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Retrofitting with low-temperature heating to achieve energy-demand savings and thermal comfort

Qian Wang*, Adnan Ploskić, Sture Holmberg

Division of Fluid and Climate Technology, Department of Civil and Architectural Engineering, KTH Royal Institute of Technology, Brinellvägen 23, Stockholm 100 44, Sweden

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ABSTRACT

Low-temperature heating (LTH) has shown promising advantages and shortcuts to improve the thermal performance of radiators. An investigation, on which renovation measures from the demand side, can cope with LTH or should be selected as 'pre-retrofit' to provide building performance improvements, were carried out in this study. IDA ICE was selected to perform the simulation of a typical Swedish multi-family archetype. Five common energy-demand retrofit options were analyzed. Thermal performance and operational energy savings before and retrofitting were in focus. The results showed that LTH with each of the energy-demand retrofit options can improve the thermal performance to an acceptable level. LTH-combined ventilation retrofitting showed the highest contribution in air temperature, predicted percentage of dissatisfied, and energy savings for space heating. Combining LTH with external wall retrofitting showed the highest effect in operative temperature and total operational energy savings. Combining LTH with all energy-demand retrofitting as a package can achieve 55.3% and 52.8% total delivered and primary energy savings, respectively. This research showed that the existing building can cope with LTH when any of the five energy-demand retrofit options from a thermal performance perspective. Optimal selection shall be based on their abilities to reduce operational energy.

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 residential building stock amounted to 147 TW h in 2012, which amounted to nearly 40% of the overall final national energy usage [2]. Among all the end-users in existing buildings, 60% of the final energy is used for space heating and domestic hot water production (DHW) [3]. With regard to energy retrofitting accomplished so far in Sweden, 17% of final energy savings were achieved by housing stock renovations in the past decades. However, the total energy utilizations in Sweden have not yet been largely reduced [2]. The greatest portion of retrofitting measures is, by far, still envelope- and ventilation-based. These commonly require multiple visits, largely impacts to occupants, and have long installation periods. Accelerating the sustainable transition of Swedish housing stock is still plagued by the disadvantages of conventional renovation, as well as challenges concerning how to make efficient retrofitting decisions and a lack of standardized technical directives. Despite the urgent need for solutions, very little investigation is currently being carried out to design and promote more efficient retrofitting technologies. These are performed in this study with both energy-demand savings and improved perceived thermal comfort.

1.1. Previous studies

As an energy-efficient alternative, low-temperature heating (LTH) technology has shown promising advantages and shortcuts to improve the efficiency of heat supply. Practically, it provides easily installed solutions in renovation projects, thermal comfort contributions, and improved coefficient of performance (COP) for heat pumps [4]. For district-heated houses, reduced supply/return temperature also have potentials to decrease the heat losses from district heating grids, and to improve power-to-heat ratio for combined heat and power (CHP) plants [5,6]. Additionally, transforming the energy mix from a high temperature fossil fuel-based system to an emission-free one bears the potential for a CO_2 emission-free operation. Moreover, these save up-stream primary energy and long-term operational costs for district heating. Innovatively, LTH

* Corresponding author. Tel.: +46 87907927; fax: +46 87907927.
E-mail addresses: qianwang@byv.kth.se (Q. Wang), adnan.ploskic@byv.kth.se (A. Ploskić), sture.holmberg@byv.kth.se (S. Holmberg).

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Nomenclatures

ACH	air-changes rate (h^{-1})
AHU	air-handing unit
BBR	Swedish building regulations (Boverkets byggnader)
COP	coefficient of performance
CHP	combined heat and power plant
DHW	domestic hot water
LTH	low-temperature heating
IDA ICE	indoor climate and energy performance simulation program
MP	Million Program (1965–1975)
PPD	predicted percentage of dissatisfied, at occupant 1 (%)
PMV	predicted mean vote, at occupant 1

systems provide larger opportunities for an integrated low-exergy renewable energy mix, such as ground source heat pump and solar thermal collectors for reducing the peak loads of both space heating and DHW production [7,8]. Previous studies have shown that low-temperature space heating methods are among the highest category to comply indoor environment quality and energy supply efficiency in both single family and multi-family houses [9,10]. It has been revealed that the combination of conventional radiators with fresh-air vents showed upgraded thermal comfort and higher temperature gradients [11,12]. Component performances have been tested and measured [13,14]; moreover, theoretical analysis and computational fluid dynamic simulation showed that low temperature radiators can efficiently block cold draught and reduce the supply temperature curve to 40–45 °C without lowering thermal outputs [15,16].

However, most of the studies carried out were 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 [17,18]. It was found that for leaky multifamily building stock with high energy demand and cold surface temperature, there is a risk that LTH may not be able to provide an operative temperature high enough to maintain the required thermal comfort level, and that the contributions to operational energy savings will be limited [18]. In another word, additional 'pre-retrofit' from the demand side is arguably required. However, how to select the corresponding energy-demand renovation measures is not sufficiently found in literatures. Investigations on their individual/joint effects after the proposed retrofitting strategies, concerning both operational energy savings and thermal comfort contributions, are not reported in the literature.

1.2. Objective

In this study, LTH-combined retrofitting solutions are designed and analyzed for one typical existing Swedish multi-family house. The individual/joint effects of energy-demand saving measures with LTH in retrofitting are in focus. The findings aim to provide technical and practical decision supports and guidelines, for both occupants and stakeholders, for future large-scale implementation of LTH in existing Swedish residential buildings.

