Indoor Environment and Energy Performance Evaluation of Low-temperature heating in Retrofitting Existing Swedish Residential Buildings

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ABSTRACT HEADING

Sweden is actively engaged in accelerating the sustainable transformation of existing energy systems in buildings. Low-temperature heating (LTH) technology has shown promising advantages in contributing to the performance of heat pumps and to the improvement of thermal comfort. In addition, the renovation measure is easily implemented with lower impacts to occupants than traditional envelope-based methods. However, most existing studies of this subject have been based on numerical investigations of component development and system simulation. While most existing methods of evaluating LTH-retrofitting have not accurately taken into account practical drawbacks and limitations of LTH reported by industries and occupants via on-site measurements. How LTH system can contribute the operative temperature in reality, and how to estimate the influence of LTH to the performance of heat pumps are still not fully attained. By implementing LTH in an existing typical Swedish single family house, this study is aimed to solve two practical concerns brought up by building industries and occupants: global thermal comfort and influence to the coefficient of performance (COP) of the installed ground-source heat pump (GSHP). Potentials to the total operational energy savings are also included.

The evaluation methods were mainly carried out by on-site measurements. One typical single family house, built in 1960s, locates at the northern-suburb of Stockholm was selected to present the study. The LTH component focused in this study were radiator boosters. Real-life performance data collected from thermo sensors, flow meters and GSHP were selected to estimate the COP, in combination with analytical models. Contributions were compared with respect to the conditions before and after retrofitting.

The preliminary measurement results showed that major contributions from boosters to thermal comfort lies in floor temperature and better distributions of heat in the room. A 3.7 % improvement of total heat outputs from radiators can be achieved by boosters. And the correspondent COP was increased by 8.6 %. However, there is no evidence showed that boosters can save the total operational energy of the studied building, under the measured outdoor temperature and full operating conditions. It is more beneficial to use radiator boosters when the outdoor temperature is below -11.5 ℃ from energy saving perspectives.

INTRODUCTION

EU is dedicated to supporting the sustainable transformation of existing buildings. Recent key instrument to progress this transformation is the EU's energy and climate target for 2030: at least 40 % domestic reduction in

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greenhouse gas emission (compared to the level of 1990), at least 27 % for the share of renewable energy used in EU, at least 27 % improvement of energy efficiency and electricity interconnection target of 10 % (Bonn, Heitmann, Reichert, & Voßwinkel, n.d.). The latest long-term EU energy road map has declared the goal of reducing greenhouse gas (GHG) emission by 80-95 % when compared to 1990 levels by 2050. This energy and climate target also assists to underpin the requirements to member states/associated countries to make a further effort in the race of energy efficiency and low-carbon technology in existing buildings, with respect to the EU "20-20-20" targets. Responding to the EU policy contexts and challenges in retrofitting, Sweden has been actively engaged to this transformation. Previous Swedish industry experiences and research have reported that low-temperature heating (LTH) method can provide promising shortcuts and advantages to serve better thermal comfort and energy savings in retrofitting practice (Hesaraki & Holmberg, 2013) (Wang, Ploskić, & Holmberg, 2015) (Wang, Ploskić, Song, & Holmberg, n.d.). Compared with conventional envelope-based energy-retrofits, LTH have mostly been accomplished by relatively lower costs, less multiple visit and shorter operating process (Wang, 2013) (V V S Företagen, 2009). The contributions from LTH components are due to the increased heat supply efficiency, such as increased heat emission efficiency of radiators, and/or, reduced heating demand. Pilot studies mostly reported the findings with respect to LTH alternatives, such as ventilation radiators, baseboard radiators and floor heating by both simulation and experimental studies (Holmberg, Myhren, & Ploskic, 2010) (Myhren & Holmberg, 2013) (Ploskić & Holmberg, 2013) (Hesaraki, Bourdakis, Ploskić, & Holmberg, 2015). As one of the most cost-effective components of LTH – installing fan units below radiators, namely, radiator boosters have also shown competitive potentials to be an easily implemented and cost-effective LTH alternative in existing heating systems. However, most of the reported studies of radiator boosters were only conducted in lab-scale testing (Gervind, 2012), or the potential contributions for district heating networks via different control strategies (Lauenburg & Wollerstrand, 2014). The contributions of radiator boosters to the performance of heat pump and thermal comfort remain unknown. Evidences by on-site measurements and real-life feedbacks from indoor environment were not found in literatures. In this study, an on-site measurement was carried out to perform a thorough real-life investigation of radiator boosters. One typical Swedish single-family house was selected to present this practice.

OBJECTIVE

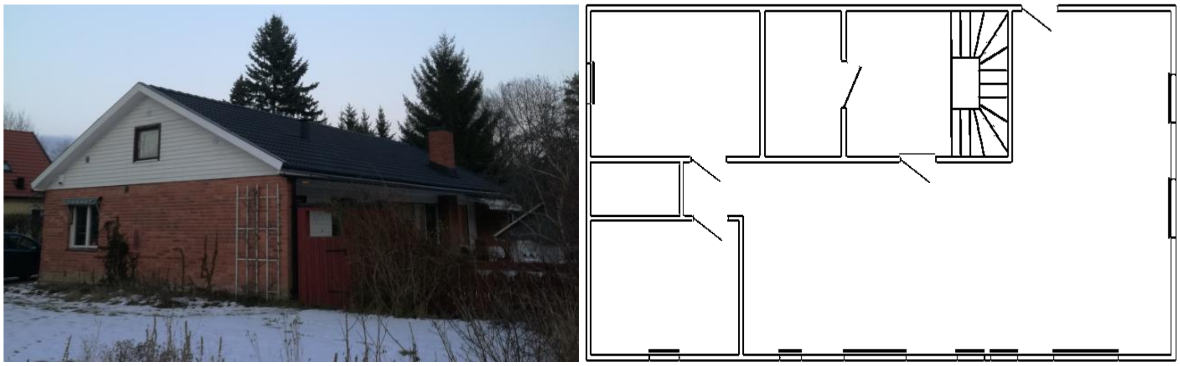
The objective of this work is to investigate indoor environment and energy savings by radiator boosters in retrofitting Swedish residential buildings. The focus was on mapping the influence of radiator boosters to the coefficient of performance (COP) of heat pumps as well as the contributions to global thermal comfort by on-site measurements. This study aimed to provide critical evaluations and technical guidance for future large-scale implementation of LTH systems in existing residential buildings.

METHODOLOGY

Selected archetype

A typical Swedish single family house was selected to carry out this practice, shown in Figure 1 (a). The house was located in the north suburbs of Stockholm, constructed in 1960s with brick foundations without basements. The 2-storey house has a total heated floor area of approximately 88 m^2. The main living area is ground floor. The attic area (first floor) is closed, and only used for guests and storage occasionally. As a result, the first floor was excluded from equipping radiator boosters. The ground floor plan of the house is shown in Figure 1 (b), consisting of one living room facing the south, kitchen and dining room (jointed). Additionally, two bedrooms, two bathrooms and entrance hall were also located on the ground floor.

The house is naturally ventilated and no cooling facilities were installed. Fans above the kitchen are only switched on when heavy smokes were generated by cooking. Domestic hot water was supplied by boilers. Space heating was supplied by ground-source heat pump (GSHP) for rooms located at the ground floor. Heat emitters are a combination of different alternatives, which are listed in Table 1. Heating system on the first floor is electric heaters, only occasionally switched on. Furnace was originally installed in the living room, but seldomly used. Radiators and floor heating on the ground floor have been installed and are supplied by GSHP. However, the total service area of floor heating is rather small. All radiators are controlled by thermostatics. Single-panel and double-panel radiators are installed based on the window sizes and external opening areas of the envelope. As a result, the radiators are connected in line and differ in height and length.



(a)

Figure 1 (a) The selected single-family house and (b) The ground floor plan

Table 1. The radiator systems

Heating method	Radiator Type/ No.	Location/Energy Supply	If Equipped with Boosters
Radiator type 1	Single panel, 2	Living room	Yes
Radiator type 2	Double panel, 7	Living room, bedrooms	Yes
Furnace	1	Living room	No
Floor heating	3	Bathrooms, entrance hall	No
Electric heater	3	Attic/first floor	No

Radiator boosters

In the measurements, both single and double panel radiators were equipped with boosters that cover the whole length of the existing radiators, shown in Figure 2. The boosters consist of four and eight fans for small and big types of radiators, respectively. All radiators were equipped with remoter controls, which can switch on/off the fans manually by off-site computers. Due to non-unified radiator types, all radiators were considered as one system in the measurement. As a result, the contributions of radiator boosters to individual/different types of radiators are not studied in this study. However, it is believed that this approach is close to depict the realistic scenario in Swedish residential buildings - heating systems are commonly consisted of different emitters, in terms of radiator sizes, types and heating methods.

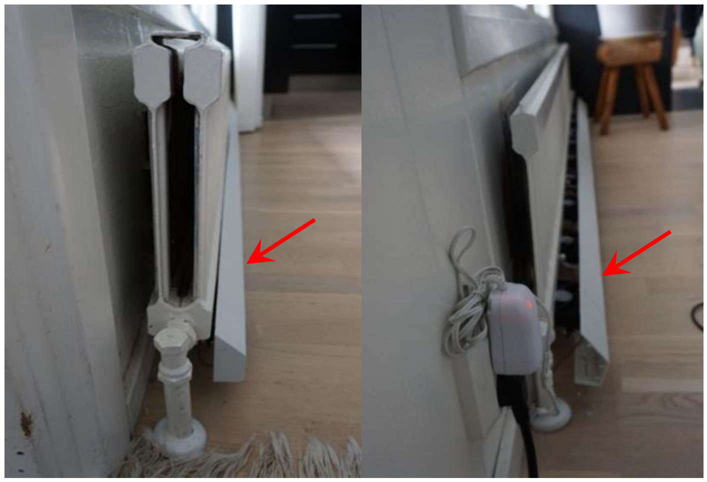
The measurement was planned for six consecutive weeks from March to April, during the heating seasons of Stockholm. The radiators were switched on/off weekly in an alternating manner. Weekly performance was applied for evaluation before and after installing radiator boosters for retrofitting practice. Set temperature was kept constant during the whole measurement period. Ambient temperature was parallelly measured. In the measurement, supply/ return temperature ($\theta_{supply}/\theta_{return}$) and hydronic flow rate ($\dot{m}_H$) was directly measured from the condenser side of GSHP. The total heat outputs before and after installing boosters were calculated by Equation (1). Energy savings were evaluated by both COP of GSHP and the total operational energy usage (E_{total}), see Equation (2). The energy savings are quantified by the net savings E_{total} of the heating system.

$$Q_P = \dot{m}_H * c_P * (\theta_{supply} - \theta_{return}) \qquad (1)$$

$$E_{total} = E_{comp} + E_{circul} + E_{boosters} \qquad (2)$$

The global thermal comfort evaluation was carried out by operative temperature, see Equation (3) (ANSI/ASHRAE Standard 55-2013, n.d.). Air temperature was measured by mean air temperature from thermo sensors installed indoor. Surface temperature was measured by ceiling temperature, floor temperature as well as wall temperature, which were set up with gradients vertically. The measurement set-ups were shown in Figure 3. All measured parameters and experimental methods were listed out in Table 2.

$$\theta_{Operative} = \frac{\theta_{Surface}+\theta_{air}}{2} \qquad (3)$$



(a) (b)

Figure 2 (a) Double-panel radiator equipped with boosters (b) Single-panel radiator equipped with boosters

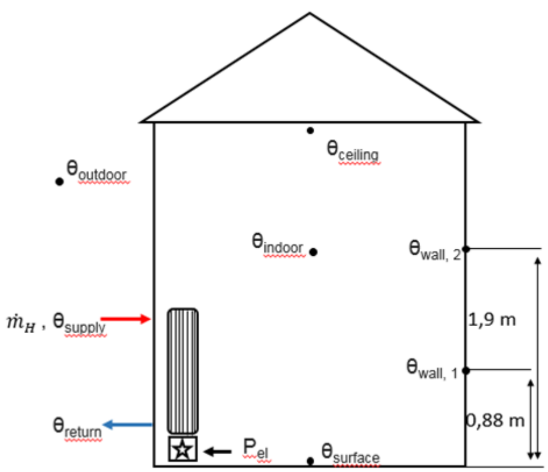


Figure 3 The set-ups of measured parameters in the building.

