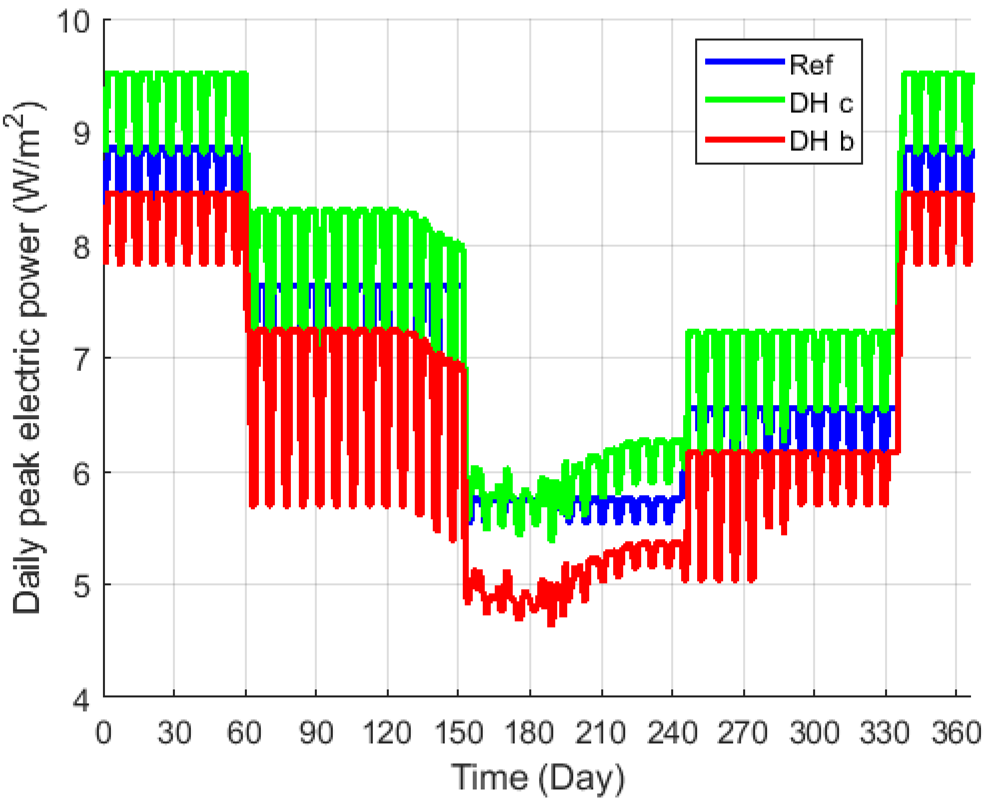


Figure 5. Daily peak hour electric power per heated net floor area in the apartment building AB1 cases with district heating.

#### *4.1.2. Ground-source heat pump system*

Replacing the district heating system with a ground-source heat pump system causes a large increase in electric power demand. The daily peak power curves for the two GSHP cases of AB1 are shown in Figure 6, along with the DH cases. The daily variance in peak power became significant as during winter, the peak electric power could change from 13 W/m$^2$ on one day to 23 W/m$^2$ on another. As shown in Table 1, the annual $CO_2$ emissions of the GSHP system were much lower than those of the DH system. The emission calculation (Hirvonen et al. 2018) was based on monthly constant emission factors for electricity (Finnish Energy 2017), which means that hourly or daily changes in the power grid's average emissions were not taken into account. This may not be important on a single building scale, but if a large fraction of district heated buildings convert into electric heating it will start to affect the national electric grid. A high peak demand will increase the use of $CO_2$-intensive peak generation plants, which increases marginal emissions and negates some of the benefits of switching to electrified heating. Thus, it is important to find ways to smoothen the power demand curve.

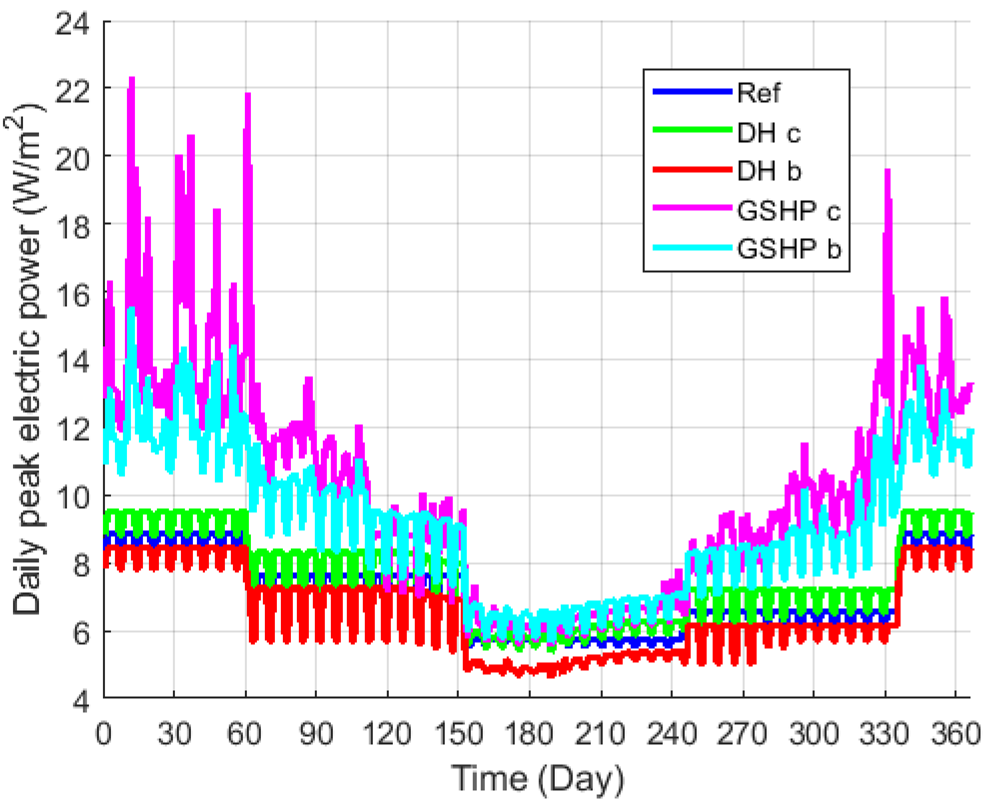


Figure 6. Daily peak hour electric power per heated floor area for apartment building AB1 with ground-source heat pump and district heating.

