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Residential buildings with heat pumps peak power reduction with high performance insulation

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Abstract. Revised EPBD directive has set ambitious targets for nearly zero energy buildings. In residential buildings, energy performance can be improved mainly by applying better insulation of building fabric and by efficient energy sources, i.e. heat pumps. Electricity use and peak powers will increase when heat pumps, both air to water and ground source heat pumps, are used for heat source in new residential buildings compared to heating solutions that do not use electricity. The purpose of this study was to determine how much the high performance thermal insulation can compensate the increase of electricity use and peak power caused by extensive application of heat pumps in Finland residential buildings. The present study used five residential buildings that describe residential newbuild market. Finnish regulation defines minimum insulation level and high performance insulation level which were applied to single family houses, terraced house and apartment buildings to simulate electric power values all year round. Hourly electrical power values were simulated with dynamic simulation software IDA ICE. Results show that electricity use and peak powers are rising significantly when heat pumps are used, but better insulation level significantly decreases or even fully compensates the amount of additional electric power. The results can be used for the assesment of implications of extensive use of heat pumps to power grid.

Nomenclature

EPBD	Energy Performance of Buildings Directive
RF	reference values
HPI	high performance insulation values
SFH	single family house
TH	terraced house
AP	apartment building
AWHP	air to water heat pump
GSHP	ground source heat pump
DH	district heating

1 Introduction

It is common to use heat pumps as heat sources in single family and terraced houses. Heat pumps are also increasingly used in apartment buildings. Using heat pumps for main heat source helps to compliance with energy efficiency requirements.

The power and efficiency of air to water heat pumps decreases as the outdoor temperature decreases. Peak power is generally covered by an additional electric heater. As a result, power consumption increases significantly at low outdoor temperatures. Extensive installation of heat pumps can affect the operation of the electricity grid by generating an additional and unstable demand for electricity. Hourly power demand generated by heat pumps has been studied in [1] for renovated apartment buildings where switching from district heating to ground-source heat pumps was found to be an effective renovation solution in order to reduce emissions under current energy mix, but on the other hand this resulted in increased hourly peak electricity demand up to 153%. Ground source heat pump was found to be one of the most cost-effective renovation measure in old apartment buildings [2].

The aim of this study was to find out the effect of application of heat pumps in new residential buildings on the hourly electricity power demand. Installation of ground source and air to water heat pumps were compared at two insulation level and in apartment builidngs also against the district heating. It was especially analysed how much the high performance insulation defined in the Finnish regulation [3] would allow to compensate the peak power effect of heat pumps compared to minimum insulation corresponding to the reference values. Five residential reference buildings were used in hourly energy simulations.

2 Methods

The energy demand of a building was calculated using the standard use of the building according to the calculation method in Finnish regulations [3].

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The coefficient of performance (COP) and HP heating power was calculated for AWHP based on the outdoor temperature. GSHP COP and heat power were constant.

Need for additional electric power was calculated for new buildings. In the scenario analyses, for the construction volume of residential newbuild the following annual estimate was used for the next ten years:

- 7 000 single family detached houses with average size of 112 m^2,
- 3 500 row house dwelling units with average size of 71.4 m^2,
- 25 000 dwelling units in apartment buildings with average size of 55.8 m^2.

This estimate is based on the average construction volume of recent years published in [4]. The average size of dwelling units of 2018 was used according to statistics of Finland [5].

2.1 Weather data

Energy consumption calculations are performed using the Helsinki-Vantaa test reference year.

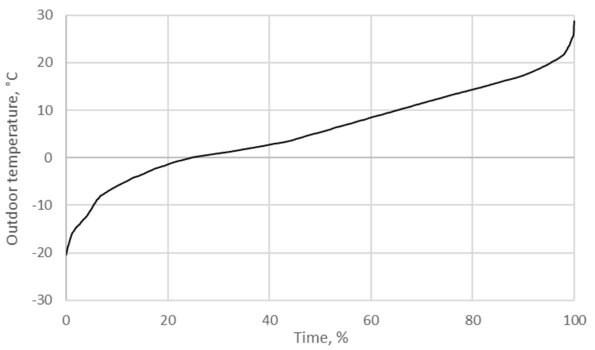


Fig. 1. Hourly mean outdoor temperature duration curve. Data from Helsinki-Vantaa TRY.

Design temperature for heating sizing was -26°C. Annual heating degree days at t_i=17°C 3952°C·d. The Finnish building code does not take into account the internal heat gains to estimate the design heat load.

2.1 Reference buildings and heating solutions

Three types of residential buildings were studied in order to cover all typical new residential buildings. Single family houses were represented by one small single storey and one two storey house. Similarly, apartment buildings were represented with one smaller and one large building.
The last reference building was a terraced house Overview of the specifications of the buildings is given in Tables 1, 2 and 3.