Table 2. Measured parameters and methods

Parameters	Equipment	Location
Supply temperature, θ_{supply}	Thermo sensors	Condenser of GSHP
Return temperature, θ_{return}	Thermo sensors	Condenser of GSHP
Water flow rate	Flow meters	Hydronic circle
Energy usage of compressor	Energy meter	Compressor of GSHP
Energy usage of pumps	Energy meter	GSHP
Ambient temperature, $\theta_{outdoor}$	Thermo sensors	Outdoor dry bulb temperature

Indoor air temperature, θ_{indoor}	Thermo sensors	Living room
Surface temperature, $\theta_{surface}$	Thermo sensors	Floor temperature (under the couch), Wall temperature, Ceiling temperature
Energy usage of boosters	0.4 W/unit with 4 fans	Below the radiators

REULST AND DISCUSSION

1008 data from whe whole measurement periods (168 hours x 2) was collected in steps of every 10 minutes with respect to the outdoor temperature. Radiators were equipped with boosters in the first week and without boosters in the second week, as a reference.

Thermal comfort

Figure 4 shows the results of air and operative temperature with/without boosters during the measured periods. The average outdoor temperature was 4.3 ℃ and 4.6 ℃ for with and without boosters, respectively. It is found that boosters can improve the operative temperature from 23.7 ℃ to 24.2℃, with an improvement of half a degree. The duration of operative temperature that fell in the category of above 24 degree has been largely extended by boosters. The largest contributions of boosters were found to the floor temperature (shown in Figure 5). Thermo sensors were placed under the couch, where occupants commonly complained about the "cold-feet effect" while sitting still for a long time watching television. It was found that the main floor temperature has been improved by 1 degree. When the radiators were equipped with boosters (red line in Figure 5), floor temperature was higher than 22 ℃ above 90 % of the time. The total heat outputs of all radiators were improved form approximately 3000 W to 3100 W, with an average improvement of 3.7 %. The temperature gradients were obtained by the placed thermosensors on different vertically levels. The results showed that the main temperature gradients from floor to ceiling with reduced by boosters from 2 degrees to 1.4 degree. The contributions of boosters to the thermal comfort are listed in Table 2. This meets the feedbacks from occupants that they felt warmer in the week when boosters were working and sometimes too warm when passive heating from the sun was high.

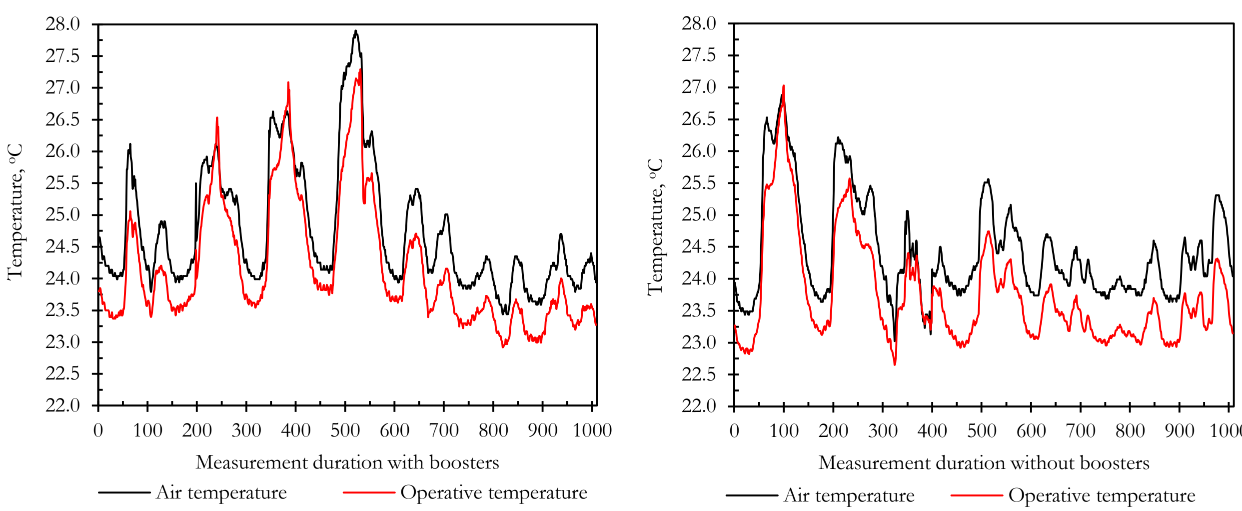


Figure 4 (a) Air and operative temperature when radiators were with boosters (b) Air and operative temperature when radiators were without boosters

Table 3. Impacts of boosters to the thermal performance of radiators

Parameter	With boosters (average)	Without boosters (average)	Contributions, % (average)
Operative temperature, ℃	24.2	23.7	1.8

Air temperature, ℃	24.6	24.4	0.6
Floor temperature, ℃	23.0	22.0	4.6
Temperature gradients ,℃	1.4	2.0	-
Total heat outputs, W	3110	3000	3.7
Mean outdoor temperature,℃	4.3	4.6	-

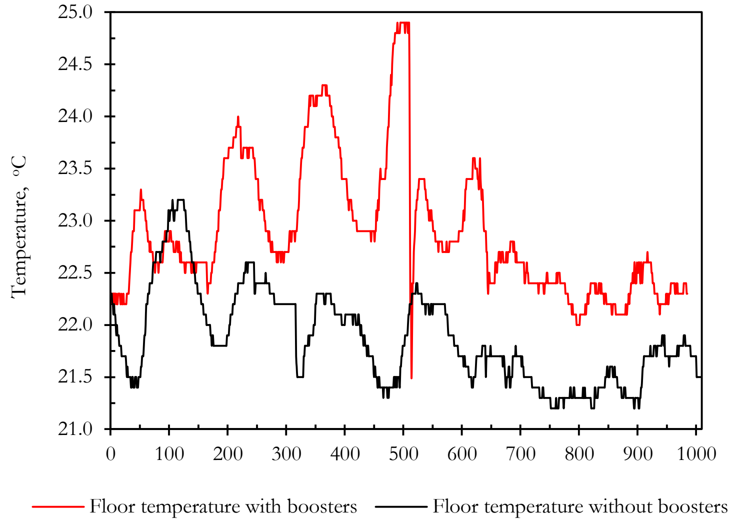


Figure 5 Floor temperatures (under the couch) with and without radiator boosters

Energy performance

Figure 6 shows the supply and return temperature of GSHP for with and without boosters, respectively. It is obtained that the main supply temperature was reduced by the boosters from 36 ℃ to 33 ℃ during the measured periods. All radiators were working with a supply temperature lower than 50 ℃ when equipped with boosters. The reduced supply temperature leads to an improvement of COP of GSHP from approximately 3.8 to 4.2 (8.6 % improvements). Correspondently, the electricity usage of compressor was decreased from 1.48 kWh/ (week · m^2) to 1.40 kWh/ (week · m^2), with an energy reduction of 4.5 %.

Total operational energy was calculated based on the obtained data from pumps, compressors as well as the electricity usage from boosters themselves. Figure 7 shows a comparison of operational energy usage with/without fans. It was found that during the measurement, radiator boosters can save the total operational energy usage, due to the boosters can decrease the electricity usage for compressors by 4.5 %. It is shown that energy usage from pumps is rather small and was almost constant for with/without fans (20 Wh for with boosters and 21 Wh for without boosters). The energy needed for boosters was rather small (0.008 kWh/m^2) when all radiators (9 radiators in total) were under full operating schedule (168 hours in a week). The total operational energy was decreased from 1.48 kWh/m^2 to 1.41 kWh/m^2 (4 % decreases) for one week period.

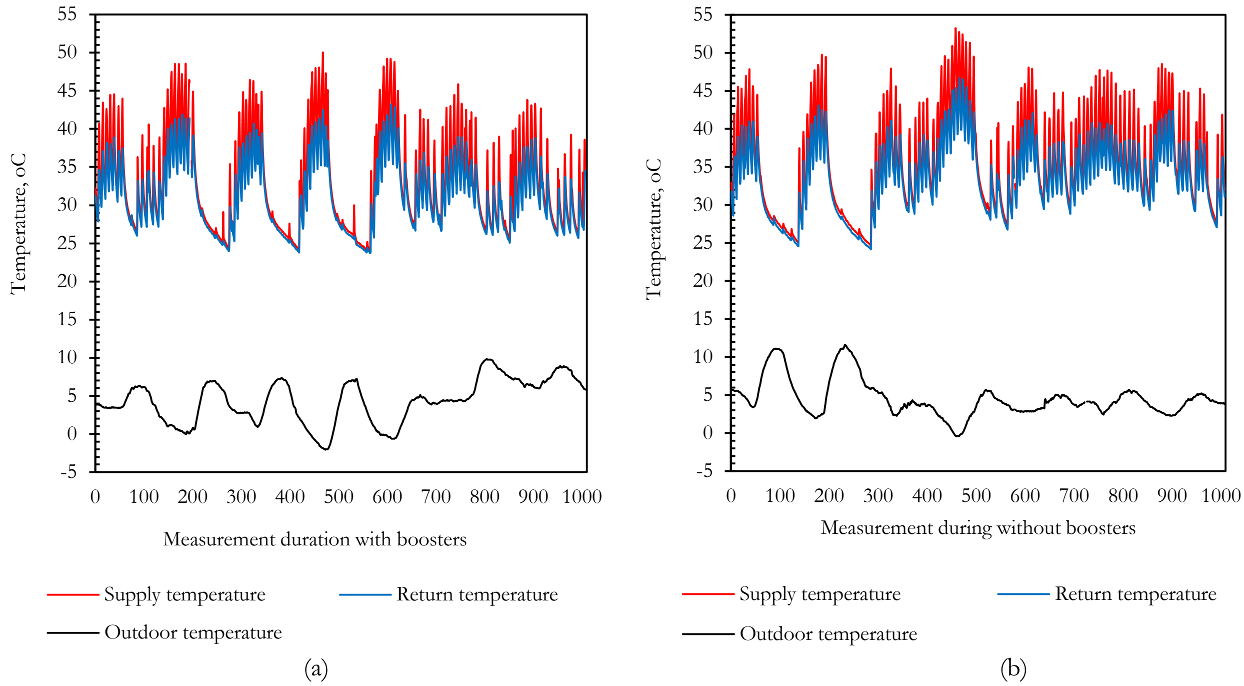


Figure 6 (a) Supply and return temperature with boosters, with respect to outdoor temperature (b) Supply and return temperature without boosters, with respect to outdoor temperature

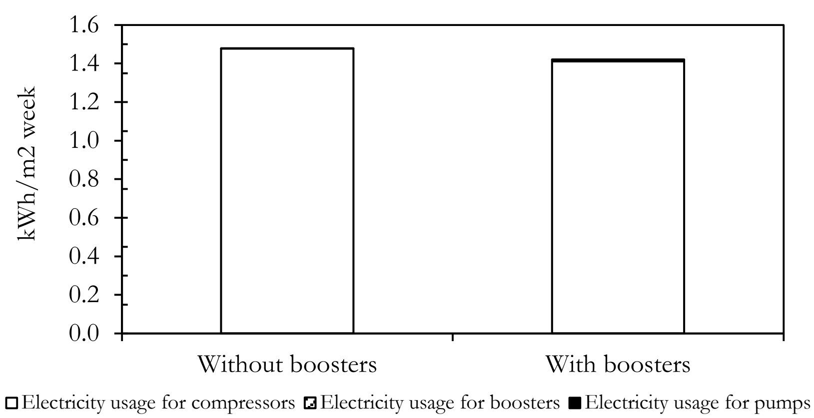


Figure 7 Total operational energy usage for space heating with and without boosters

CONCLUSION

In this paper, the authors measured the impacts of implementing radiator boosters in retrofitting a typical Swedish residential building. Two consecutive weeks were carried out for preliminary comparing the performance and contributions of boosters to the heating system. Three criteria were presented to assess the retrofit contributions: thermal comfort, COP and total operational energy savings. Based on the measured conditions and the studed case, the following conclusions are drawn:

- Boosters can assist the studied heating system serving as low-temperature heating, with an average supply temperature of 33℃.

- The largest contributions for thermal comfort were found in floor temperature, with an average improvement of 1℃.
- Boosters can improve the COP of studied ground-source heat pump by 8.6 %.
- Boosters can decrease the electricity usage of compressors by 4.5 %.
- Boosters were can save total operational energy under the studied condition, but limited.