### *4.2. New building (post-2010) - AB4*

#### *4.2.1. District heating system*

Out of the analysed building age classes, AB4 was the newest one. This building type was very energy efficient even before energy renovations. Regardless, in the DH case with energy retrofits, the peak power demand was lowered further by 19 to 38% and the annual emission by 42 to 55% (Table 1). Figure 7 shows the duration curves of the power demand in the district heated cases of AB4.

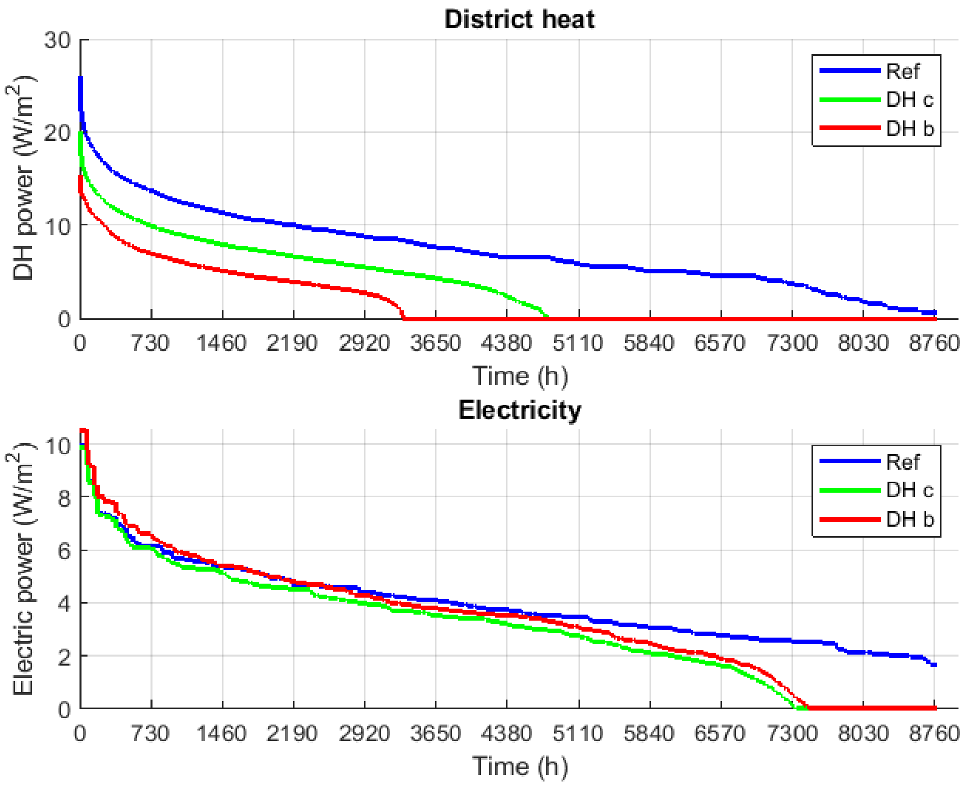


Figure 7. Duration curves of district heating and electric power demand per heated net floor area for the three cases of apartment building AB4 with district heating.

The effect of the retrofits was great. In case c, the DH power was at zero 45% of the time and in case b this happened 64% of the time. The significant changes compared to the reference case were the use of demand-based ventilation (DBV) and sewage heat recovery as well as the installation of both solar electric and solar thermal systems (Table 1). In case b the solar thermal capacity was doubled compared to case c and the sewage heat recovery was enhanced with a heat pump. The peak heat demand was reduced from 25 W/m$^2$ (reference case) to 20 W/m$^2$ (case c) and to 15 W/m$^2$ (case b). Demand-based ventilation reduced ventilation rates in the basement, stairwells and unoccupied living spaces by 60%, generating significantly lower demand for heating. Because of the good level of thermal insulation and ventilation heat recovery, most of the heating demand in AB4 originated from DHW. Thus, sewage heat recovery had a significant effect on heating power demand.