2. Methodology

2.1. Selecting the representing archetype and service systems

Sweden experienced a residential building boom during 1950–1975 (the so-called "Record Years"), especially during the implementation of the Million Program (MP) between 1965 and 1975. During those 25 years, 1.4 million dwellings were erected, including single-family houses, multi-family houses (6–8 storey apartment blocks and tower houses), and some 2–3 storey apartment blocks [1]. Particularly during the MP era, 2–3 storey low-rise multifamily houses were constructed en masse. This archetype consists the basis of the MP era housing stock, commonly with similar architectural designs and construction materials [19]. In order to mass-produce the houses, the construction process was simplified in this archetype. After 40–50 years of usage, this archetype cannot meet energy and thermal comfort requirements set by the latest Swedish building regulations (BBR). More systematic strategies and efficient retrofitting are needed for future standardized district/city-level implementations.

Fig. 1. The appearance of the selected archetype (northern façade).

A 2-storey, low-rise multi-family house located in Stockholm was selected to represent the investigation, as shown in Fig. 1. Bookshelf frames were supplemented with concrete slabs as the building foundations. Flats were directly built upon the basements, which normally had heights of 2.66–2.71 m [1]. The façade of the housing stock was coated by brick strips. Typical MP houses were designed with two types of flats: 76 m^2 heated floor area with two bedrooms, one living room, one kitchen, and bathroom, as shown in Fig. 2a; or 50 m^2 heated floor area with one bedroom, one living room, one kitchen, and bathroom, as shown in Fig. 2b. Each flat had one storage room. Only minor maintenance work has been done so far. Table 1 summarizes the main building envelope parameters and construction materials.

The selected building had a total heated floor area of 1580 m^2. Heating system before retrofitting was conventional high-temperature district heating with a reference supply/return temperature of 75/50 °C. Ventilation system before retrofitting was exhaust ventilation without heat recovery. The exhaust grills were placed in both bathrooms and kitchens. Each kitchen and bathroom was equipped with one fan to extract air (decentralized). The flow rates in kitchens and bathrooms were 1.5 l/s m^2 and 1.8 l/s m^2,

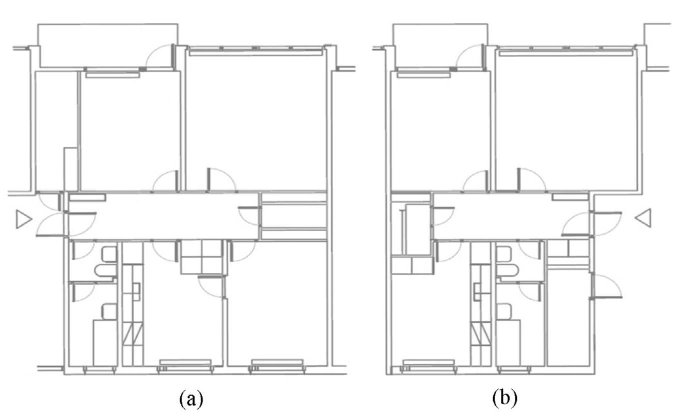

Fig. 2. Two types of flats in the studied archetype: (a) 76 m^2, (b) 50 m^2.

Table 1
Descriptions of the building envelope materials and parameters.

Basic building data before retrofitting	
Housing design	Two-storey, designed as parallel or perpendicular with basements (flat height: 2.71 m)
Windows	Double glazing window with aluminum cladding and natural ventilation openings (with windcatcher)
External walls	Concrete slab foundation with reinforced brick beams and brick façade, 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
Roof/attic	Light slope roof covered with cardboard; eaves lined with trapezoidal sheet metals; 200 mm mineral wool insulation
Basement	Concrete slab, directly on gravels. 20 × 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 asfaboard; concrete studs

respectively, according to the minimum exhaust ventilation flow-rate limitation set by BBR for residential buildings. Air-tightness level was 2.5 ACH under the pressure differences of ±50 Pa, which were calculated as wind-driven ACH. Wind profile was based on the suburban inventory, Ashrae-1993 [20]. Conventional hydronic radiators were installed under windows. The number of radiators in each flat was: six in Flat Type 1 (Fig. 2a) and five in Flat Type 2 (Fig. 2b). The design of the radiators was based on the principle that radiator were sized based on the design loads for the design outdoor temperature. In usual practice, the widths of radiators were further considered in order to fit the window widths and avoid cold draught caused by window surfaces and leakages from window claddings/joists. Annual outdoor temperature was based on the climate data of Stockholm/Bromma, shown in Fig. 3. The lowest design temperature period was marked with a red box: −18 °C in February. There was no cooling installation in the building. An hourly profile of internal heat gains from occupants, equipment, and lighting for one day was assumed based on the living schedule shown in Fig. 4a–d. Three schedules were categorized as follows: working-day schedule (Fig. 4a), holiday schedule (Fig. 4b), and DHW-usage schedule (categorized as working days (Fig. 4c) and holidays (Fig. 4d)). These schedules were assumed as constant both before and after retrofitting. The number of occupants in each flat was assumed as four in Flat Type 1 (Fig. 2a) and three in Flat Type 2 (Fig. 2b).