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NOMENCLATURE

θ_{supply} = Supply temperature
θ_{return} = Return temperature
$\theta_{Operative}$ = Operative temperature
$\theta_{Surface}$ = Suraface temperature
θ_{air} = Air temperature
$\dot{m}_H$ = Hydronic flow rate
c_P = Heat capacity of water
Q_P = Heat outputs of radiators
E_{total} = Total energy usage of heating system
E_{comp} = Energy usage of compressors
E_{circul} = Energy usage of circulation pumps
$E_{booster}$ = Energy usage of radiator boosters

Subscripts

COP = Coefficient of Performance
GSHP = Ground-source heat pump
LTH = Low-temperature heating

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Topic 7. Sustainable and advanced built environments

Performance Analysis of Low Temperature Heating in Retrofitting Practice of Existing Swedish Multifamily Houses – An Investigation Including Simulation and measurements

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Keywords: Retrofitting, Low temperature heating radiator, Flow temperature pattern, Heat pump, Energy savings

SUMMARY

Two types of low-temperature heating (LTH) radiators (ventilation/ baseboard radiators) are evaluated with respect to conventional radiator (high-temperature) based on simulation and measurements in retrofitting existing Swedish multi-family house. The flow temperature variations of LTH are found and the influences to COP of heat pump are quantified. The primary energy savings by retrofitting conventional to ventilation/baseboard radiators are 12.4 and 10.2 %, respectively.

Nomenclatures	
ACH	Air-changes rate, h^{-1}
AHU	Air-handing unit
BBR	Swedish building regulations (Boverkets byggnader)
BR	Baseboard radiator
COP	Coefficient of performance
CHP	Combined heat and power plant
CR	Conventional radiator (high-temperature based, before retrofitting)
BR	Baseboard radiator (low-temperature based, after retrofitting)
DHW	Domestic hot water
HSPF	Heating season performance factor
IDA ICE	Indoor climate and energy performance simulation program
LTH	Low temperature heating
MP	Million Program (1965-1975)
VR	Ventilation radiator (low-temperature based, after retrofitting)

INTRODUCTION

Sweden is actively engaged in sustainable transition of national building stock, targeting at least 50 % of the total energy use, 49 % share of renewable energy sources, and 40 % reduction of GHG emissions compared with 1990 levels by 2020 (Energimyndigheten (Energy Agency), 2011). As an energy-efficient alternative, low-temperature heating (LTH) technology has shown promising advantages and shortcuts to improve the efficiency of heat supply. In addition, it provides easily installed solutions in renovation projects practically, thermal comfort contributions, and improved coefficient of performance (COP) for heat pumps. These benefits have been previously pointed, which are able to further accelerate the low-operational-energy transformation of building stock (Hesaraki & Holmberg, 2013b)(Wang, Laurenti, & Holmberg, 2015)(Maivel & Kurnitski, 2015). LTH radiators that investigated in this study have been numerically and experimentally investigated in previous studies from thermal performance perspectives (Myhren & Holmberg, 2013)(Ploskić & Holmberg, 2014). However, most of the studies carried out were focused on the component development for radiators. From a building level, existing studies reported were mainly based on the newly constructed archetypes such as net-zero buildings designed with existing relatively low energy demands, or idealized zone environment for numerical analysis (Hesaraki & Holmberg, 2013a)(Ploskić & Holmberg, 2013). For existing multi-family houses, how LTH will precisely impact the heat supply system and further save operational energy by retrofitting exiting conventional radiator (CR, high-temperature based) to ventilation radiator (VR, low-temperature based) / baseboard radiator (BR, low-temperature based) are still not found in literatures. Implementation of LTH is existing buildings retrofitting are largely plagued by lacking of concrete evidence for their abilities to save operational energy.

In this study, LTH-based retrofitting solutions are designed and analyzed for one typical existing Swedish multifamily house. Quantify the influence of LTH radiators to the heat supply system and evaluate the operational energy savings by retrofitting CR to VR and BR are in focus. The findings can provide technical guidelines for both occupants and stakeholders for future large-scale implementation of LTH in existing Swedish residential buildings.

METHODS

IDA ICE 4.6 (Indoor Climate and Energy performance simulation program) was applied for the simulation of heating balance/load. The accuracy of the IDA ICE program was evaluated by the IEA Solar Heating and Cooling Program, Task 22, Subtask C, in 2003 (Achermann & Gerhard, 2003). The applications of IDA ICE for heat balance modeling were further validated in several studies, for both single-family houses and multi-family houses. It is found that good agreements with measurements have achieved for the air temperature and surface temperature results for different types of heating systems in multifamily houses (Hasan, Kurnitski, & Jokiranta, 2009). For single-family houses, it has been revealed that the maximum deviation of annual operational energy modeling with on-site measurements is below 7 % (Hesaraki & Holmberg, 2013a). In this study, 85 zones were established in the model; these were based on living room, bedroom, bathroom, kitchen, public corridors, storage rooms, and basements. The selected building has a total heated floor area of 1580 m^2. Heating system before retrofitting is high-temperature based CR. Conventional hydraulic radiators are installed under windows before retrofitting. The sizing of the radiators was based on the design principle that radiator width should both fit the window width and avoid cold draught caused by window surface and leakages from window claddings/joists. CR is replaced by VR and BR after retrofitting. The system layouts are shown in Fig.2a. Heat pump is employed in the model to supply hot water for space heating. Ventilation system before retrofitting is exhaust ventilation without heat recovery. The exhaust grills are placed in both bathrooms and kitchens. Each kitchen and bathroom is equipped with one fan to extract air (decentralized). Air-tightness level is 2.5 air-changes rate (ACH) under the pressure differences of +/-50 Pa, which are calculated as wind-driven ACH. Wind profile is based on the suburban inventory, Ashrae-1993 (Engineers, 1993). Technical descriptions of the building and its service system are shown in Tab.1. Outdoor temperature is based on the climate data of Stockholm/Bromma, shown in Fig. 1. The lowest design temperature period is marked with a black box in February. Heating season starts from September to May.

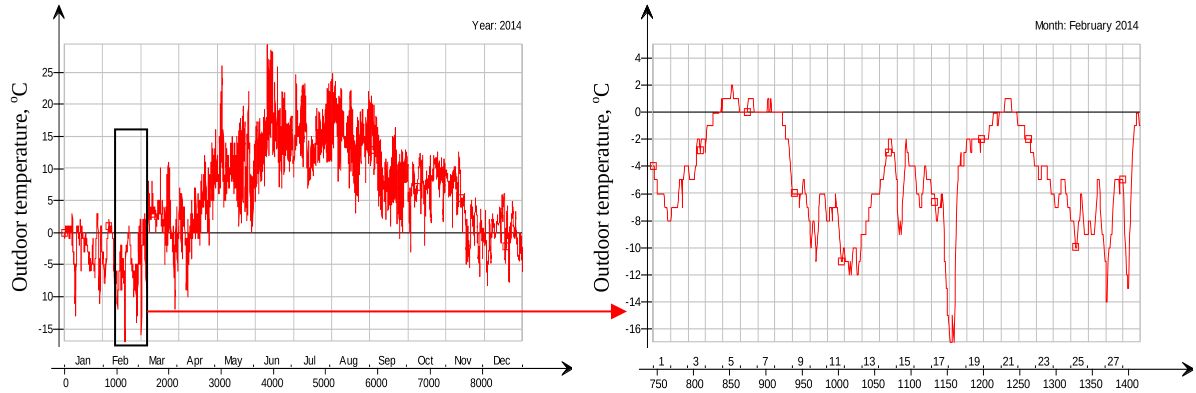

Figure 1. Outdoor temperature-based climate profile employed in IDA ICE and the design temperature

Table 1. Building parameters and service systems before retrofitting

Building parameters	Material description	Technical descriptions
Housing design	2-storey designed as parallel or perpendicular with basements (flat height 2.71 m)	Constructed in MP (1965-1975), Stockholm
Window/glazing systems	Double glazing window with aluminum cladding and natural ventilation openings (with wind catcher)	U value = 2.85 W/m^2K
External Walls	Concrete slab foundation with reinforced brick beams and brick facade, covered by 1.3-cm plasterboard inside and 100-120 mm mineral wool insulation layer; 5-cm mineral wool between brick wall and slab edge	U-value: 0.48 W/m^2K
Roof/Attic	Light slope roof covered with cardboard; eaves lined with trapezoidal sheet metals; 200 mm mineral wool insulation	U-value: 0.26 W/m^2K
Basement	Concrete slab, directly on gravels. 20 x 40 cm insulation layers are placed on the edge between foundation slab edge and joists.	-
Ground floor	Concrete slab covered by linoleum or plastic mats on surface of fiberboard	-
Balcony/Terrace	Suspended 10 cm precast slab concrete foundation covered by 1.2 cm healed asphalt-impregnated fiberboard; concrete studs	Linear thermal bridges: 1.2 W/m K

There is no cooling installation in the building. An hourly profile of internal heat gains from occupants, equipment is assumed based on the living schedule. The schedules are categorized as working-day and holiday schedules. These schedules are assumed as constant both before and after retrofitting. Indoor temperature is set as 21 ℃ in the model. The thermal performance of studied radiators have been previously investigated and tested. The working principle of VR and BR can be found in (Myhren & Holmberg, 2011)(Ploskić & Holmberg, 2011), and the products are available in the market. The component layout of VR and BR are shown in Fig. 2b and 2c. Measurement-based data, provided by radiator manufactures of the studied three types (CR/VR/BR), are employed to evaluate the energy performance of space heating circuits. In this study, 8 mm heating pipes are selected, which is believed to be a realistic piping size for normal Swedish radiator systems in existing residential buildings. All three radiators are selected as the approximately the same surface areas. For CR, the size is 1m x 0.5m, Purmo type 11 with surface area 1.54 m^2. For VR, it is the same size and surface area as CR. For BR, the size is 10m x 0.15m with the surface area of 1.5 m^2.

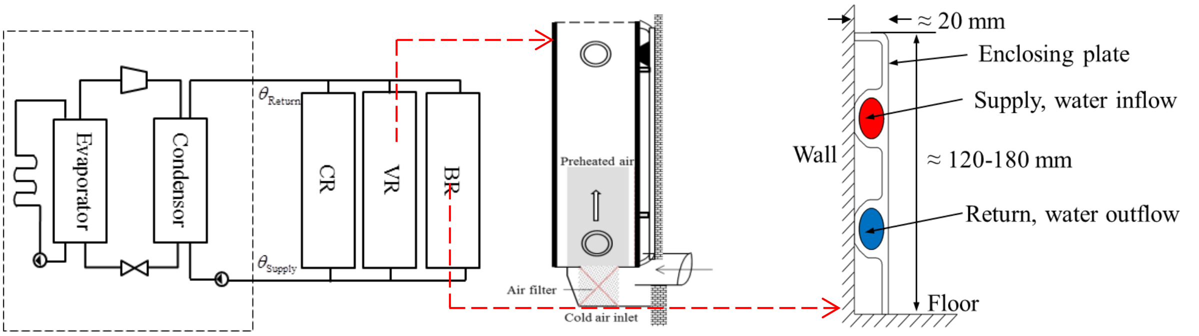

Figure 2. The layout of LTH-based ventilation radiator (VR, Fig.2b) and baseboard radiator (BR, Fig.2c)

The supply/return temperature ($\theta_{supply}/\theta_{return}$) of radiators is obtained by Eq. (1). The mass flow of hydraulic circuit is controlled as the same for CR, VR and BR. Heat outputs are heating-load compensated. The actual heat outputs of radiators based on measurements are designed with a deviation below 1 % of modelled heating load. The approach tries to present the performances and differences of studied heating system as close as to the reality.

$$\Phi = c_{\text{water}} \cdot \dot{m} \cdot \left(\theta_{supply} - \theta_{return}\right) \tag{1}$$

COP of heat pump is calculated by Eq. (2). Heat pump is modelled by only serving space heating. Domestic hot water (DHW) is not included in this study. The Carnot efficiency of heat pump is selected as 0.5. The evaporation temperature ($T_{\text{evaporator}}$) is selected as 266.15 K.

$$\text{COP} = 0.5 \cdot \frac{T_{\text{supply}}}{T_{\text{supply}} - T_{\text{evaporator}}} \tag{2}$$

The calculation of primary operational energy (Φ_{primary}) is obtained by Eq. (3) based on (European Committee for standardization, 2007). Primary energy factor ($f_{primary}$) is selected as 2.15 for electricity produced by Swedish mix (Frangopoulos, 2012).

$$\Phi_{\text{primary}} = f_{primary} \cdot \Phi_{delivered} \tag{3}$$

RESULTS and DISCUSSION

Figure 3 shows the constructed building model in IDA ICE. The room that has the worst thermal performance in a year was found: it was observed that the worst room is located at the most northwest position of the building, shown by the frame in Fig. 3b. This is explained by the outdoor temperature profile, orientation (solar radiation under Stockholm climate), large envelope area connecting the outside and as-built ventilation system. This room is further selected as a reference zone (Fig.3a) for investigation. The zone has a heated floor area of 12 m^2, the window size is 1.2m x 0.8m. The zone is assumed occupied by 2 occupants. The presences of the occupants are assumed according to the schedule (introduced in Section Method). Heat balance during the annual heating seasons is modeled by IDA ICE. Internal heat gains take into account heat gains from occupancies, solar-direct and diffuse, and heat from domestic appliances. Fig. 4 shows the modelled heating load in the reference zone (Fig.3a) compensated as outdoor temperature. Weekly heating load in annual heating seasons is presented. The heating load varies from maximum 460 W from February to 50 W in May.