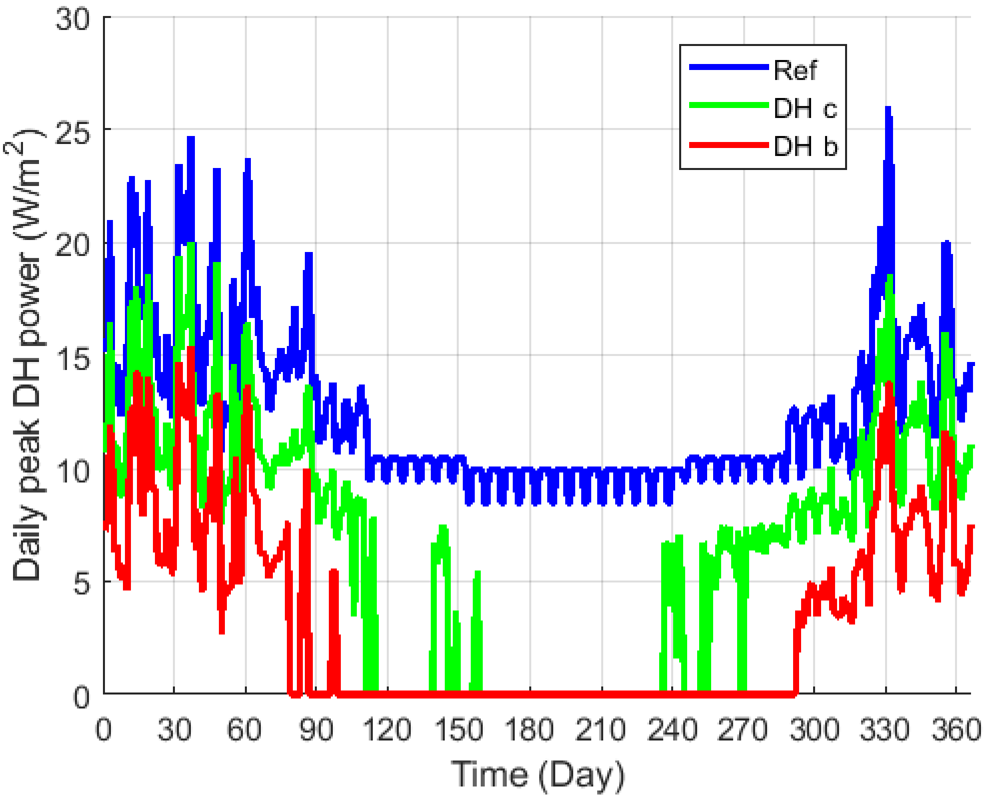


Figure 8. Daily peak hour district heating power per heated net floor area in apartment building AB4.

Figure 8 shows the daily peak district heating power for the whole year. The district heating demand of the cases b and c were zero around summer. Especially in the case b, solar energy covered all heating needs remaining after heat recovery systems for most of the year. Despite the lower base level demand, the peaks caused by low outdoor temperatures did not disappear through energy retrofits, though they were clearly lower in both the optimized cases than in the reference case.

With respect to electricity, the change was smaller. The effect of solar electricity is evident on the lower side of the demand curve, where solar energy sometimes reduced electricity demand to zero. Above the middle of the curve, the electricity demand in case c does not differ from the reference, while it is increased in case b, due to the sewage heat recovery system's electricity requirements.

Figure 9 shows the daily peak electricity consumption in the three district heated AB4 cases. Both the peak and base levels were about 1 W/m$^2$ higher than in AB1, due to the use of the mechanical supply-exhaust ventilation and heat recovery. Otherwise the profile is quite similar to the one in the older building. Solar electricity only reduced daily peak power during summer.

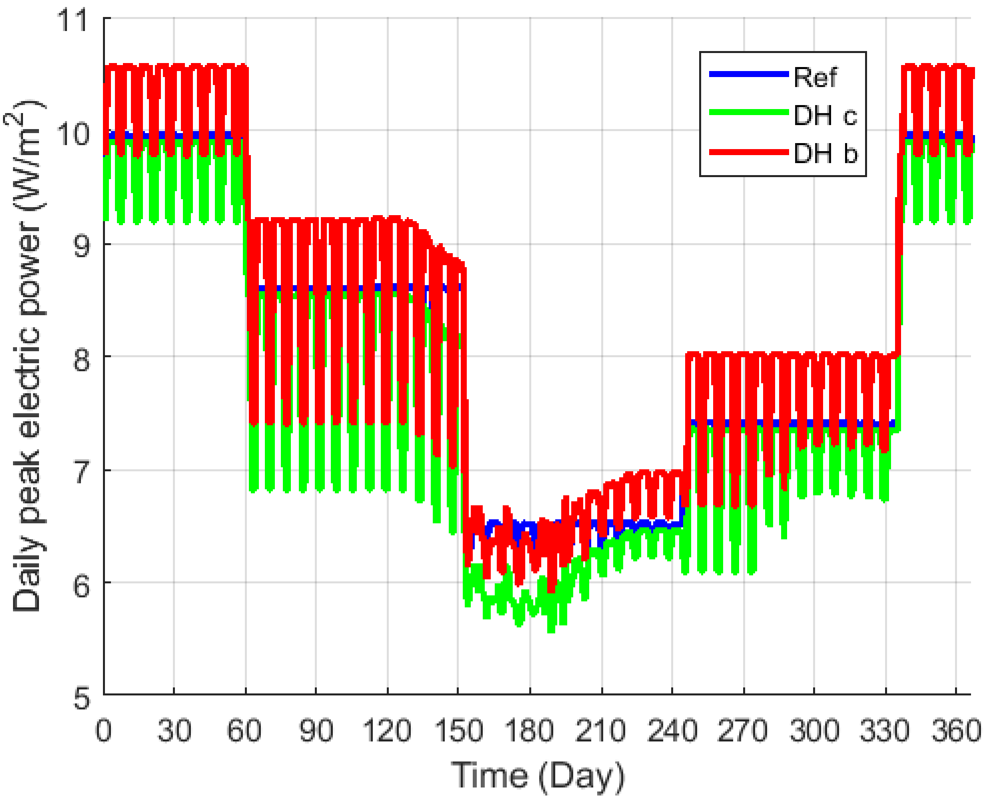


Figure 9. Daily peak hour electric power per heated net floor area in apartment building AB4.

### *4.2.2. Ground-source heat pump system*

Figure 10 shows the hourly peak electric power demand for each day of the year for apartment building AB4 in both the DH and GSHP cases. Peak demand in winter for case GSHP c was 17 W/m$^2$, while it was below 15 W/m$^2$ for case GSHP b.