2.2. Simulation method

IDA ICE 4.6 (Indoor Climate and Energy performance simulation program) was applied for the simulation of thermal performance and operational energy modeling. The accuracy of the IDA ICE program was evaluated by the IEA Solar Heating and Cooling Program, Task 22, Subtask C, in 2003 [14]. The applications of IDA ICE for LTH modeling were further validated in several studies, for both single-family houses and multi-family houses. It was found that good agreements with measurements had been achieved for the air and surface temperature for different types of LTH systems in multifamily houses [10,18]. For single-family houses equipped with LTH, it was revealed that the maximum deviation of annual energy modeling with on-site measurements was below 7% [17]. 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 constructed model in IDA ICE is shown in Fig. 5. In the simulation, it was assumed that there were

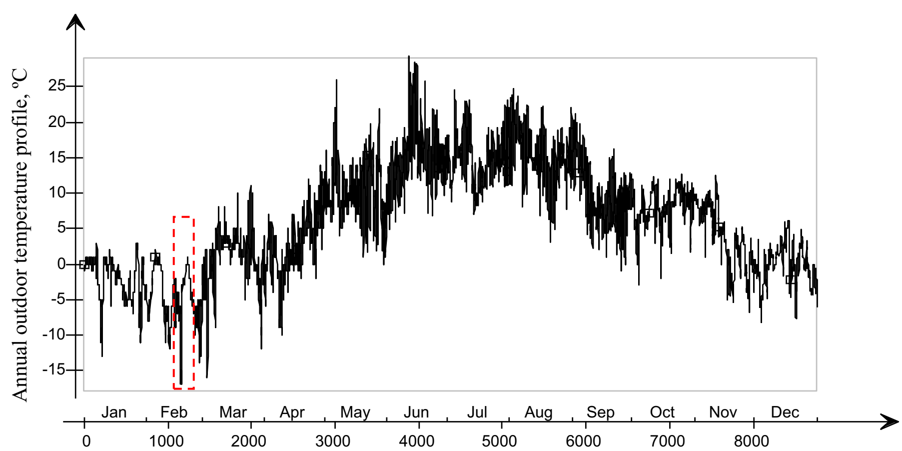

Fig. 3. Annual outdoor air temperature profile used in the study (Stockholm/Bromma). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

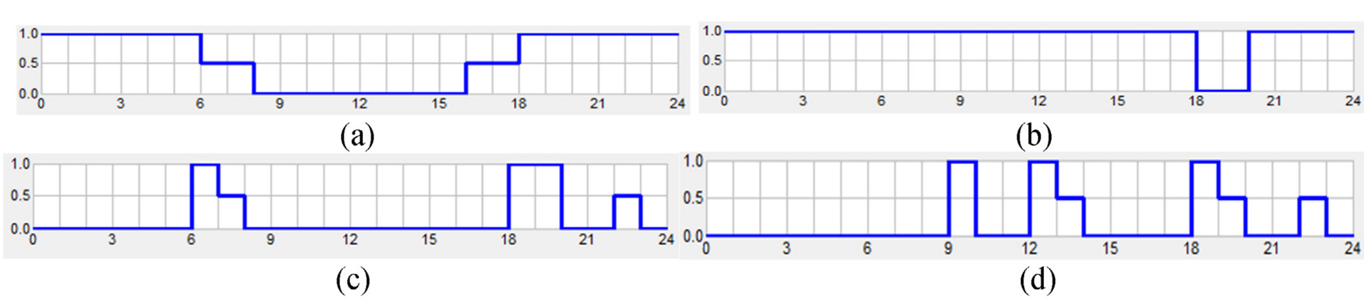

Fig. 4. Occupancy and DHW schedule selected in the model (for *y*-axis, 1 presents the full occupancy and 0 presents no occupancy). (a–b) Working and holiday schedule for space heating. (c–d) Working and holiday schedule for DHW.

Fig. 5. Constructed building model in IDA ICE (southern façade).

no occupancies and equipment in storage rooms and basements. Internal openings (internal doors and corridor doors) were controlled equally to the living schedule of the corresponding rooms. External openings and windows were controlled by indoor temperature. When the indoor room temperature is above 26 °C, the windows and fresh-air openings were simulated as partly open.

The evaluation of energy performance was based on the Swedish BBR regulations about delivered energy for residential buildings and the European standard EN15316-4-5 boundaries for primary energy estimation [22,23]. Specific delivered energy (often referred to as 'purchased energy') was selected to represent the level of final operational energy, in normal use during a reference year, needs to be supplied to a building for space heating, comfort cooling, DHW and building's property energy. The building's property energy consists of the electricity used for building service systems, and where the electricity usage unit is, under or affixed to the exterior of the buildings [22]. This means that all permanently installed public lighting fittings (internal public spaces and utility rooms), heating cables, fans of AHU, motors, controls and circulation pumps shall be included in the calculation. Domestic electricity usage (electricity used for household appliances and domestic purposes) was not included. Specific primary energy was selected to represent the level of primary operational energy, in which corresponding up-stream energy mix and energy producing systems were considered. The modeling of specific primary energy was estimated by multiplying specific delivered energy with the corresponding primary energy factor of the investigated energy supply system (space heating, DHW production, and building's electricity).

2.3. Design retrofitting combining LTH with energy-demand savings

As introduced in Section 1, this study aims to investigate the individual/combined effects of LTH with energy-demand saving measures such as 'pre-retrofit'. Thus, two types of energy-demand retrofitting were selected to (1) reduce the transmission heat loss through building envelope, and (2) reduce the ventilation heat loss. The concerns of energy-demand retrofitting were based on three fundamentals: current energy utilization levels of the building; prevailing local Swedish climate conditions; and the specific characteristics of commonly implemented retrofitting measures from the Swedish building industry. Fig. 6 shows the statistics of energy-demand retrofit options in existing renovation projects achieved so far from Swedish multi-family housing stock. The selections of energy-demand retrofitting were based on two reasons:

(1) Retrofit options were based on on-site survey and statistics [24–26]. Fig. 6a shows that four major commonly implemented measures in building-envelope retrofitting are: adding insulations on walls and façade renovation; window replacements; adding insulations on attic/roof; and ground-floor renovations (deviations are based on different archetypes of multi-family houses). New insulation layers on the walls facing the inside (internal walls) are often not included for space reduction and condensation problems in MP slab houses, which has been reported in the literature [27,28]. Fig. 6b shows that the ventilation systems in Swedish multi-family houses are shifting from natural/exhaust ventilation to ventilation systems with heat recovery (trends are shown by the mean percentage of installed ventilation with heat recovery, marked as a red line). Heating is served by both recovered ventilation supply and radiators. Minimum recommended ventilation flow is 0.35 l/(s m^2) or 4 l/s per occupant, as set by BBR [22]. However, engineering design guidelines have specified the minimum exhaust ventilation flow rate from kitchen and bathrooms as 10 l/s if the heated-floor area is less than 10 m^2 [29]. For non-low pollutant rooms, 2–3 l/(s m^2) is practically recommended for ventilation flow rate [30].
(2) Retrofit options are further designed with respect to previous findings in this archetype [27,31]. Except the above retrofit

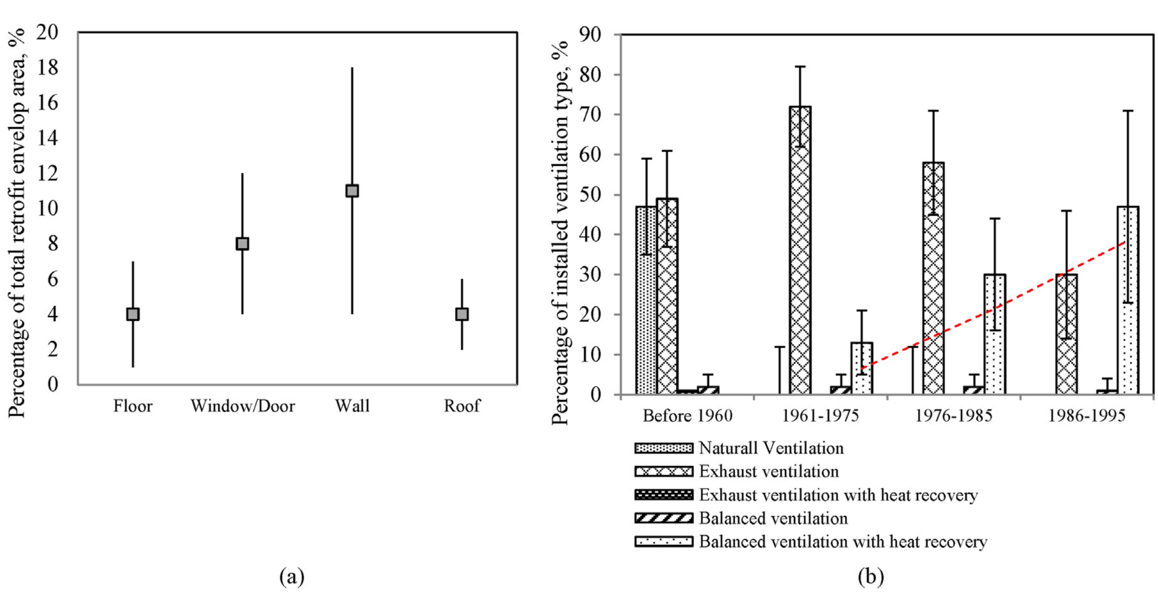

Fig. 6. Energy-demand retrofit options in Swedish multifamily housing stock before 1995. [24,25]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Selected retrofitting and technical description before and after retrofitting (retrofitting is numbered from 1 to 5 and additional combined retrofitting consisting 1–5).

Retrofit number	Technical description of the energy-demand retrofitting (measure 1–5 listed as following)	Technical parameters before retrofitting	Technical parameters after retrofitting
R1	**1.** Upgrade the air-tightness by 60% by adding extra insulation of ducts and pipes. Seal all cracks and air leaks in joists Seal all joints and intersections of the sheathing in the balcony and studs connecting with external wall with improved thermal bridges (replacing glazing and frames of window is not included)	2.5 ACH 1.2 W/m K	1 ACH 0.15 W/m K
R2	**2.** Existing ventilation system installed with heat recovery exchanger and required AHU. Heat recovery efficiency is addressed as 80%	Without heat recovery	With 80% heat recovery
R3	**3.** Replacements of the existing windows with high-performance glazing systems and window frames	U value = 2.85 W/m^2 K	U value = 0.8 W/m^2 K
R4	**4.** New insulation layers on the roofing and attic structures: 300 mm mineral wool insulations + roof tiles	U value: 0.26 W/m^2 K	U value = 0.08 W/m^2 K
R5	**5.** New insulation layers on the external walls: 150 mm mineral wool insulation + 15 mm sheathing	U value: 0.48 W/m^2 K	U value = 0.18 W/m^2 K

options summarized in (1) on-site surveys and statistics, existing studies also reported that improving the air-tightness and linear thermal bridges show high effectiveness to energy-demand savings in this archetype. Adding ground floor insulation shows relatively low effectiveness in this archetype [31]. As a result, five major energy-demand saving measures were selected in this study to combine with LTH for practice.

The selected five measures are briefly summarized as following: upgrade the air-tightness level and thermal bridges reductions (R1), ventilation retrofitting with heat recovery exchanger (R2), window retrofitting (R3), roof/attic retrofitting (R4) and external wall retrofitting (R5). The measures are further technically explained in Table 2.