(a) (b)

Figure 3. Constructed building model in IDA ICE (Fig.3b) and selected reference zone with the worst thermal performance (Fig.3a, framed in red in Fig 3b)

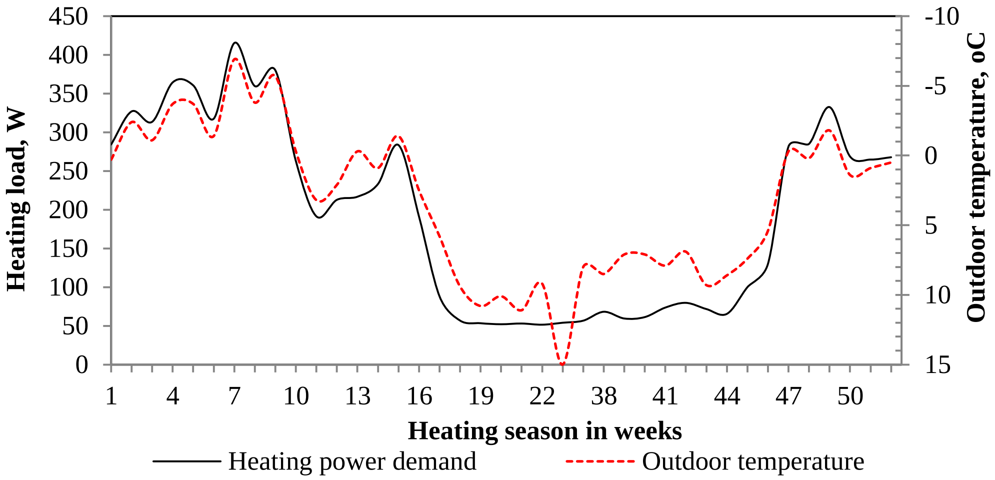

Figure 4. Weekly heating power demand with respect to the outdoor temperature during the annual heating season of the selected reference zone

Fig. 5 shows the temperature variation pattern before and after retrofitting (CR to VR/BR). The mass flow is controlled constantly as 36 kg/h in all radiators. The highest supply temperature for CR is 54 °C. Correspondently, the highest supply temperature for VR and BR are 48 °C and 45 °C, respectively. From week 13 (April) to 46 (November), supply temperature for CR falls in 40 °C. For VR, supply temperature that higher than 40 °C starts from week 2 (January) to week 9 (February). The supply temperatures above 40 °C for BR are week 4 to week 9. In addition, maximum return temperature is reduced from 42 °C (CR) to 37 °C and 34 °C, (VR and BR), respectively. Fig. 6 and 7 show the influences of studied radiators to COP and primary energy usage during the heating seasons. CR shows an averaged heating season performance factor (HSPF) of 3.6. The HSPF is improved to 4.0 for BR and 4.2 for VR. It is observed that when outdoor temperature is relatively high (since week 11 to 46, above 0 °C). VR shows larger advantages in heat emission performance than BR. This can be explained as when convection is plagued by relatively reduced temperature differences, VR can still boost up the convection by forced ventilation channels beneath the radiators. This leads to a better performance of VR than BR in mild outdoor temperature. It can be also observed from Fig. 7 that the impact of LTH to operational energy usage mainly occurs in limited duration of whole heating seasons. From week 16 to 46 when the outdoor temperature is above 0 ℃, the differences of energy performance among CR and VR/BR are limited. Major contributions of LTH for operational energy savings coming from the weeks when outdoor temperature is below 0 ℃.

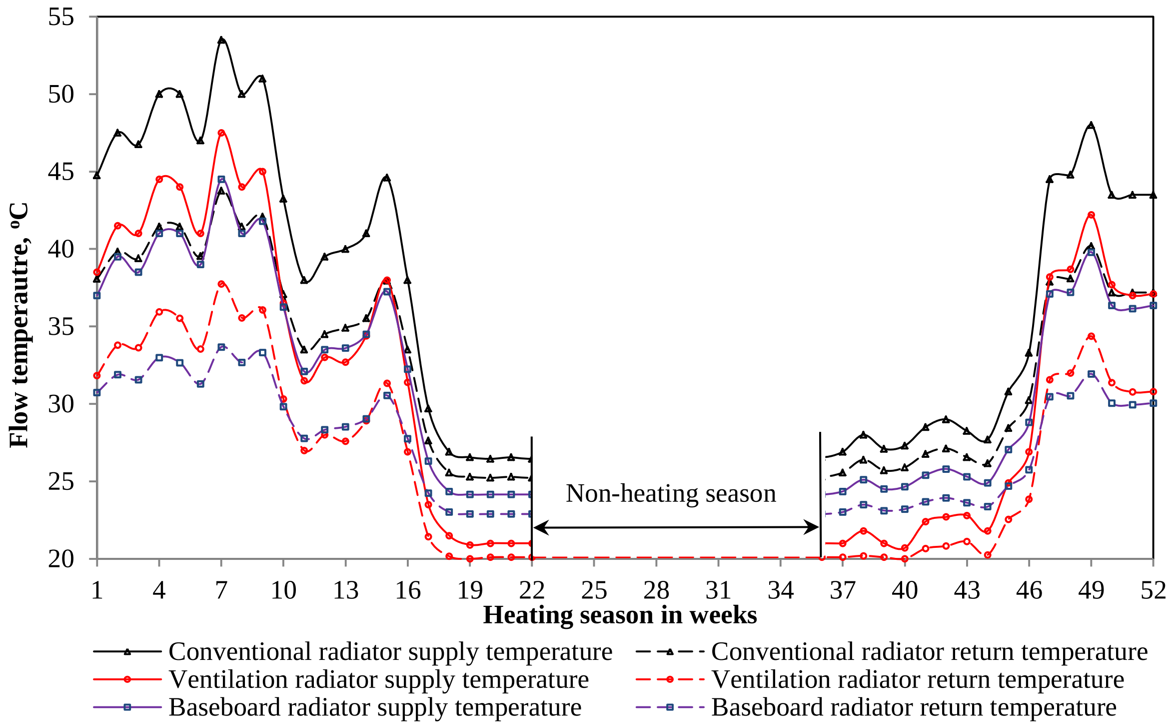

Figure 5. Weekly supply and return temperature variations for three studied heat emission systems during the annual heating season of the selected reference zone

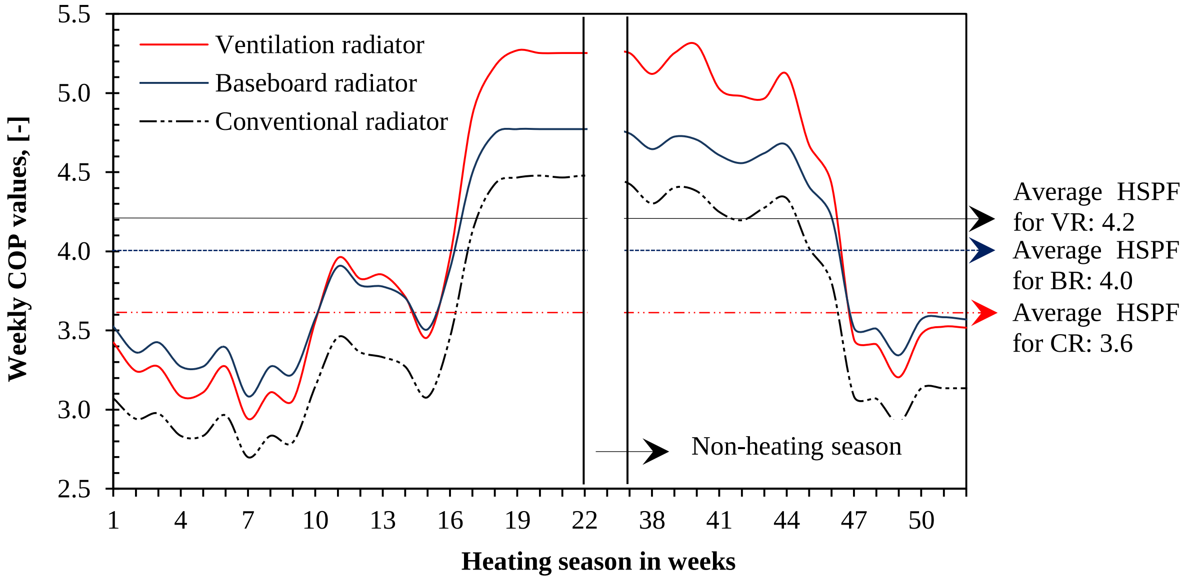

Figure 6. Weekly COP and averaged HSPF of heat pump for the three studied heat emission systems during the annual heating season of the selected reference zone

Fig. 8 shows the weekly primary energy savings. VR and BR are compared with CR as a reference. It is observed that VR has the highest primary energy savings up to 12.4 %. The contributions are significantly noted particularly when outdoor temperature is mild (above freezing point of water). This results agree with the previous studied by (Myhren & Holmberg, 2013) and (Hesaraki & Holmberg, 2013a) that the energy savings for VR fall in the range of 12 to 13 %, but with a more accurate indication from a building level in this study. BR has primary energy savings up to 10.2 %, which means more energy savings when the outdoor temperature is low and when baseboard can be well designed and placed in skirts of the studied room.

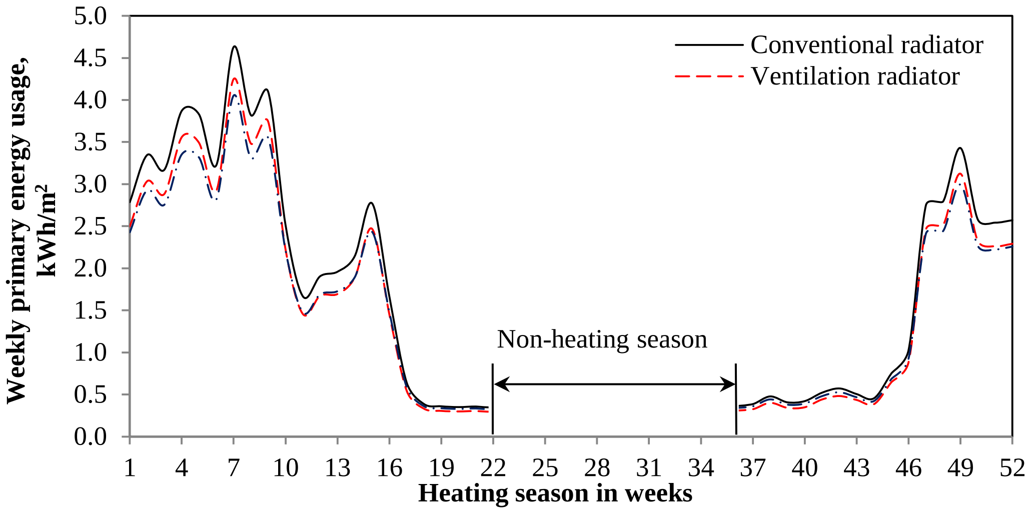

Figure 7. Weekly primary energy usage for the three studied heat emission systems during the annual heating season of the selected reference zone