During summer, AB4 GSHP c had spiking power demand compared to the reference DH case. While there was no space heating demand, the DHW demand required running the heat pump, thus increasing peak electricity demand. In the case AB4 GSHP b, a greatly increased amount of solar thermal collectors was used (95 m$^2$ in case b vs 30 m$^2$ in case c), which reduced the need for heat pump operation. The use of demand-based ventilation reduced peak electricity demand in all retrofitted cases. Solar electricity also reduced peak demand during summer in case GSHP b.

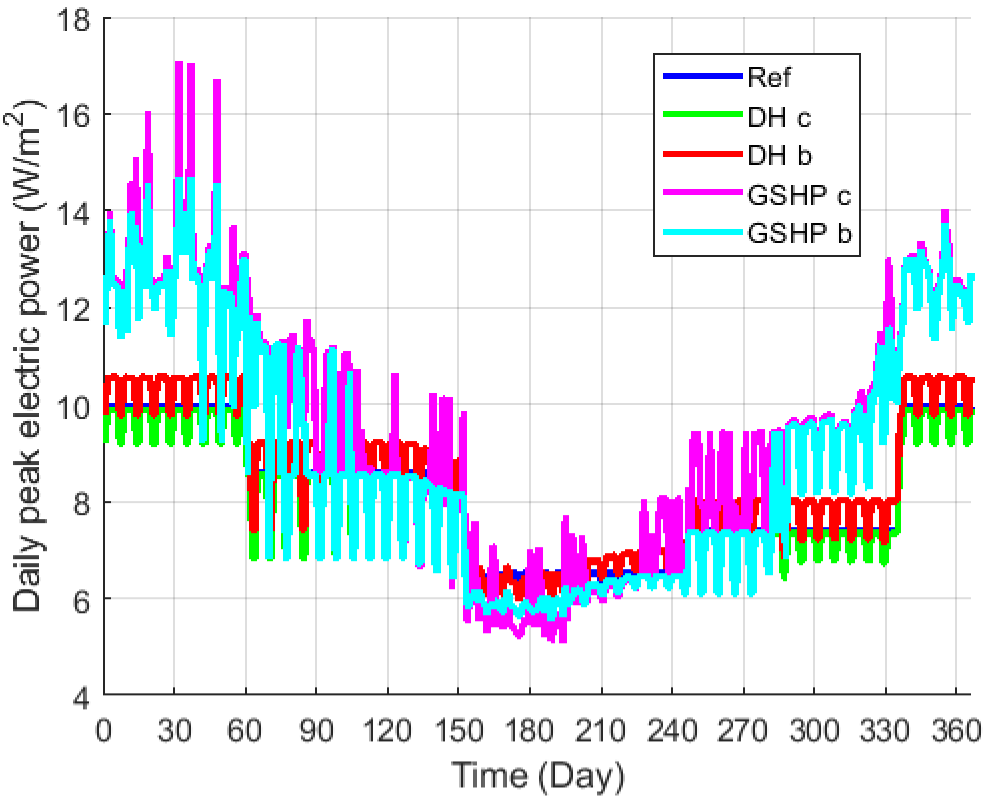


Figure 10. Daily peak hour electric power per heated floor area for apartment building AB4 with ground-source heat pump and district heating.

### *4.3. Summary of power consumption changes*

The main heating system for the reference building of all age classes was district heating. The renovation measures used in the optimized buildings were the installation of exhaust air or ground-source heat pump, solar energy and DHW and/or ventilation heat recovery systems as well as adding thermal insulation to the walls and roof, changing the windows to energy-efficient ones and the installation of demand-based ventilation systems (Table 1).

Figure 11 shows the range of district heating power demand for all the reference cases and the optimally retrofitted buildings. The values are shown for January and July, which represent high and low emission months of the energy system in Finland, according to average monthly emissions of the Finnish electric grid in years 2011-2015

(Finnish Energy 2017). The red lines indicate the median power, while the boxes show where 50% of the hourly power demand lies. Extreme values (peak and minimum power) are indicated by the dashed lines.

The tightening of building energy performance requirements is seen in the January plot of Figure 11, as the peak and median powers in the reference buildings go steadily down from AB1 to AB4. The differences between different retrofit levels are also clearly shown, as both the peak and median powers go down significantly, especially in the case of AB1 and AB2 (Figure 11). In the district heated AB1 case, the peak heating power goes from 59 W/m$^2$ in the reference, to 47 W/m$^2$ in AB1 DH c and to 34 W/m$^2$ in AB1 DH b. Even with the more significant improvements of case b, the peak power was not reduced to the level of the newer reference buildings AB3 and AB4. However, with AB2 DH cases the advanced retrofit could bring the peak heating power even below the retrofitted AB3 cases. The district heating peak and median power demand was reduced further by the use of exhaust air heat pumps, with peak DH power reducing to 27 W/m$^2$ in AB1 EAHP c and to 24 W/m$^2$ in AB1 EAHP b. However, the use of EAHP caused a corresponding increase in electricity demand.