The supply/return temperature for the ventilation radiator (after retrofitting) was constructed as 45/40 °C based on the design outdoor temperature. Lower supply temperature was not further considered for design outdoor temperature in this study. The reason lies in current technical limitations. For example, it is still technically unclear how to renovate conventional high-temperature district heating and how to further operate it with low-temperature supply. Pilot recommendations suggest installing secondary circuits with a mixing valve to lower the operating temperature and renovate the district heating substations [10,32]. However, most of the solutions have not been practically achieved. The relationship between supply water temperature and outdoor temperature is assumed as a linear function, between 26 °C in summers and −18 °C in winters. The constructed supply temperature curve is shown in Fig. 7. For each zone, the control of room temperature is set as 21 °C. For ventilation with heat recovery after retrofitting, the zones are connected to centralized air-handling units (AHU). Living rooms and bedrooms are supplied by fresh air that is pre-heated by the heat recovery units with rotating heat exchanger. The heat recovery efficiencies are set as 80%, which has been reported by empirical achievements from industry [33]. Exhaust grills are placed at kitchens and bathrooms, in which the air is extracted and filtered.

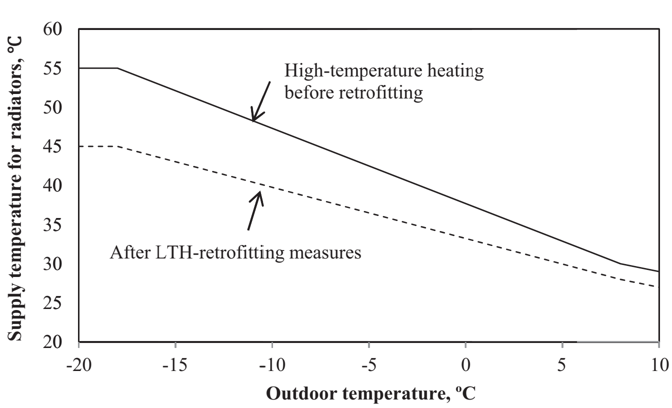

Fig. 7. Constructed supply temperature curve as a function of outdoor air temperature.

In summary, the modeling work is performed in the following three steps:

(1) Identify thermal performance and operational energy before retrofitting. In this step, thermal performance before retrofitting provided an 'as-built' situation, which was defined as the reference performance to further evaluate LTH-combined retrofitting efficiencies. A special focus was placed on finding the representing zone that has the worst existing thermal performance under the design outdoor temperature during the annual simulation.
(2) Energy-demand retrofitting was simulated individually with LTH. Air temperature, surface temperature, operative temperature, and operational energy were selected to evaluate the retrofitting efficiency. Both delivered and primary energy were presented separately to indicate the sustainability improvements.
(3) LTH combined with all selected retrofit options was simulated. The same thermal performance and energy criterion were selected, but with a focus on the combined effects of retrofitting packages. Energy usage after retrofitting was further compared with the limitation of Swedish building regulations (BBR). The reason for investigating the combined effect is based on the fact that interdependence exists between retrofit options and the total energy savings. A combination of all of the measures at their best level would not yield maximum operational energy reductions or would be net-zero building because concurrent effects exist. For example, when implementing heat recovery efficiency improvements with a reduction in ventilation airflow, changes in airflow do not decrease heating demand as much as was expected [31]. The reason is that the ventilation heat losses for the particular building were relatively low compared to the transmission heat losses. Thus when heat recovery is installed, slight reductions of ventilation air flow would not significantly reduce the total energy demand. The selected archetype is currently occupied as public-renting houses. Practically, retrofitting is commonly implemented as a package – rather than individually – in order to avoid multiple visits, which has been recommended in pilot studies [27].

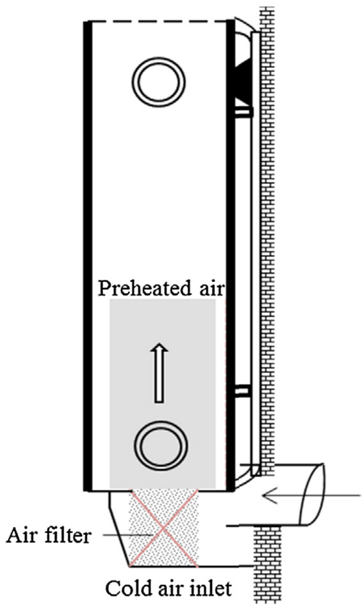

Fig. 8. The layout of a LTH-combined ventilation radiator.

A ventilation radiator was selected for this study. Radiators were designed with the same width and height as conventional radiators, but equipped with a ventilation vent connecting to outdoor fresh air. Increased temperature difference between radiator panels and passing airflows improved convective heat flows. No additional fan (radiator booster) was equipped below/above the radiator. Outdoor air was filtered and preheated inside the radiator, which contribute the thermal performance of radiators. The working principle of a ventilation radiator can be found in [4,13,17,34], and the product has been available in the market. Components of the ventilation radiator are shown in Fig. 8. Measurements and modeling results showed that supply/return temperature could be reduced to 35/28 °C to cover a heating demand of 30 W/m^2 by the studied ventilation radiator. The reduced supply/return temperature in hydronic circuits can benefit the performance of heat supply system, for example, heat pump. The *n*-value (radiator exponent) of the ventilation radiators was modeled as 1.29, based on the experimental results [13]. No extra energy is needed to operate the radiator. Normally, low-temperature radiators have average life spans of 40 to 50 years, which leads to a longer durability for maintenance and extended service life after retrofitting [35]. Low-temperature radiators were assumed as equipped with proportional controllers on water flow in each radiator in the IDA ICE simulation.