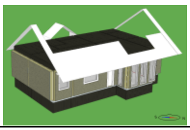
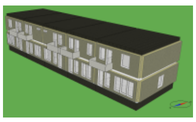
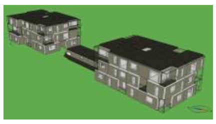
Table 2. Technical data

	Single family and terraced houses	Apartment buildings
Heat recovery ventilation supply air reheating coil type	electric	electric
Supply air temperature, °C	18	18
Room heating system type	underfloor heating	radiators
Heating curve, °C/°C	40/33	45/35
Heating set point, °C	21	21

Table 3. Finnish reference and high performance insulation U-values [3] and other input data

	Single family and terraced houses		Apartment buildings	
	RF	HPI	RF	HPI
External wall, W/(m^2·K)	0.17	0.12	0.17	0.14
Roof, W/(m^2·K)	0.09	0.07	0.09	0.07
External floor, W/(m^2·K)	0.17	0.1	0.17	0.1
Window and door, W/(m^2·K)	1.0	0.7	1.0	0.7
Window Solar factor	0.55	0.46	0.55	0.46
Air leakage rate q_{50}, m^3/(h·m^2)	4.0	0.6	2.0	0.6
Ventilation rate, l/(s·m^2)	0.4	0.4	0.4	0.4
Heat recovery temperature ratio	75%	80%	75%	80%
Heat recovery annual efficiency	70%	73%	70%	73%
SFP, kW/(m^3/s)	2.0	1.5	2.0	1.5

Table 1. Specifications overview of the studied buildings.

Building	SFH1	SFH2	TH	AP1	AP2
3D view of the building model in IDA-ICE					
No of stories, -	1	2	2	4	5
Net floor area, m^2	100.2	176.1	506.7	1670.7	5203.2
Heater floor area, m^2	100.2	176	506.7	1670.7	5203.2
Net cubature, m^3	270.5	455.4	1317.9	4532.1	16608.9
Envelope area, m^2	325.6	401.2	907.7	2879.8	5874.1
$A_{envelope}/V_{net}$, m^{-1}	1.20	0.88	0.69	0.64	0.35
WFR, %	19.2	25.8	18.7	25.1	23.6
WWR, %	17.3	21.9	24.7	30.4	39.0

2.2 Simulations

Dynamic simulations are used to calculate the energy use of the building. The indoor climate and energy simulation program IDA-ICE 4.8 was used for the energy simulations.

Table 4. Standard use of the building [3]

	Single family and terraced houses	Apartment buildings
Occupant, m²/per	42.5	28.3
Usage	0.6	0.6
Lights, W/m²	6	9
Light schedule	0.1	0.1
Equipment, W/m²	3	4
Equipment scedule	0.6	0.6
Ventilation schedule	1.0	1.0

Heat pump and additional top-up heating element electricity consumption were calculated with postprocessing in Excel.

2.3 Heat pump COP and heating power

Air to water heat pump COP and heat output depends on the outdoor temperature. Depending on the heating system type the supply flow temperatures at design outdoor temperature were the following:
- underfloor heating 40°C,
- radiators 45°C,
- domestic hot water 55°C.

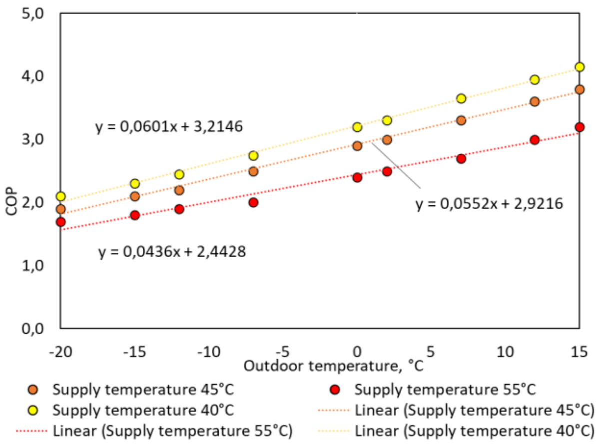


Fig. 2. AWHP COP equations as a function of outdoor temperature and heating curve

For the air to water heat pump a product specific performance map data was formalised to COP and heating power equations shown in Figures 2 and 3. COP depends on the supply flow temperature. The higher the flow temperature, the lower the COP. The heat pump was scaled for each building. In the calculations of single family and terraced houses HP nomimal heating power was 100% of heating load at design outdoor temperature. For apartment buildings, 70% of power sizing was used. This approach has been chosen to avoid overdimensioning. The extra cost of a powerful heat pump is greater than the savings.