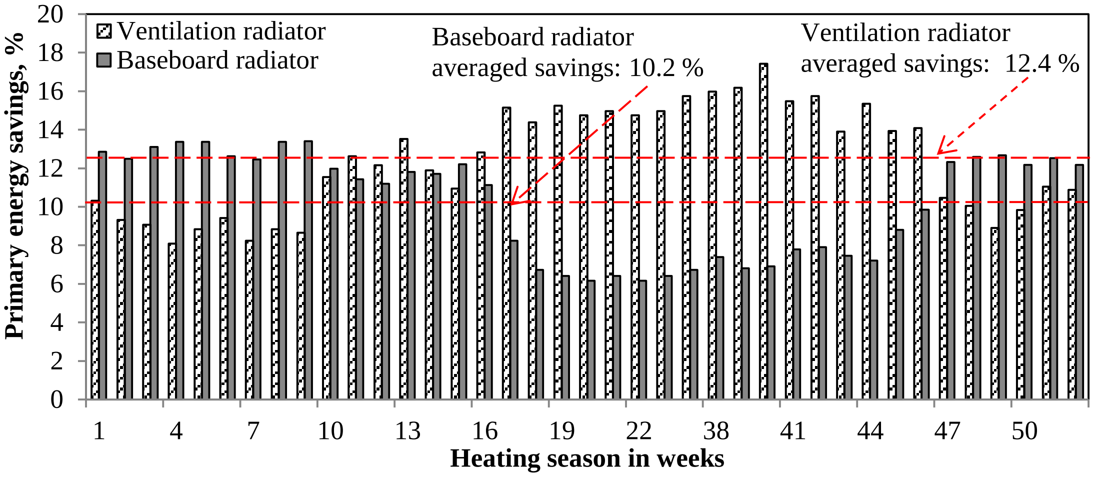

Figure 8. Weekly primary energy savings for LTH-based systems (CV as reference system) during the annual heating season of the selected reference zone

CONCLUSIONS

This study shows how much low-temperature heating radiators will impact the flow pattern of the heating system, compared with conventional radiators during annual heating seasons. Moreover, this investigation gives indications of primary operational energy savings for heat pump. It is concluded that ventilation and baseboard radiators give 12.4 % and 10.2 % energy savings, respectively, compared with conventional radiators.

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Combined Retrofitting with Low Temperature Heating and Ventilation Energy Savings

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Abstract

This paper presents the modeling results of combining low temperature heating (ventilation radiator) with ventilation energy-demand savings. Investigations on operational energy and thermal comfort are in focus.
IDA ICE is employed to investigate the thermal performance and energy usage. The results show that low temperature heating can reduce mean air temperature fluctuations in the selected archetype. When combining low temperature heating with ventilation and air-tightness renovations, the thermal performance of the heating system can be largely improved to an acceptable level. The retrofitting strategy can save 41 % of heating energy demand and 27 % of total primary energy.

Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL

Keywords: Retrofitting, Low temperature heating, Simulation, Ventilation, Energy savings

1. Introduction

In response to tightening EU energy and climate directives, Sweden is actively engaged toward sustainable transition of national building stock, targeting at least 50 % of the total energy use, 49 % share of renewable energy sources, 40 % reduction of greenhouse gas emissions compared with 1990 level by the year 2020 (1). Specifically to the existing residential buildings, Swedish government has established an ambitious energy efficiency target in housing stock by 50 % (per heated floor area) by 2050 compared with 1995 level (2). As regards energy retrofitting accomplished so far in Sweden, a 17 % of final energy savings were achieved by energy-renovations in the past decades. However, total energy utilization in Sweden has not been largely reduced (3). The by far greatest portion of

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retrofitting measures is still envelope and ventilation renovation-based, which commonly need multiple visits, large impacts to the occupants and have relatively long operating process. As an energy-efficiency alternative, low temperature heating (LTH) technology has shown promising advantages and shortcuts to improve the efficiency of heat supply. These are contributed by easily installed solution, thermal comfort contributions and improved radiator emission efficiency (4). Previous studies show that low temperature ventilation radiator based space heating methods/ the combination of different LTH with conventional pre-heated ventilation convectors are among the highest category to comply indoor environment quality and energy efficiency (5)(6)(7)(8). Moreover, theoretical analysis and computational fluid dynamic simulation have shown evidences that advanced design and selection of LTH components can efficiently avoid cold draught and reduce the supply temperature curve to 40 - 45 ℃ without compensating thermal outputs (9)(10).

However, most of the studies carried out were based on the new constructed archetypes such as single-family house and ideal zone environment, or net-zero buildings designed with existing relatively low energy demand (5)(11). It was found that in existing leaky multi-family building stock with high energy demand, there is a risk that LTH may not be able to provide enough temperature to maintain the required thermal comfort level (11). Pilot retrofitting projects from industry and existing studies reported that for low-raise Swedish multifamily houses, renovating the existing exhaust/natural ventilation to mechanical balanced ventilation with heat recovery (FTX) can contribute 30-40 % energy-demand savings (12)(13). Air-tightness retrofitting also shows high sensitivity. However, investigations about combining LTH with ventilation energy savings in retrofitting practice are far less reported in literatures.

In this study, combined measures consisting of LTH and ventilation retrofitting are simulated and analyzed for one typical low-raise Swedish multi-family housing stock built among 1965-1975. Investigations on operational energy savings and thermal comfort improvements when combining LTH with FTX ventilation are in focus. The findings aim to provide technical decision supports for both occupants and stakeholders for future large-scale implementation of LTH in existing Swedish residential buildings.

Nomenclature

ACH	Air changes rate, h^{-1}
AHU	Air handing unit
BBR	Swedish building regulation
FTX	Mechanical balanced ventilation with heat recovery
IDA ICE	Indoor climate and energy performance simulation program
LTH	Low temperature heating

2. Methodology

IDA ICE 4.6 is applied for the simulation of thermal performance and operational energy use. Validation of IDA ICE program was evaluated by IEA solar heating and cooling program, Task 22, Subtask C in 2003 [14]. The applications of IDA ICE for LTH and ventilation modeling were further validated in several studies, including both single family houses and multi-family residential buildings. It was found that good agreements with measurement was achieved for air temperatures and temperature gradients in multi-family houses (11) (15). For houses installed with low temperature ventilation radiators, it is revealed that the maximum errors of annual energy modelling are below 7 % compared with on-site field measurements (16).

In this study, a 2-storey district-heated Swedish multifamily house from Million Program (1965 – 1975) is selected to represent our analysis. The selected building has a total heated floor area of 1580 m^2 and is located in the northern suburbs of Stockholm. The appearance of the archetype (northern façade) is shown in Fig.1a. Constructed building model (southern façade) is depicted in Fig.1b. Each flat consists of one balcony oriented to the south, and one storage room (without window and openings). On basis of the different occupancies, the building is modelled by 85 zones, including three types of occupant schedule:

- Living room and bedroom
- Bathroom and kitchen, domestic hot water (DHW) usage schedule
- Window and opening based on the set temperature controls schedule (open when operative temperatures exceeds 25 ℃)

Wind profile is based on the suburban inventory, Ashrae-1993. District heating supply/return temperature is set to 75/50 ℃ before retrofitting, based on the averaged statistics of Swedish district heating (17). Annual ambient temperature is based on the climate data of Stockholm/Bromma, shown in Fig.2a, in which the lowest design temperature is marked in red box as -18 ℃. Supply temperature to the hydraulic circuits and radiator is design temperature compensated, which is shown in Fig.2b. LTH supply temperature is further designed as a function of decreased energy demand as two retrofitting scenarios, Fig.2b shows:

- LTH (ventilation radiator) + FTX system with 85 % heat recovery
- LTH (ventilation radiator) + FTX system with 85 % heat recovery + air-tightness (60% improvements)

The selection and sizing of low temperature heating radiator is based on the principle of increasing emission efficiency of radiators. Ventilation radiator is designed with the width of conventional radiators, but with one more ventilation vent connecting radiator with outdoor air. Increased air temperature differences in the ventilation channel beneath the radiator will improve heat convection. Outdoor air is then preheated and fileted by the radiator. Pilot testing and modelling results show that the supply/return temperature can be reduced to 35/28 ℃ without compensating the heat outputs (18), no extra energy is needed to operate the radiator. The working principle of ventilation radiator can be found in (4) (16).

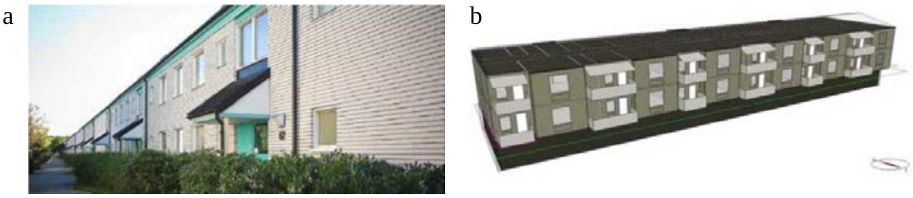


Fig. 1. (a) The appearance of the selected archetype; (b) Constructed model in IDA ICE simulation

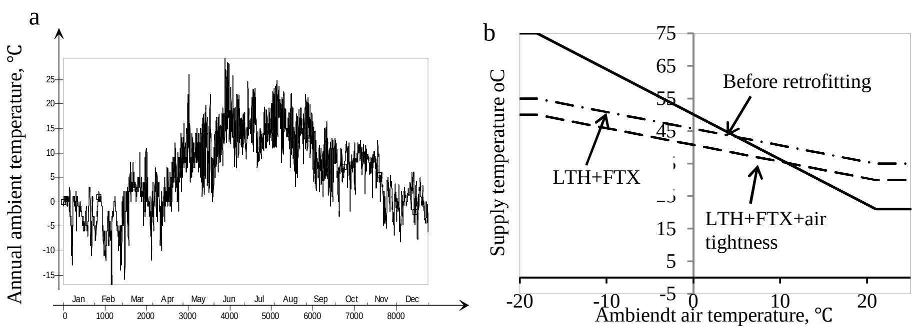


Fig.2. Ambient temperature for annual building performance simulation

3. Results and discussion

Annual dynamic simulations are performed to find the indoor air/operative temperature variations and energy use before and after retrofitting. Due to differences in living schedule and internal heat gains from occupancies, bathroom and kitchen were considered separately from living room and bedroom. The total annual simulation duration is approximately 6 hours. Fig.3a shows the hourly simulation results of operative and air temperature before retrofitting. The zone that has the worst thermal performance in a year is found. It is observed that the worst apartment locates at the most northwest position of the building, shown by frame in Fig.3b. The kitchen in this apartment has the lowest mean air temperature and highest operative temperature fluctuations (shown in Fig.3a), during 960-1120 simulation hours, first week in February (marked in Fig.3a). This is explained by the orientation (solar radiation) and as-built ventilation system. Exhaust ventilation only installed in kitchen and bathroom. This simulation period is further investigated as a representative periodic reference to evaluate the retrofitting profits when implemented with low temperature heating and ventilation renovations. Fig.4 shows the mean air temperature fluctuations before retrofitting and when the existing radiator is replaced with ventilation radiator (without ventilation system renovation).

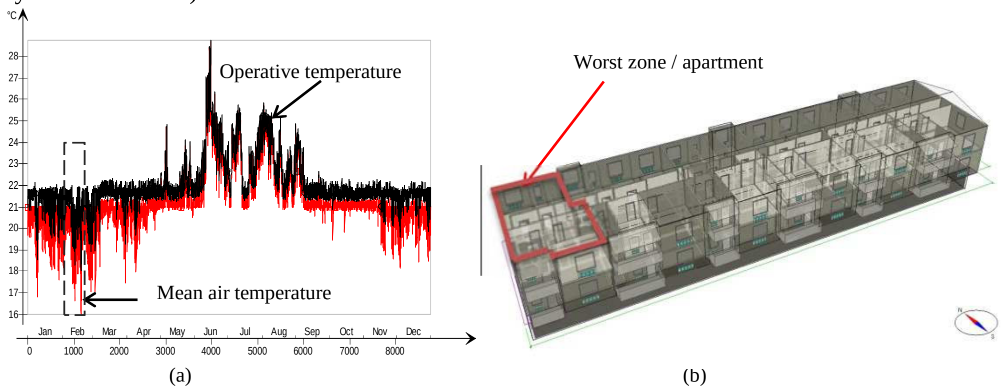


Fig.3. Annual mean air temperature in the room with worst performance before retrofitting and location (b) in the constructed building model (framed area)

It is observed that LTH can contribute reduced mean air temperature fluctuations from 16.6-21.0 ℃ (before retrofitting) to 17.3-20.6 ℃ (after LTH). However, the averaged main air temperature (18.9 ℃) is not improved before retrofitting (19.2 ℃). This result confirms that low temperature ventilation radiator will not significantly improve the mean air temperature if no extra energy-demand renovation is implemented in the presented archetype.