3. Results

Simulations were performed with a focus on evaluating the thermal performance (annual air/surface temperature, operative temperature) and annual operational energy for space heating, DHW production, and building's electricity demand. The flat that has the largest heating demand in a year was found: it was observed that the worst flat was located at the most northwest position of the building, shown by the frame in Fig. 9. The lowest mean air temperature and operative temperature were noticed

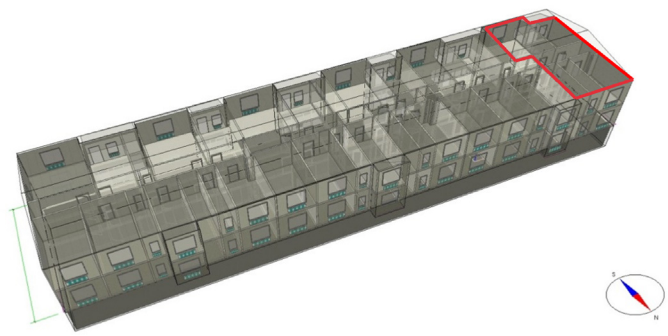

Fig. 9. Annual operative and mean air temperature in the flat with the worst performance before retrofitting, and its location in the constructed building model (framed area).

in February during 960–1120 simulation hours (marked in Fig. 9). This is explained by the outdoor temperature profile (Fig. 3), orientation (solar radiation under Stockholm climate), large envelope area connecting the outside, and as-built ventilation system, in which exhaust ventilation only installed in kitchen and bathroom without heat recovery. This simulation period was further investigated as a representative periodic reference to evaluate the profits when implemented with LTH and energy-demand retrofitting. The specific operational energy performance before retrofitting (for both delivered and primary energy) is indicated in Table 3. Primary energy factor has been recommended by EU directives to achieve sustainable energy and climate targets [23]. Primary energy indicates energy that has not been subjected to any conversion or transformation process [36]. Primary energy factor is implemented to quantify the savings and losses occurring from energy generation to the delivery to the building. The factor represents the energy delivery but excludes the renewable energy component of primary energy based on the calculation boundaries of CEN-standard [23]. The calculation of primary energy factor for fossil fuels has been constructed by conversion efficiencies of steam power plants, heat plants, combined heat and power (CHP) or residential heating systems supplied by combustible energies [37]. In another word, the renewable portion of delivered energy is considered as zero contribution to the primary side. The advantages of applying primary energy factor lie in revealing the benefits of using fuel and energy that would be emitted into the environment unused. In Swedish multifamily houses, district heating is the most competitive energy supplier (35%), which mainly distributes energy from CHP through urban district networks. Biomass, biogas, sewage sludge, and surplus heat from industrial processes are commonly used as CHP sources. Simultaneously, electricity production from CHP is equivalent to an average of 10% of Sweden's total electricity consumption [6]. As a result, the renewable energy carrier part in Swedish district heating production commonly leads to a factor less than unity (less than 1). The primary energy factor for conventional high-temperature district heating and electricity (Swedish mix) was based on the statistics [38], selected as 0.98 and 2.15, respectively. The total delivered energy before retrofitting was 144.9 kW h/(m^2 year), which exceeds the current limitation for non-electric heated buildings set by BBR (90 kW h/(m^2 year)) [22].

Table 3
Operational energy performance before retrofitting.

Specific delivered energy (kW h/(m^2 year))				Specific primary energy (kW h/(m^2 year))			
Space heating	DHW	Electricity	Total	Space heating	DHW	Electricity	Total
118.5	20.2	6.2	144.9	116.13	19.8	13.3	149.3

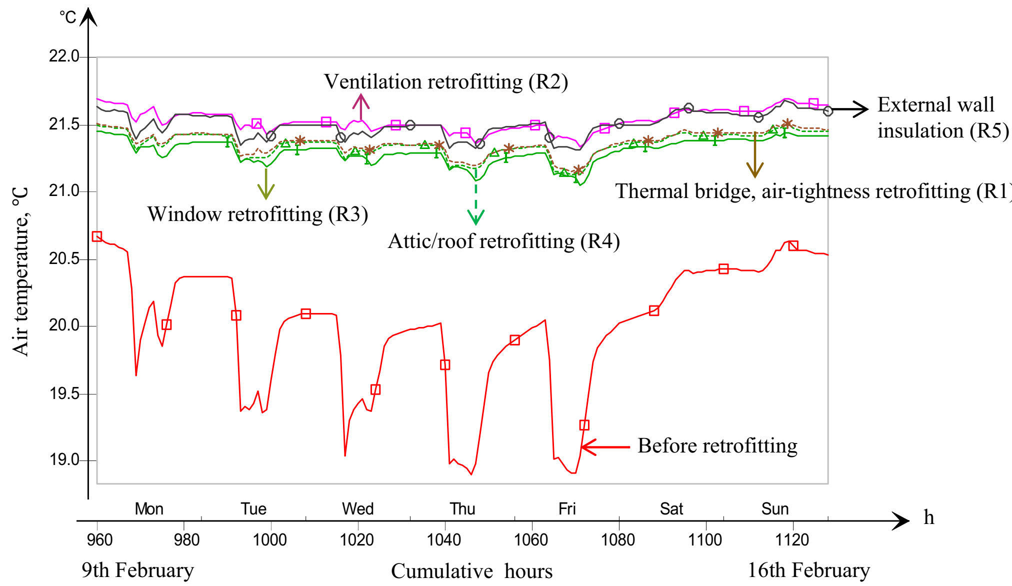

Fig. 10. Air temperature (under the representative outdoor design temperature) before retrofitting and after LTH combined with each energy-demand retrofitting.