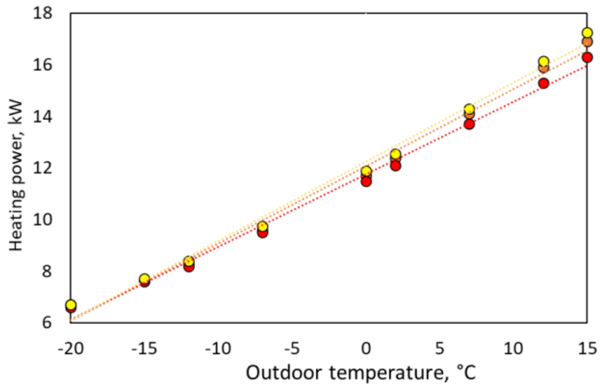


Fig. 3. AWHP heating power according to outdoor temperature

For the ground source heat pump the product specific average values of the coefficient of performance were used:
- ground source heat pump (heating system supply temperature 40°C) COP=4.21,
- ground source heat pump (heating system supply temperature 45°C) COP=3.78,
- ground source heat pump heating of domestic hot water COP=2.99.

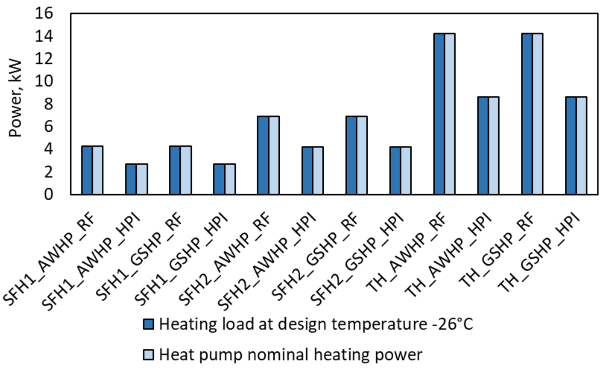


Fig. 4. Heating load at design temperature and heat pump nominal heating power

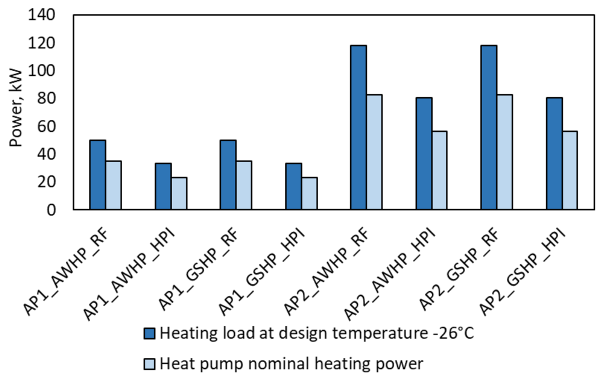


Fig. 5. Heating load at design temperature and heat pump nominal heating power

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Table 5. Heat pump Seasonal Coefficient of Performance

	Single family and terraced houses		Apartment buildings	
	AWHP	GSHP	AWHP	GSHP
Room heating system SCOP (includes additional heating)	2.43-2.73	3.51-3.79	1.99-2.25	3.73-3.78
Domestic hot water system SCOP	2.62	2.99	2.62	2.99
Heat pump SCOP	2.53-2.70	3.16-3.54	2.31-2.48	3.11-3.34

3 Results and discussion

3.1 Annual electricity need

In single family and terraced houses with high performance insulation level annual total electricity consumption decreases by 21…24% when using air to water heat pumps for heating in comparison minimum insulation level. Buildings with ground source heat pumps electricity consumption decreases 9…21 %.

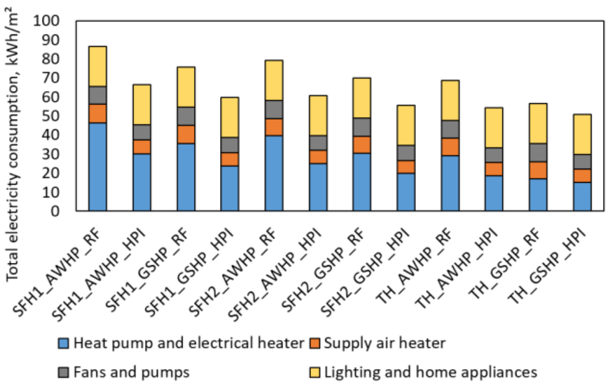

Fig. 6. Single family and terraced house annual electricity consumption

The energy consumption of apartment buildings decreased according to the heating source as follows:
- AWHP 14…18 %,
- GSHP 8…14%,
- DH 8…9%.