Fig.5a shows the mean air temperature and operative temperature when combining LTH with FTX system. Additional air-tightness renovation by 60 % air leakage upgrading (1.0 ACH under 50 Pa difference after retrofitting) is shown in Fig.5b. It is observed that when combining LTH with FTX, the thermal performance can be largely for both relatively stable mean air temperature and operative temperature. The results are further improved by air-tightness improvements to 1.0 ACH, which is not difficult to achieve and also easy to operate from empirical retrofitting reports. No additional renovation on building envelope is required to achieve this thermal performance. Generic results of PMV-based mean PPD level before and after each LTH-based retrofitting is also performed. The mean PPD is 22 % before retrofitting (44.8 – 5.4) %. Among the five LTH-based retrofitting, ventilation retrofitting has a contribution of 12.3 % (average), with a deviation of 26.2 – 5 %. This means this retrofitting can provide sufficient thermal comfort level by the joint effect, according to the lowest PPD limitation set by EN ISO 7730. No any further renovations are needed.

Tab.1 shows the energy usage before and after retrofitting (combining LTH + FTX+ air tightness). Primary heating source is district heating with an average initial primary energy factor of 0.98 and 0.79 for high and low temperature district heating in Stockholm, respectively. Primary electricity energy mix is selected as Swedish mix with a primary energy factor of 2.15. The energy performance results show that combining LTH with FTX system and air-tightness renovation may save up to 41.3 % of heating energy demand, shown in Tab.1. The contribution of total delivered energy is limited due to the fact that replacing exhaust ventilation and high temperature radiator by LTH+ FTX system needs an extra 5.3 kWh/m^2 year electricity to operate the AHU and circulation pump in the district heating substations. Total delivered energy is 96.2 kWh/m^2 year, this is still higher than the limited value of BBR (90 kWh/m^2 year). However, it can be further compensated by reducing building electricity usage, such as more efficient circulation pumps in district heating substations and DHW energy savings. The largest contribution is obtained for total primary energy: a saving potential of 26 %, shown in Tab.1. This can explained by the reduced distribution heat loss in LTH system, which leads to a relatively lower primary energy factor and distribution efficiency in district heating grids.

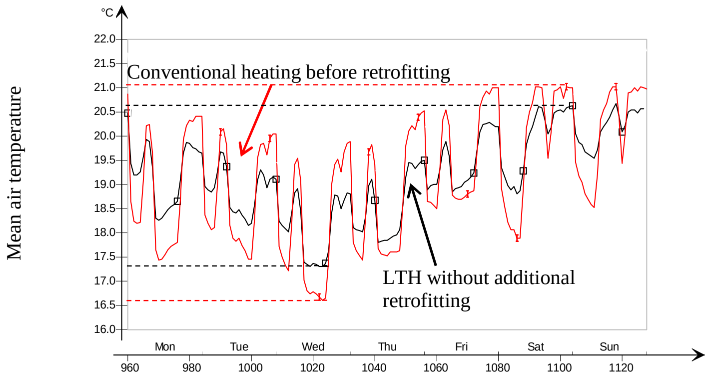
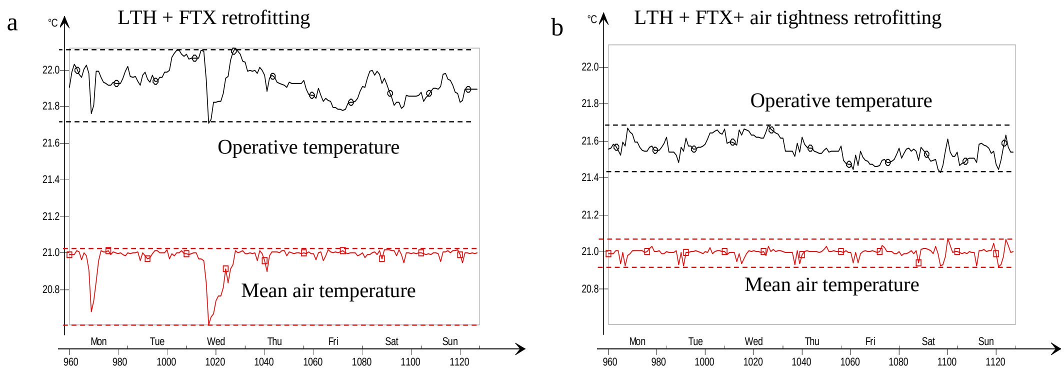


Fig.4. Air temperature under design temperature before and after retrofitting without ventilation renovation (selected zone)



(a) (b)

Fig.5. Operative and air temperature under design temperature after renovating ventilation with heat recovery and air tightness

Table 1. Energy usage before and after retrofitting combining LTH with FTX and air-tightness renovation

	Before retrofitting (*kWh/m2 year*)	After LTH+FTX +air tightness retrofitting (*kWh/m2 year*)	Savings (%)
Heating	87.1	51.1	41.3
Electricity	18.0	23.3	No savings
DHW	21.8	21.8	No savings
Total delivered energy	126.9	96.2	24.1
Total primary energy	145.4	107.6	26.0

4. Conclusion

This study shows that the proposed retrofitting strategy with LTH + ventilation+ air-tightness renovation leads to higher and more stable thermal performance of heating system. The ventilation system is renovated from exhaust ventilation to balanced ventilation with 85 % heat recovery. Air tightness is improved by 60 % before retrofitting. The proposed system can contribute 41 % and 27 % savings of heating and total primary energy, respectively.

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THE IMPACT OF AIR-TIGHTNESS IN THE RETROFITTING PRACTICE OF LOW TEMPERATURE HEATING

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ABSTRACT

In Sweden, the energy usage in existing residential buildings amounted to 147 TWh in 2012, equivalent to almost 40 % of the final overall national energy usage. Among all the end users in building service sectors, 60 % of the final energy in Sweden is used for space heating and domestic hot water (DHW) production in 2013. In order to reduce the supply temperature for space heating in existing buildings, combined approaches are favorably adopted: to reduce the net energy demand by air-tightness and insulation retrofits; and renovate the conventional high temperature heating to low temperature heating (LTH) systems. As an energy-efficiency alternative, LTH technology has shown promising advantages and shortcuts to improve the coefficient of performance (COP) of heat pump system, which further saves primary energy. However, existing modeling achievements and field testing reveal that the attained application of LTH has a relatively high requirement to the air-tightness in new constructed single-family houses. Moreover, in some leaky multi-family building stock with low envelope surface temperature, LTH may have limited energy saving potentials. How to evaluate the impact of air-tightness for the LTH implementation and energy saving potentials in existing houses are not sufficiently attained so far. This paper presents a modeling approach combining LTH simulation with air-tightness evaluation, aimed to estimate whether the selected existing building types can cope with LTH with upgraded primary energy savings. In addition, the impact of air-tightness retrofits for LTH implementation in selected Swedish residential buildings is of interests.

In the simulation Consoli Retro are employed to simulate the energy performance. It is revealed that the combined effect of floor heating/ ventilation radiators and air-tightness retrofits to 1/1.5 ACH can contribute 19 % to 36 % primary energy savings in total. However, different LTH systems and archetypes have varies sensitivities to air-tightness retrofits. Benchmark the impact of air-tightness to different LTH systems needs further investigations among other archetypes and on-site measures for future application of LTH on a larger scope.

KEYWORDS

Air-tightness, retrofitting, energy savings, low temperature heating, Swedish residential buildings

Nomenclatures	
Acronyms	
ACH	Air changes rate, h^{-1}
BBR	Swedish building regulations

CHP	Combined heat and power
COP	Coefficient of performance
DH	District heating
DHW	Domestic hot water
FH	Floor heating (hydraulic)
HP	Heat pump
LTH	Low temperature heating
PE	Primary energy
PEF	Primary energy factor
VR	Ventilation radiator (low-temperature)
T_1	Building type 1, Swedish slab houses (low raise), before 1950
T_2	Building type 2, Swedish slab house (three- to four storeys), 1960–1975
T_3	Building type 3, Swedish slab house (high raise), 1970–1975
Symbols	
$U - value$	Heat transfer coefficient of building elements, W/m^2K
t_{op}	Operative temperature, ℃
t_a	Air temperature, ℃
t_r	Mean radiant temperature, ℃
$E_{F,HOB}\ (i)$	Energy for fuel type *i* during heat production provided in heat boilers
$E_{F,CHP}\ (i)$	Energy for fuel type *i* during heat production provided in CHP
$PEF_{HOB}(i)$	Primary energy factor for fuel type *i* during heat production provided in heat boilers
$PEF_{CHP}(i)$	Primary energy factor for fuel type *i* during heat production provided in CHP
$\alpha_{h,i}$	Allocation factor for on-site or off-site production for fuel type *I*
Φ_E	Total energy demand, kWh/m^2
Φ_H	Monthly heating demand, kWh/m^2
Φ_{EL}	Electricity demand, kWh/m^2
Φ_{DHW}	Domestic hot water energy demand, kWh/m^2
$\Phi_{H,T}$	Transmission heat loss, kWh/m^2

1 INTRODUCTION

In Sweden, existing residential building stock comprises approximately 2.5 million dwellings, including apartment units and multi-family houses, and approximately 2 million detached or semi-detached single-family houses/villas [1]. The energy usage in this part amounted to 147 TWh in 2012, equivalent to almost 40 % of the final overall national energy usage [2]. As a baseline and essential technique, energy retrofitting is considered as an effective way to accelerate the sustainable transformation of existing Swedish building stock [3]. However, the industry approach and pilot project typically oriented with operational energy costs savings or tap-water savings/treatments, therefore, the retrofitting solutions tend to be highly case-specific and conventional, the primary energy saving potentials are limited [4][5][6].

As an energy-efficiency alternative, low temperature heating (LTH) technology has shown promising advantages and shortcuts to improve the efficiency of heat supply in terms of improved coefficient of performance (COP) with HP (heat pump), thermal comfort contributions and easily installed solution [7]. The advantages further provides more renewable based heating solutions with upgraded primary energy (PE) savings [8]. Nevertheless, theological studies have revealed that the air-tightness and energy demand of the existing buildings play major roles for the energy performance of LTH [9][10]. More importantly, little is known about the impact of air-tightness, particularly to those buildings which are planning to be renovated by low-temperature ventilation radiator (VR) or hydraulic floor heating (FH). Available models and studies from other countries are mainly based on local building energy codes and national heating directives. For example, Hasan et al. [8] and Cellura et al. [11] investigated both the delivered and primary energy saving potential of FH and low temperature radiators with respect to the Finnish climate condition. The findings revealed that with a reduction of supply/return temperature to 40/35℃, the LTH can save both delivered energy and PE without compensations on thermal comforts (1.0 m-1.3 m elevations). Furthermore, the energy usage of FH in the bathroom of the studied buildings can be amounted up to 33% to 43% of the total energy use. Specific to Swedish residential buildings, Energy Europe TABULA project [12] performed a general energy retrofitting guideline based on 44 typology categories of existing Swedish residential buildings for simplified heating system alternatives with respect to energy demand retrofits. Zou [13] developed a bottom-up approach to classify and assess existing Swedish buildings by improving the air infiltration database and construction techniques. Hesaraki and Holmberg [14] and Myhren and Homberg [7] evaluated long-term energy savings by low-temperature VR in Swedish multi-family houses. It is found that with the air-tightness level of 0.68 l/(s m^2), annual on-site measurements shows 48 kWh/(yr m ^{2}) to 55 (kWh/yr m ^{2}) energy usages for both space heating and DHW can be achieved when the buildings are equipped with LTH and HP. Gustavsson, Dodoo, Truong and Danielski [15][16] modeled the combined effects of heat supply and demand retrofits considering four major types of heat production systems in Sweden. It is found that the PE savings are largely dominated by the heat producing systems and the capacities to reduce the existing energy demand, in which air-infiltrations are commonly one of the most sensitive parameters for the studied archetypes. Other possible software and modelling techniques, including IDA ICE, Design Builder/EnergyPlus, Trnsys, eQuest$^{@}$, have been employed in some LTH practices to evaluate different heating parameters that impact the energy performance and thermal comfort before and after retrofitting [8][17][18][19]. The models are capable of providing relatively accurate one- or multi-zone air temperature and radiant temperature simulations for the reference buildings. However, these tools have had limited usage in retrofitting Swedish residential buildings and are not easily adapted to larger contingents of similar archetypes under Swedish climate conditions. Based on the target, this study simulated the PE saving potentials led by LTH retrofits and further defines the impact from air-tightness variances based on the current air penetration levels in the selected archetypes.