3.1. Thermal performance evaluation after retrofitting

Fig. 10 shows the hourly simulation results of air temperature inside the reference zone in the reference duration (960–1120 simulation hours), based on the thermal performance of the building before retrofitting (introduced above in Section 4). LTH was combined with each energy-demand retrofit to compare with the 'as-built' reference situation (before retrofitting, plotted as red line). Fluctuations in air temperature are due to the combined effects of outdoor temperature changes, internal heat gains, and the corresponding living schedule of occupants in the studied zone. More importantly, the air temperature distributions are largely impacted by the performance of installed heating radiators, building insulation levels and ventilation heat loss. It can be observed that for air temperature, all LTH-combined retrofit options can reduce the fluctuations and upgrade the lowest temperature level from 18.7 °C (before retrofitting) to above 20.8 °C (after retrofitting). The highest improvement is observed by implementing LTH-combined ventilation retrofitting (R2) and adding external wall insulations (R5). Ventilation retrofitting (R2) shows further decreased air temperature fluctuations compared with adding external wall insulation (R5). LTH-combined window retrofitting (R3), attic/roof retrofitting (R4), and improving thermal bridge + air-tightness show relatively low—but similar effects. However, all measures are individually sufficient enough to improve the air temperature to 21–22 °C when combined with LTH.

The temperature duration curve is a presenting method to plot the temperature range during the whole simulation time interval. It shows the temperature variations with respect to their correspondent cumulative time (*x*-axis). As a result, the diagram does not show constant increase or decrease of temperature, and is not used to indicate which transient temperature is larger or smaller than another one. Instead, it shows a whole picture of how many hours (during a year) of the surface/operative temperature fall in the selected temperature range before and after retrofitting. For example, a retrofit option can improve the thermal comfort if it can result in the operative temperature variations falling in comfort temperature range with more cumulative hours (than before retrofitting). Fig. 11 shows the annual floor surface temperature duration curve. The reason for investigating floor surface temperature is that humans tend to be very sensitive to the temperature of their feet in residential buildings (sedentary occupants). The 'cold-feet effect' may increase dissatisfaction regarding comfort level even when the main radiant temperature has reached the acceptable level. The recommended comfort levels for floor temperature are indicated as (21–28.5) °C for bare feet (floor covered by carpet and concrete floor, respectively) [39]. Generally, when each of the five energy-demand saving measures is combined with LTH, the corresponding floor surface temperatures in all measures can be improved from 19.3 °C (before retrofitting) to above 21 °C (after retrofitting). Fig. 11 also reveals that adding external wall insulation (R5) and ventilation retrofitting (R2) shows high effects in contributing to the surface temperature performance when they are implemented with LTH. It is notable that the highest rise in floor surface temperature takes place after combining LTH with adding external wall insulation, in which the lowest floor surface temperature is improved to 21.9 °C. Additionally, adding external wall insulation (R2) can efficiently contribute to heating duration above 23 °C. There are only slight differences in floor surface temperature among window retrofitting (R3), attic/roof retrofitting (R4), and thermal bridge + air-tightness retrofitting (R1) when they are combined with LTH. These three measures can improve the minimum floor surface temperature to approximately 21 °C. Attic/roof retrofitting (R4) shows a slightly higher floor surface temperature than R1 and R3, and particularly longer duration above 23 °C. This can be explained by the fact that the reference zone is located at the second floor of the building, which is more sensitive to heat loss through the ceiling and roofs. It should be noted that the results present the proportional control of radiators. PI control by surface temperature is not presented.

Based on the results regarding the impacts of combing LTH with each energy-demand retrofitting, it is interesting to investigate how they would influence the operative temperature and its fluctuations with time. Fig. 12a presents the annual operative temperature variations before and after the proposed retrofitting. Fig. 12b presents the captured operative temperature fluctuations during the represented simulation week. It can be found that the lowest operative temperature improvement took place when combing LTH with window retrofitting (R3): minimum operative temperature is improved from 18.9 °C (before retrofitting) to 20.7 °C. However, this is considered close to the standard level of 21 °C suggested by ASHRAE standards [40]. The highest contributions for operative temperature were found by combining LTH with adding external wall insulation (R5) and ventilation

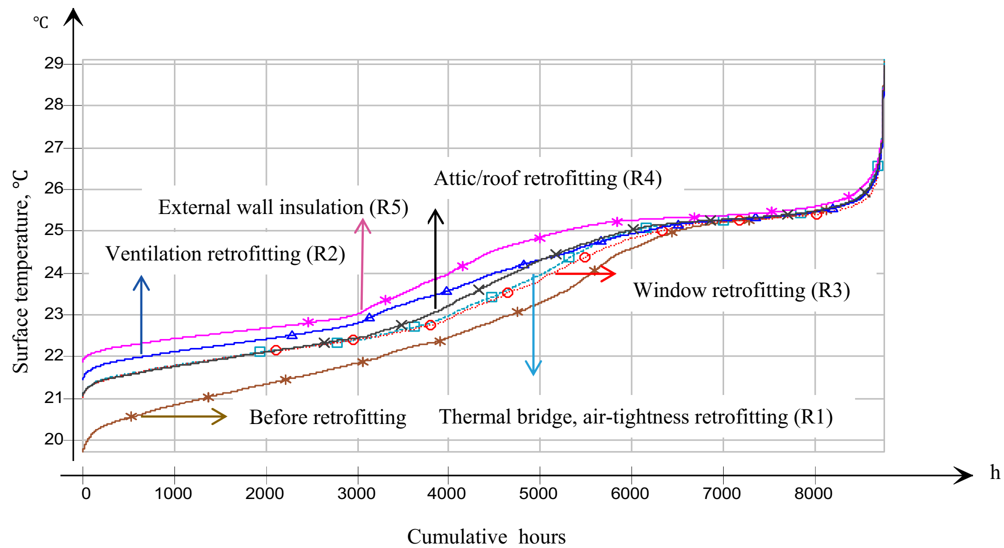

Fig. 11. Annual floor surface temperature duration curve before retrofitting and after LTH combined with each energy-demand retrofitting.