During July, district heating demand went to zero in all optimized exhaust air heat pump cases and even in the optimal district heated cases of AB2, AB3 and AB4. Solar thermal energy, supported by sewage heat recovery and heat pumps was able to meet all DHW demand in summer. The great difference between heating power demand in January and July highlights the fact that in the Nordic conditions solar energy provides no benefit against space heating demand in winter

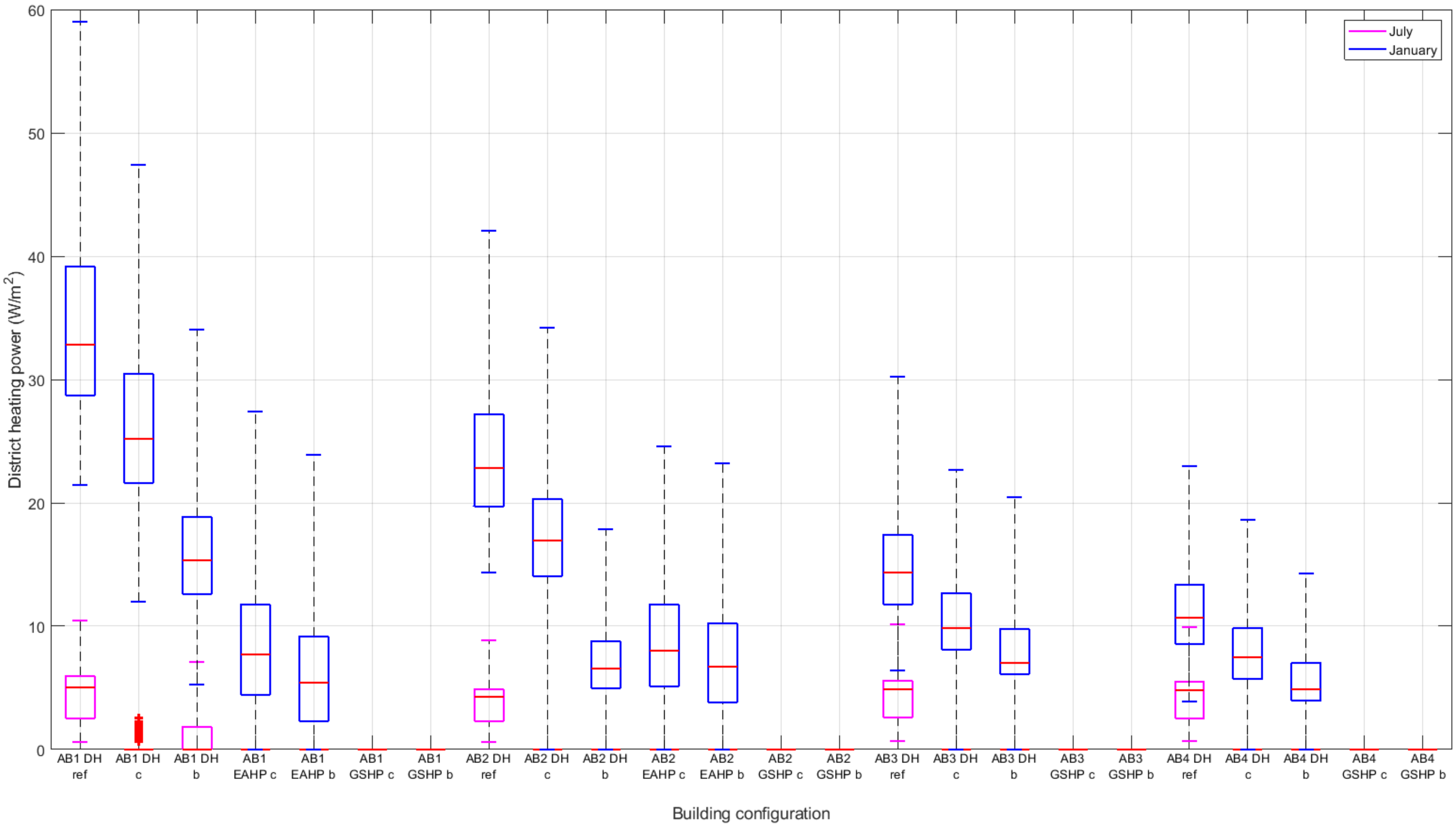


Figure 11. Boxplot of distribution of hourly DH power demand in all the reference and optimized cases. Results are shown for July and January, which represent months with low and high emissions.

Figure 12 shows the electricity power demand levels for all the cases in January and July. The key point to note is the rise of the peak electric power demand when heating systems are electrified. In January, the peak power rose significantly as DH was changed into EAHP or GSHP. In the EAHP cases the rise in maximum power was limited by the air exchange rate in the buildings, but in the GSHP cases the electricity peak demand increased by more than 100% in AB1, AB2 and AB3. The median power also rose as the heating system was changed, but the change was smaller than with peak power. In the GSHP systems the common range of power demand also increased, as indicated by the larger boxes, which contain 50% of all power values. In AB2 GSHP cases, both the peak and median power levels were even lower than in AB3, and partially lower than in AB4 because of very extensive retrofits, which in some portions exceeded those in the newer buildings. The retrofitted ventilation heat recovery systems had a higher efficiency of 72% compared to the existing HR systems in AB3 and AB4, which had efficiencies of 60% and 65%, respectively.

During July, the differences in electricity power consumption were small, even when district heating was switched to ground-source heat pumps. Summertime DHW demand was mostly met by solar thermal energy. All retrofitted buildings also included solar panels, which reduced the need for imported electricity and lowered the power demand to zero during some parts of the summer months.