2 METHODOLOGY AND SIMULATION MODEL

2.1 Energy performance model

The main advantages of installing LTH in retrofits are the potential of reducing primary energy and providing more sustainable heating energy alternatives along with thermal comfort contributions. Designed with Excel tools, Consolis Retro is employed in the study. The model is based on the simplified calculation and parametric analysis of energy usage, applying EN ISO 13790 calculation methodologies [20]. The model is capable of handling 1 or 2-zones at the same time for the reference building. The building block was set heat balanced with variable major parametric factors that impact the heat loss and heat distributions in the calculation zone. Parameters are set previously to indicate the building archetypes. The total net energy usage Φ_E is calculated from Equation (1):

$$\Phi_E = \Phi_H + \Phi_{DHW} + \Phi_{EL} \tag{1}$$

To simplify the calculation process, the transmission heat loss $\Phi_{H.T}$ is calculated by building envelope parameters and linear thermal bridges. Old Swedish slab houses might be constructed with no insulations with cold surface temperatures, this will lead to rather high differences between operative and air temperature [11]. In another word, occupants may feel colder than the air temperature is set 20 °C. As a result, 22°C is set for air temperature of heated space in the modeled archetypes. The operative temperature of the buildings are gained by Equation (2)

$$t_{op} = (t_a + t_r)/2 \tag{2}$$

In the model, delivered energy are calculated as net building demand of the selected archetypes, primary energy saving potentials is calculated by both the delivered energy and primary energy factor (PEF) variances before and after LTH retrofitting, which is obtained as Equation (3) [21]:

$$\mathrm{PEF} = \frac{\sum_{i=1}^{n}(E_{F,HOB\,(i)}*PEF_{HOB(i)})+\sum_{i=1}^{n}(\alpha_{h,i}*E_{F,CHP\,(i)}*PEF_{CHP(i)})}{\sum_{J=1}^{n}Q_{del,j}} \tag{3}$$

In Sweden, district heating (DH) accounted for around 60 TWh in 2013, which is considered as the most common space heating system for existing multi-family houses and apartment blocks. In single family houses, district heating and electricity are used in 7 % and 22 % of all detached and semi-detached houses, respectively[22]. Swedish district heating are mainly produced by combined heat and power (CHP) for residential buildings, it has a PEF of 0.5-1.3 depending on the energy sources (waste heat, biomass, coal and natural gas, etc) [23].Within the last decades, heat pump (HP) shows increasing competences with DH because of its PE saving potentials when designed with LTH. Up to 2012, Sweden has the largest application of HP systems for both new and retrofitting buildings among EU [24]. The PEF of LTH combined HP systems are calculated based on the supply temperature and the COP of the heat pump [25]. Validation and testing of the calculation model was conducted [26]. The tool was compared with IDA ICE and EnergyPlus for accuracy analysis, with an acceptable agreement of 0 to 8 % error [27]

2.2 Air-tightness retrofits in existing Swedish residential buildings

Air-tightness is one of the most significant parameters to not only provide hygienic protection for the occupants but also reduce the operational energy usage[28]. Sweden has a relatively long heating season (6-7 months), it is found that the impact of air-tightness can be higher than transmission heat loss through building envelopes in some Swedish detached/semi-detached houses. In addition, the large application of exhaust ventilation systems in Sweden led to a relatively higher air-infiltration compared with balanced ventilation systems [29]. The air-tightness retrofits have been commonly recommended in some conventional renovation projects, nevertheless, despite measurements and blow-door tests have been conducted in pilot houses, the existing information on ait-tightness and its impact to energy usage are still scarce, particularly for those buildings heated with reduced supply temperature lower than 50℃ [30]. In 2012, the revised BBR (Swedish building regulations) provides no specific limit values in respect of tightness, but the significance of good ventilation is stressed in an advisory in order to decrease the moisture damage and hygienic issues. To obtain a well performance of LTH, a good guideline minimum value for 0.80 l/(s m^2) and 0.35 l/(s m^2) surface area at a pressure difference of +/- 50 Pa are recommended for existing and new Swedish residential buildings, respectively [31]. However, 1400 existing Swedish building stock statistics from derived field studies shows that the actual air-tightness level ranges from less than 0.3 l/(s m^2) to approximately 1.5 l/(s m^2), at pressure difference of 50 Pa [13]. And it varies largely among different archetypes and exhaust/balanced ventilation systems. Figure 1 shows the air-tightness level of existing residential buildings in Sweden compared with other countries [13][29].

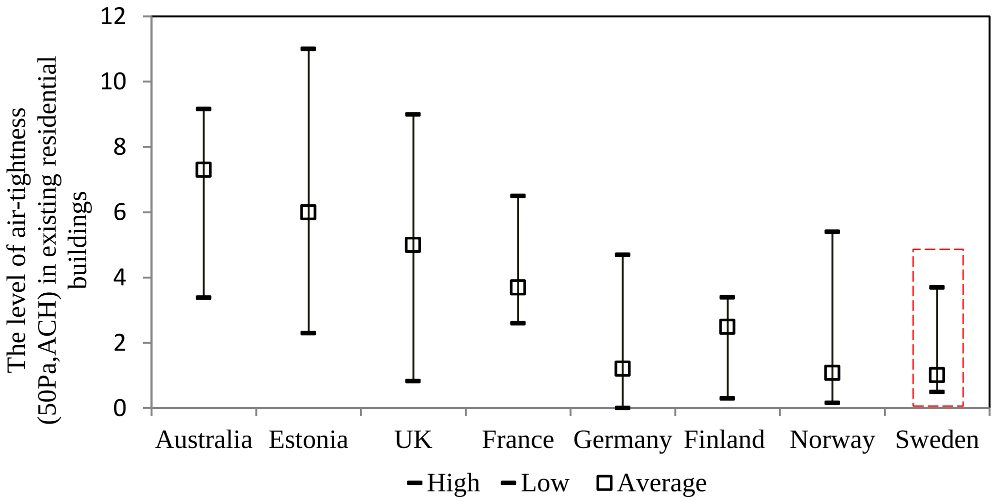

Figure 1 The air-tightness level (50 Pa) of Swedish residential buildings compared with other countries.

The existing retrofitting techniques in Swedish residential buildings are based on the following three perspectives in the models [32]:

- Insulate the air gaps existed in joints between ceiling/floor/balcony to the walls, particularly for two or three storey slab houses.
- Install more efficient mechanical (balanced preferably) ventilation systems.
- Insulate the ventilation studs and piping systems.

The improvements and variances of air-tightness level are based on the existing performance of in the selected building types.

2.3 LTH retrofits and selected archetypes

The heating system in Swedish slab houses is usually district heating (DH), occasionally heated partially by electricity, gas, oil and renewable sources in some renovated cases [23]. To standardize the archetypes, low-rise slab houses are classified in this study by age according to three periods: pre-1950 (T_1), 1951-1960 (T_2). Additionally, special booming time 1965-1975 for high slab apartments (T_3) is chosen in the category. Two types of LTH are selected as the retrofitting alternatives: FH and VR, the structure and components are shown in Figure 2. For FH, in order to fit the existing old slab floor in renovation practice, overlay floor panels are installed with embedded PEX tubing circus, shown in Figure 2, left. FH is set as 100 W/m^2 heat outputs with design temperature 35 °C/ 29 °C. The coverage area is 12 m^2/circuit. The new floor layers are set as tiles in bathroom and laminate in other rooms. For VR (shown in Figure 2, right), the cold air is preheated by the radiator through the slab wall vents and filtered as clean warm air. Because most of the selected multi-family houses have installed exhaust ventilation, 10 P pressure drop between indoor and outdoor are set as the driven force for the cold air , no extra energy is needed for the convection [33]. The supply/return temperature is designed with 45 °C/ 35 °C in the study for VR.

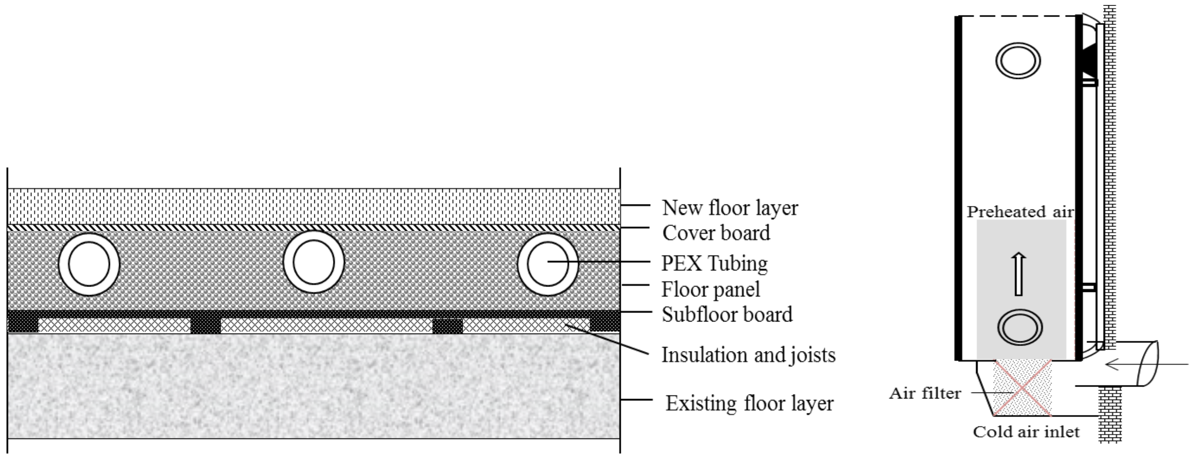

Figure 2 Left, The principle of overlay FH, floor panel units embedded with PEX tubing and, Right, VR, designed as preheated air and low-temperature radiator

In each archetype, four retrofits are designed and compared for implementing LTH, these are indicated in Table 1. For system 1, living rooms are renovated with VR under the windows, two-pipe hydraulic existing radiators are kept in the rest rooms. For system 3, hydraulic FH are implemented only in bathrooms, the rest rooms are kept with existing high temperature radiators. For system 2 and 4, the whole buildings are renovated by VR and FH, respectively. The parameters of the LTH retrofits are indicated in Table 1.

The building material for floors and ceilings in the studied archetypes was primarily 10- 50-centimeter-thick, reinforced concrete, and relatively thinner slabs were applied as exterior paving and coating [6][1]. Although Swedish slab houses may have different facades and terraces, the buildings' main elements and service systems are similar. Three types of Swedish slab houses (T_1, T_2, T_3) constructed during different years were selected for this retrofitting investigation. The archetypes, building features and parameters were generalised and collected through surveying the statistics; these are presented in Table 2. The corresponding energy system retrofits are designed as water-to-water HP. The PEF are calculated by the supply temperature and the COP of HP [34], shown in Table 3.