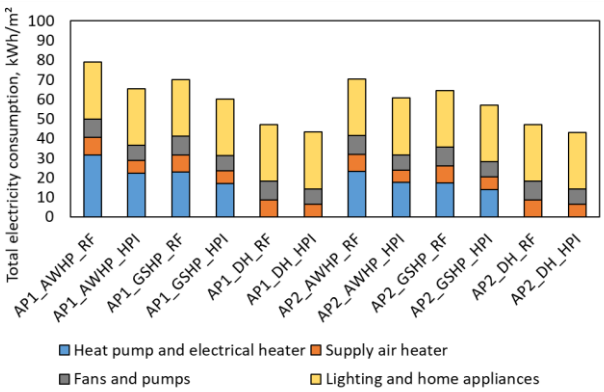

Fig. 7. Apartment building annual electricity consumption

3.2 Hourly peak powers

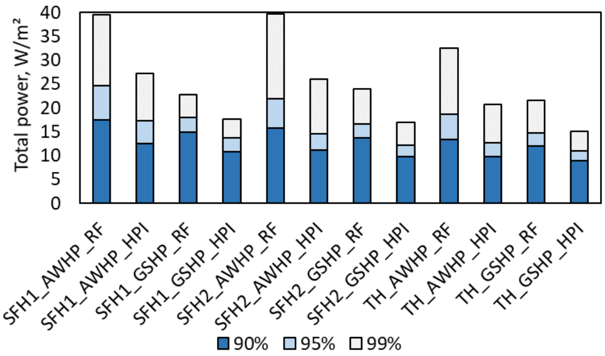

Fig. 8. Single family and terraced house total electricity power need

In single family and terraced houses using high performance insulation instead of minimum insulation, reduced electricity power need by 31…36% for AWHP and by 23…30% for GSHP.
Comparing apartment buildings with minimum insulation level and high performance insulation level, the total power need decreased by -25% with AWHP and -21% with GSHP.
When apartment buildings with heat pumps are compared with district heating, heat pumps increased peak electricity power need by :
- AWHP and RF +144%,
- AWHP and HPI +83%,
- GSHP and RF +68%,
- GSHP and HPI +32%.

This is due to the fact that the space heating and domestic water were supplied by heat pumps and additional top-up electrical heater.

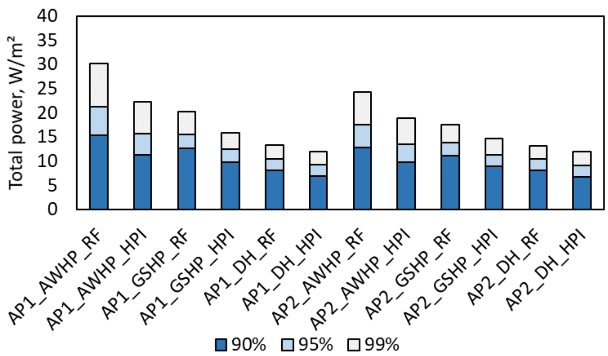

Fig. 9. Apartment building total electricity power need

3.3 Need for additional electric power due to new construction

This calculation takes into account the newbuild construction volume of 10 years. Three scenarios were simulated:
- minimum insulation level, apartment buildings with district heating, single family and terraced houses with heat pumps (reference scenario),
- minimum insulation level, all houses with heat pumps,

• high performance insulation level, all houses with heat pumps.
It was assumed that 50 % of installed heat pumps are AWHP and 50% GHSP. Renovation and demolition were not considered in this scenario calculation.

Table 6. Need for additional electrical power for 10 years newbuild of residential buildings

Scenario	SFH, MW/10y	TH, MW/10y	AP, MW/10y	Total, MW/10y
RF and district heating	419	144	214	777
RF and heat pumps	419	144	442	1004
HPI and heat pumps	333	91	337	760

Scenario calculation shows that the electric power increase is lower when high performance insulation is used. Compared to the reference scenario (minimum insulation and apartment buildings with district heat), high performance insulation and heat pumps in all buildings resulted even in slightly lower additional electric power need. Therefore, the application of high performance insulation allowed to fully compensate the installation of heat pumps to apartment buildings.

4 Conclusions

The aim of this study was to determine the impact of extensive use of heat pumps as a main heat sources on the power grid. Application of high performance insulation reduced hourly peak powers by 13…37% in different buildings relative to the minimum insulation. In apartment buildings, high performance insulation compensated about the half of additional electric power when buildings with heat pumps were compared to district heating. In the scenario calculation for residential newbuild for 10 years, the application of high performance insulation fully compensated the installation of heat pumps to all apartment buildings. This result depends on the proportion of heat pump types which was 50/50% for both heat pump types. Preference for ground source heat pumps over air to water heat pumps would further reduce the electricity power need. The results can be utilised for energy efficiency policy development and escpecially for the assesment of implications to power grid.

Acknowledgements

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Access method: http://www.stat.fi/til/asas/2018/asas_2018_2019-05-14_tau_002_en.html