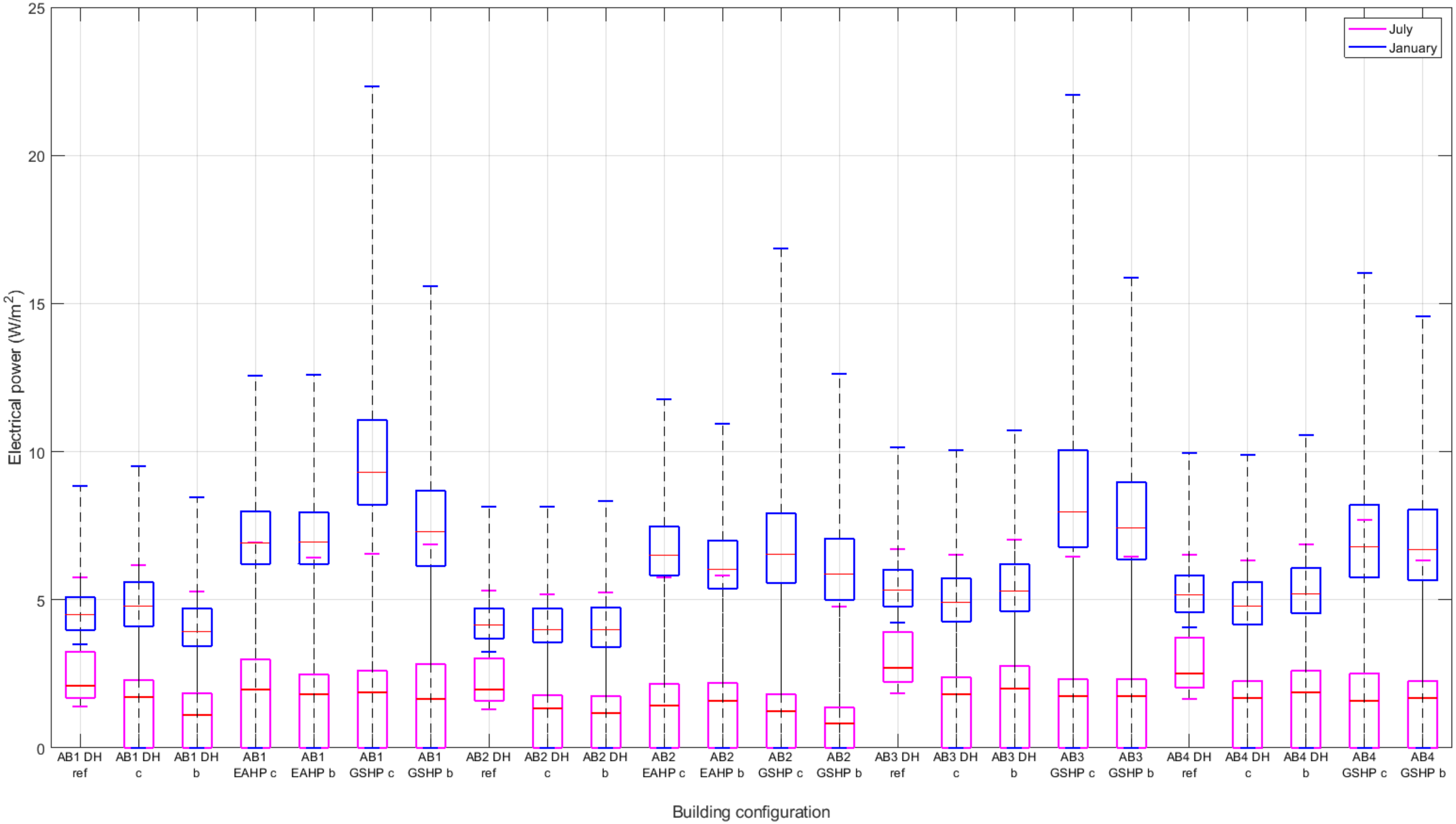


Figure 12. Boxplot of distribution of hourly electric power demand in all the reference and optimized cases. Results are shown for July and January, which represent months with low and high emissions.

Table 2 summarizes the changes in energy and hourly peak power demand in all the optimal cases compared to their reference cases. It shows that in the DH and EAHP cases the total district heating energy demand was lowered more than peak heating power. In the district heated cases the reduction in the peak power was 11 to 33% less than the change in energy demand. This means that while the peaks were lower than before in absolute terms, they were relatively higher compared to the average power demand. This could be a problem for utilities, which generally prefer stable energy demand to variable demand. Conversely, in the GSHP cases the peak electric power rose more than the energy demand, posing a similar problem. This differed from the EAHP case, where the total electric energy consumption rose more than the peak power, because the EAHP system’s power was limited by the ventilation air flow and heating peaks were covered by DH. Thus, the EAHP had lower maximum power and ran a larger fraction of the time on full power than the GSHP systems.

Table 2. Relative change in energy consumption and peak power demand for retrofitted buildings compared to their reference cases.