Table 1: LTH retrofitting designs

System	**Retrofit room**	**Supply/return temperature (℃)**	**Non-retrofit room**	**Supply/return temperature (℃)**
System 1	VR in living rooms	45/35	Conventional radiator	55/45
System 2	Whole building VR	45/35	-	
System 3	FH only in bathroom	35/30	Conventional radiator	55/45
System 4	Whole room FH	35/29	-	-

Table 2: Selected archetypes and energy systems for retrofitting analysis

	T1	**T2**	**T3**
Archetypes			
Dwelling types	Single family house	Multi-family house	Apartment block
Age	Before 1950	1960-1975	1970-1975
Foundation	Lightweight concrete	Concrete slab	Polished concrete
External wall	10 cm mineral wool insulation	13 cm mineral wool insulation	15 cm mineral wool insulation
Window	Double glazing, aluminium frame	Double glazing, timber frame with ventilation fan	Double glazing, aluminium frame with one-side ventilation fan
Roof /ceiling	Brick and cutter coke ash insulation	Flat roof covered with cardboard and mineral wool	Concrete foundation with

			galvanized sheet metals, mineral wool insulation
Ground floor	Linoleum and coke ash	Slab covered with linoleum mats or plastic board	Slab covered with mineral wool or linoleum
Heating	Furnaces /electricity	District heating	District heating
Radiator	Furnaces/electricity	Single-pipe hydraulic radiator	Two-pipe hydraulic radiator
Ventilation	Natural ventilation	Exhaust ventilation	Exhaust ventilation
Energy mix	Gas/oil/partly el.	CHP	CHP
Air-tightness	2 ACH	2 ACH	5 ACH

Table 3: PEF modeling of LTH retrofits

Supply/return Temperature (℃)	**Heating system**	**COP**	**Energy mix**	**PEF**
70/60	Conventional supply temperature District heating	-	CHP	0,90
50/40	Medium supply temperature output District heating	3.1	CHP	0.80
45/35	Low supply temperature output	3.5	HP	0.68
40/30	Low supply temperature output	3.6	HP, Nordic mix	0.68
35/29	Low supply temperature output	3.8	HP, Nordic mix	0.60

3 REUSLTS AND DISCUSSION

All archetypes were selected within the same Swedish climate zone III, Stockholm, for comparison. Figure 3 shows the monthly energy flow before and after implementing retrofitting for the selected archetypes. Among the four archetypes, system 4 (whole building with FH) shows the largest energy savings from 26 % to 33 % after retrofitting compared with other systems. Among all the archetypes, relatively new archetype (T_3) shows the highest PE saving potentials. Followed by system 2 and system 1 (whole building VR and living room VR), PE savings range from 20 % to 25 % and 15 % to 18 %, respectively. Among the three archetypes, older houses (T_1) show lower saving potentials compared with apartment block. The reason could be that the old multi-family houses are more sensitive to the air-infiltrations due to their existing leaky conditions. The exhaust ventilation system installed in T_2 and natural ventilation in T_1 make the envelope leakage larger when installed with VR, compared with other archetypes. System 3 shows the lowest energy saving potentials compared with other types in both FH and VR. It didn't show promising energy savings in selected single family houses and low-raise multi-family houses. Furthermore, T_1 shows the lowest energy savings when renovated only in bathroom FH (system 3). The reason can be its limited heated bathroom areas. Among the archetypes, the bathroom FH retrofits shows the greatest savings for apartment block T_3 (5 % savings). Attention should be paid that the operative temperature in bathrooms sometimes can be 3℃ to 5 ℃ higher than the rest rooms, practically. With respect to the occupations, this will lead to an increased uncertainties when focusing on modeling the energy savings only in bathrooms and its conjunct effects with other heated zones [8].

Figure 4 shows the primary energy saving potential after implementing both LTH and air-tightness retrofits. The impact of air-tightness shows linear reduction of PE. Due to the high variety of ventilation vent designs in the windows, the high slab house (T_3) is set with greater variances. The rests of the archetypes are set as approximately from 2.0 ACH to 1.5/1.0 ACH before and after retrofitting. The combined effect of LTH and air-tightness shows that the energy saving potentials from 28 % to 36 % in most of the archetypes can be achieved. Among all the archetypes, T_2 shows the highest sensitivity to the air-tightness retrofits, particularly for VR. When the air-tightness level is reduced to 1.5 ACH, 38 % of PE savings can be achieved by VR retrofits. In addition, T_3 shows the lowest impact by air-tightness to the LTH in general (approximately 6 % to 19 %). The reason can be the existing ventilation systems have a relatively higher performance in the archetypes. In addition, the modern constructions made the building envelope much less sensitive by the air-infiltration through joists and ventilation ducts.

4 CONCLUSIONS

In the study, a simplified calculation model is developed and integrated with parametric investigations to three major Swedish archetypes that are planned to be renovated with FH and VR. PE (Primary energy) saving potentials led by LTH retrofits is in focus. The variation in terms of air-tightness levels among the archetypes are of interests. It is revealed that the PE savings can be up to 33 % depending on the LTH systems. FH in all rooms shows the highest savings in most archetypes while VR shows high savings in relatively modern archetypes. The air-tightness retrofits shows 4.5 % to 6 % energy savings in most archetypes except the highest savings 18 % in T_2. The combined effect of air-tightness and LTH retrofits can contribute 19 % to 36 % PE savings in total; however, the VR retrofits shows high limitation and sensitivities in T_2. Furthermore, high slab houses T_3 shows the relatively stable PE saving levels and the impact by air-tightness is relatively low among all the studied archetypes. Given the limited data sources and the basic target for performing the air-tightness impact analysis, retrofits from building demand sides in terms of wall insulation, windows and on-site measurements are not included in the current analysis, which will be further performed and verified.

5 Acknowledgements

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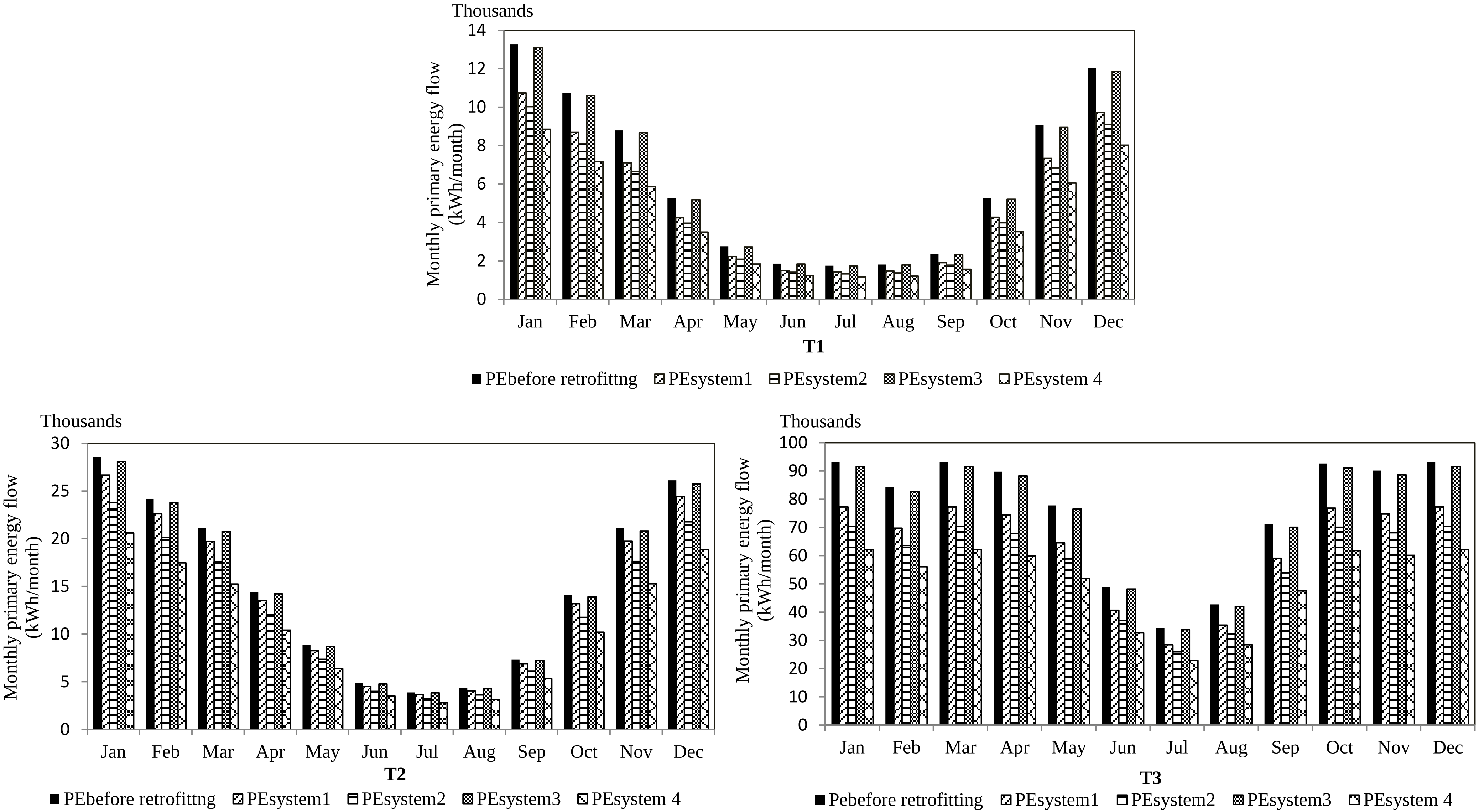

Figure 3 Energy monthly flow of the archetypes installed with LTH systems before and after retrofitting

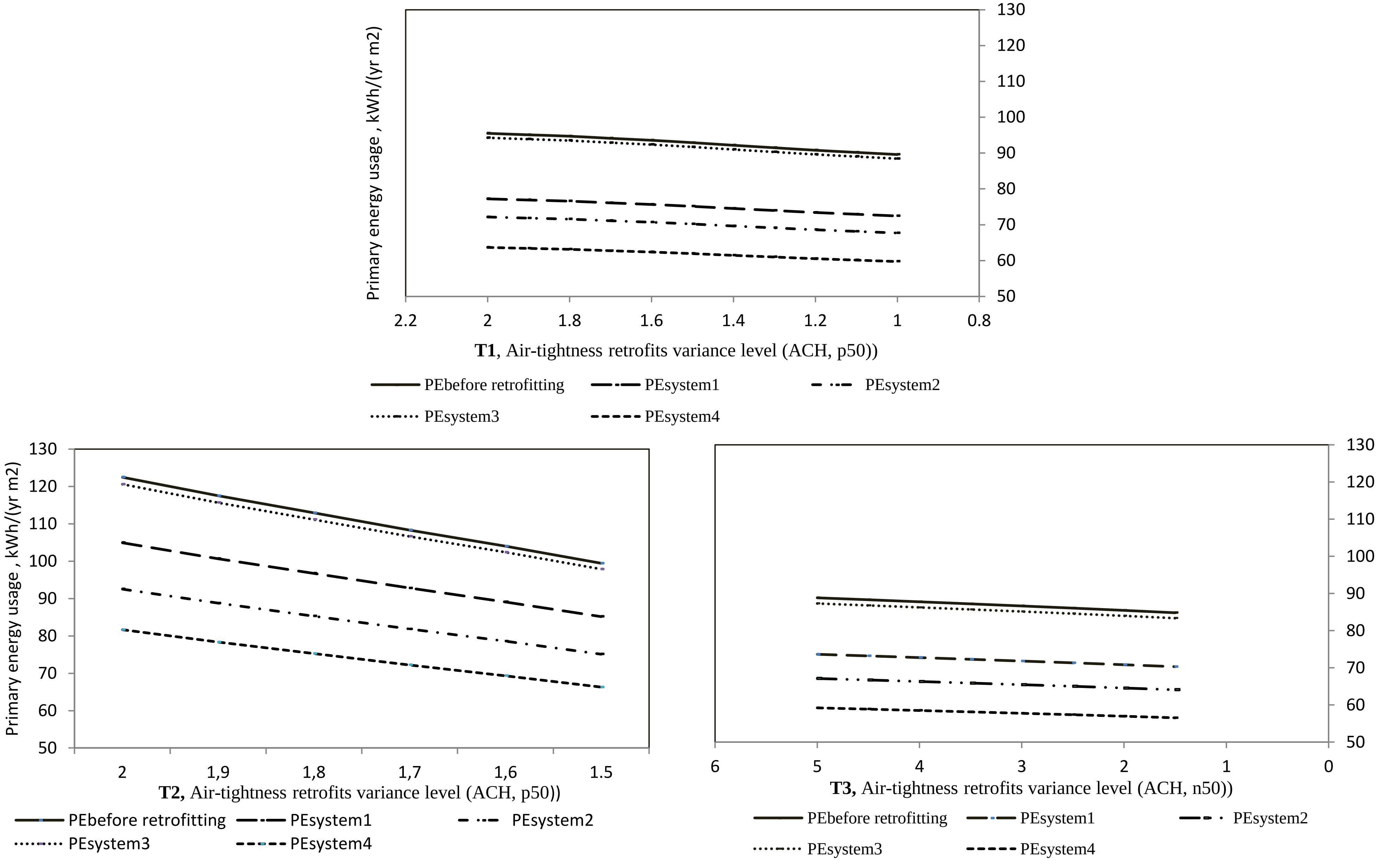

Figure 4 The impact of air-tightness variance levels to the primary energy usage of studied archetypes (kWh/yr m^2)

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