| | District heating energy change (%) | | District heating peak power change (%) | | Electricity energy change (%) | | Electricity peak power change (%) | |
|---|---|---|---|---|---|---|---|---|
| **Case** | **January** | **July** | **January** | **July** | **January** | **July** | **January** | **July** |
| Ref: AB1 DH | | | | | | | | |
| AB1 DH - c | -22.2 | -99.3 | -19.7 | -75.5 | 5.1 | -31.2 | 7.6 | 7.4 |
| AB1 DH - b | -53.1 | -76.0 | -42.4 | -32.1 | -11.0 | -51.6 | -4.4 | -8.4 |
| AB1 EAHP - c | -74.5 | -100 | -53.6 | -100 | 52.4 | -20.4 | 41.9 | 20.8 |
| AB1 EAHP - b | -81.2 | -100 | -59.6 | -100 | 53.3 | -26.6 | 42.5 | 11.5 |
| AB1 GSHP - c | -100 | -100 | -100 | -100 | 107.7 | -26.1 | 152.5 | 14.1 |
| AB1 GSHP - b | -100 | -100 | -100 | -100 | 58.6 | -24.2 | 76.1 | 19.2 |
| | | | | | | | | |
| Ref: AB2 DH | | | | | | | | |
| AB2 DH - c | -26.4 | -100 | -18.7 | -100 | -3.5 | -44.7 | 0.0 | -2.1 |
| AB2 DH - b | -70.0 | -100 | -57.5 | -100 | -5.0 | -48.0 | 2.3 | -1.1 |
| AB2 EAHP - c | -62.3 | -100 | -41.6 | -100 | 52.6 | -41.5 | 44.4 | 8.4 |
| AB2 EAHP - b | -68.3 | -100 | -44.8 | -100 | 43.1 | -35.8 | 34.4 | 9.7 |
| AB2 GSHP - c | -100 | -100 | -100 | -100 | 57.7 | -46.1 | 106.8 | 4.6 |
| AB2 GSHP - b | -100 | -100 | -100 | -100 | 38.7 | -58.5 | 55.0 | -10.4 |
| | | | | | | | | |
| Ref: AB3 DH | | | | | | | | |
| AB3 DH - c | -28.5 | -100 | -24.9 | -100 | -7.1 | -45.3 | -0.8 | -2.9 |
| AB3 DH - b | -44.9 | -100 | -32.4 | -100 | -0.4 | -38.0 | 5.8 | 4.7 |
| AB3 GSHP - c | -100 | -100 | -100 | -100 | 53.5 | -48.2 | 117.4 | -3.5 |
| AB3 GSHP - b | -100 | -100 | -100 | -100 | 39.3 | -48.3 | 56.5 | -3.5 |
| | | | | | | | | |
| Ref: AB4 DH | | | | | | | | |
| AB4 DH - c | -28.1 | -100 | -18.9 | -100 | -6.4 | -45.2 | -0.6 | -2.7 |
| AB4 DH - b | -49.1 | -100 | -37.9 | -100 | 0.5 | -37.7 | 6.1 | 5.1 |
| AB4 GSHP - c | -100 | -100 | -100 | -100 | 32.3 | -45.5 | 61.1 | 18.2 |
| AB4 GSHP - b | -100 | -100 | -100 | -100 | 30.1 | -45.2 | 46.3 | -2.7 |

### *3.4 Peak shaving*

It was shown that peak demand of electricity is increased significantly by the use of electrified heating. Thus, it should be estimated how easy it would be to reduce the peak demand through measures such as energy storage and demand response. Figure 13 shows the total heating power demand with space heating and DHW for the case AB1

GSHP c, during the peak demand day in January. To avoid the peak demand, the heat pump could be used pre-emptively to store energy into a storage tank or building thermal mass. In this case, the peak heat demand was 38 W/m$^2$, while the average heat demand was 37% lower, only 24 W/m$^2$. If the heat pump was sized to lower than full capacity, the peak demand would need to be covered by stored heat that was accumulated in a hot water tank before the peak. Figure 13 shows the actual heat demand compared to constant power demand in cases where the heat pump is sized to 75% or 50% of the peak demand. The storage starts in a fully charged state and is completely drained at the end of the day.

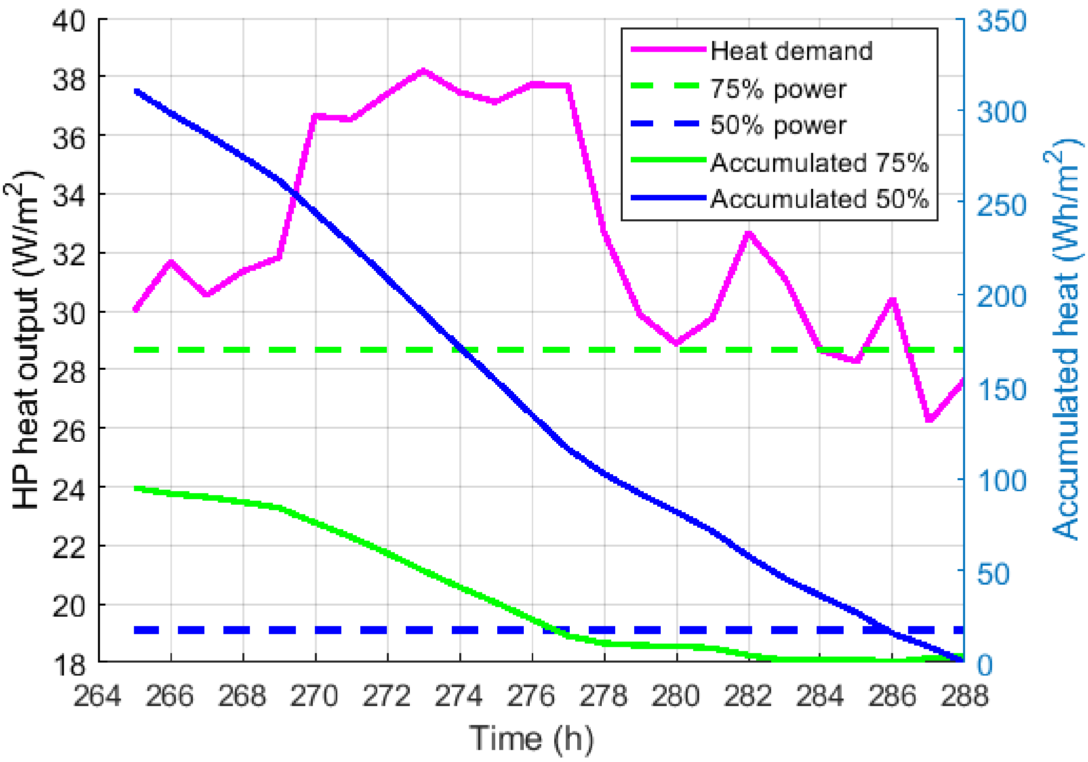


Figure 13. Heat generation by heat pumps in the case AB1 GSHP c. Also shown are two levels of constant power generation and the net energy accumulation assuming the use of energy storage.

Using thermal storage and undersized heat pumps, the peak power demand could be reduced. Sizing the GSHP to 75% of peak load (29 W/m$^2$) required 95 Wh/m$^2$ of supporting storage capacity, which in AB1 would translate to 8.2 m$^3$ or 2.0 L/m$^2$ of water volume (assuming a ΔT of 40 °C). With 50% sizing (19 W/m$^2$) the required storage would be 311 Wh/m$^2$, 27 m$^3$ or 6.7 L/m$^2$. Other methods to lower the peak demand could also be used, such as thermal storage into the building thermal mass or lowering the space heating power during DHW demand peaks. The electric power demand could also be reduced by improving the COP of the heat pump through the use of seasonal borehole thermal energy storage (Hirvonen & Sirén, 2017).

When the building thermal mass is used for energy storage, the tradeoff is necessarily a loss of thermal comfort. The larger temperature perturbations are allowed, the larger the storage capacity. However, the thermal inertia of the building means that such a storage method cannot react to fast changes in thermal loads. It may not be possible to use all available storage capacity if overheating is to be avoided. Next, a simple calculation of the thermal mass potential is presented. A more detailed examination of this specific issue was shown in (Alimohammadisagvand et al. 2017).

If thermal comfort conditions are reasonably relaxed, the indoor air temperature could vary, for example, from 20 °C to 24 °C, allowing the thermal mass of the building to be used as storage. As an example, Table 3 shows the energy storage potential in the thermal mass of the building envelope and the room air itself, compared to tank storage in the case of AB1 with 50% GSHP sizing. The change in the temperature of the building mass would be limited by the air temperature and thus a 3 °C temperature difference was assumed. The air itself couldn't provide significant storage capacity due to its low heat capacity. However, heating up the active thermal mass of the building by 3 degrees could cover 20% of the required energy storage to reduce power consumption during peak demand. Thus, there is potential to reduce the hourly power demand of heating even without using large hot water tanks. However, if the heat pump capacity is close to the base heating demand, there may not be extra capacity available to charge any storage system. In addition, if the demand peak lasts for several days, shaving the peak demand during consecutive days becomes harder.

Table 3. Thermal mass comparison for demand flexibility assessment using the properties of AB1.

| | **Tank (Water)** | **Room air (Air)** | **Building envelope (Brick)** | |
|---|---|---|---|---|
| Specific heat capacity | 4190 | 718 | 1000 | J/(kgK) |
| Density | 1000 | 1.22 | 1500 | kg/m$^3$ |
| Volume | 27 | 10 000 | 200 | m$^3$ |
| Heat capacity | 113 | 8.8 | 300 | MJ/K |
| Temperature change | 40 | 4 | 3 | K |
| Stored energy | 310 | 2.4 | 62 | Wh/m$^2$ |
| Fraction of demand met | 100 | 0.77 | 20 | % |

## 5. Discussion

In a previous study, the greatest reductions in building emissions were obtained by converting district heating systems into ground-source heat pump systems (Hirvonen et al. 2018). This change into electrified heating was now found to increase peak electric power demand by 50 to 150% compared to district heated buildings. In the scale of a single building this poses no problems, but if such a change was widespread, this would significantly increase the national peak electricity usage as well. Much of the emission benefits of HP utilization relies on the lower average emission factor of electricity compared to district heating in Finland and the emission benefits are sensitive to changes in the electricity generation mix. High electric heating intake would necessarily increase both base and peak power demand and drive more demand to the margin, where emissions are much higher than on average. Such a change could negate much of the emission reductions caused by heat pumps. In principle, local biomass boilers or centralized biomass peaker plants could be used to bring down emissions during peaks, because biomass is considered emission free within the EU emission trading system. However, the carbon neutrality of biomass can be disputed (Schulze, et al. 2012) and Finland already utilizes large amounts of biomass in energy generation, raising the question of whether biomass use can be sustainably increased (Natural Resources Institute Finland 2018).

For the electrified heating to bring the expected benefits, significant effort must be undertaken to bring down the peak demand and operate heat pumps in a more stable manner, using intelligent demand response control and energy storage. Hourly emission factors should be utilized for more accurate estimates of the emission effects. The future development of district heating should also be considered, as the use of the DH grid also depends on the electricity markets. Changes in electricity price could reduce combined heat and power production or increase the use of large-scale heat pumps (Helin et al. 2018b).

## 6. Conclusions

To reach the emission reduction targets of the European Union, the revised Energy Performance of Buildings Directive requires member states to present a road map on how to achieve deep renovation of buildings. In this study, we examined how optimized energy retrofits of Finnish apartment buildings reduced energy demand and the peak power demand of both heating and electricity. The analysis was done for buildings of four age classes and three heating systems. The reduction in peak power after retrofits was always less than the corresponding reduction in energy use. In district heated buildings, the heating energy demand during the peak month was reduced by up to 53, 70, 45 and 49% after the energy renovations, for buildings AB1, AB2, AB3 and AB4, respectively. At the same time, the peak heating power demand was reduced by only 42, 58, 32 and 38%, respectively. Thus, retrofitted buildings have relatively higher variability between the peak and base level demand. This is a challenge for energy utilities, as a greater fraction of their energy generation portfolio will have to be peak power plants with a lower capacity factor.

Electricity demand was increased as district heating was switched to exhaust air or ground-source heat pumps. With EAHP, the increase in peak electric power demand was 44% and with GSHP it was up to 153%. With a significant uptake of heat pumps, this will require the expansion of low emission electricity generation capacity in the national grid. If the power is to be produced by variable energy source, more focus must also be given to demand response services, energy storage and transmission line development.

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