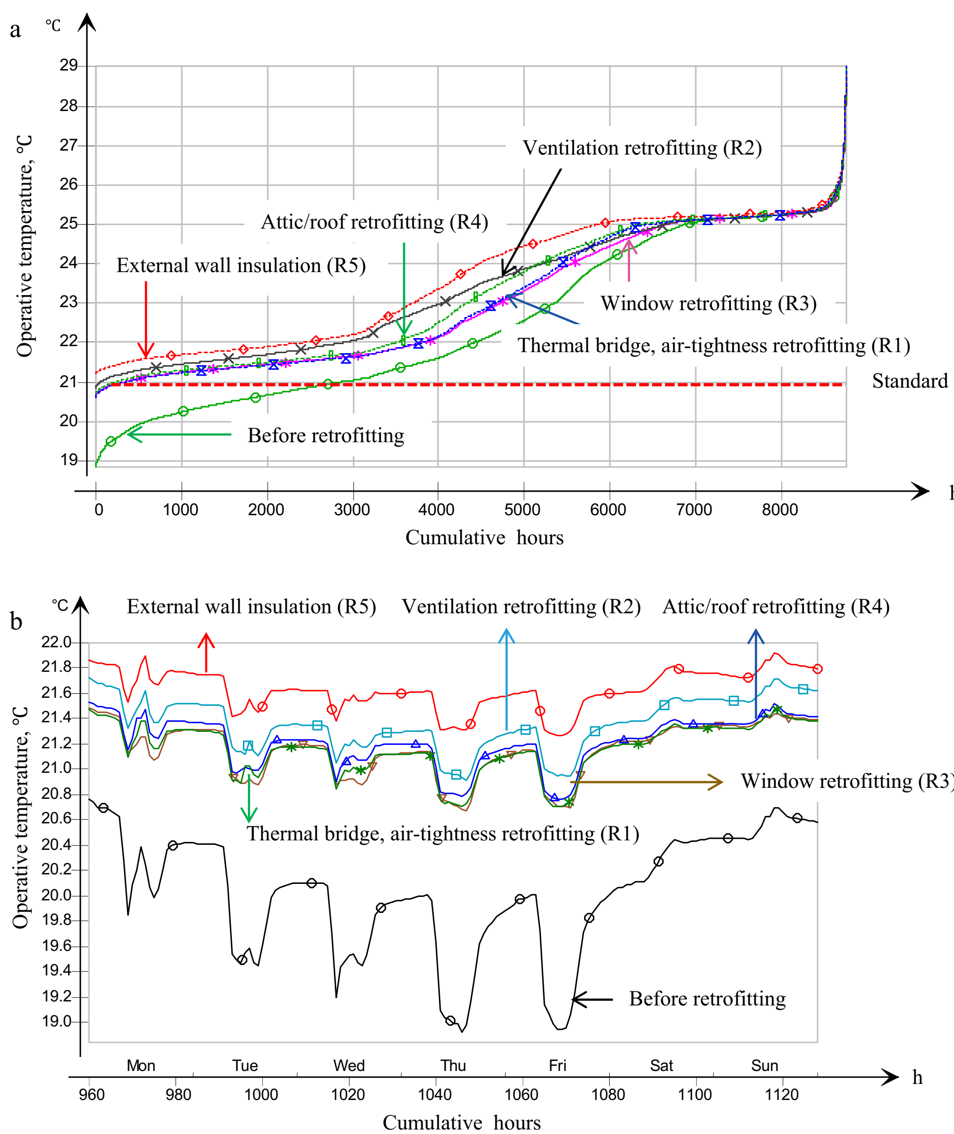

Fig. 12. (a) Annual operative temperature duration curve before retrofitting and after each energy-demand retrofitting combined with LTH. (b) Difference in operative temperature within the represented simulation duration.

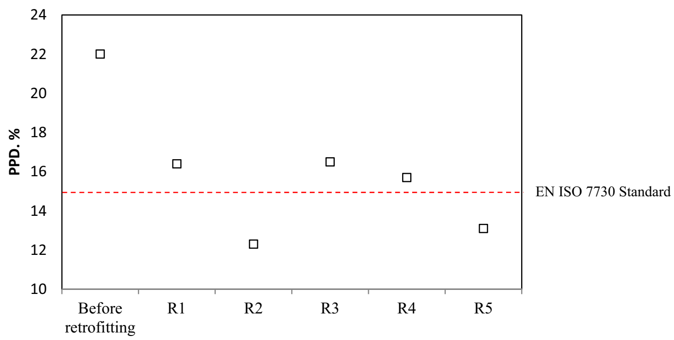

Fig. 13. Average PMV-based PPD level before and after retrofitting (individual effect combined with LTH) during the whole-year simulation.

retrofitting (R2), showing similar results to those of air and floor surface temperature; this can be explained by the fact that operative temperature is a function of air temperature and mean radiant temperature. Annul simulation results are difficult to clearly present the details of operative temperature due to the large time interval. As a result, an additional observation of operative temperature variations during the reference simulation duration (framed in Fig. 3) is presented in Fig. 12b to evaluate the temperature drifts and ramps. Fig. 12b shows that combining LTH with different energy-demand savings can notably reduce the fluctuations of operative temperature, which is also one of the major advantages of LTH retrofitting. All measures after retrofitting fell in 1 °C variations, which met the maximum allowable limits on drifts and ramps of operative temperature specified by ASHRAE standards (maximum of 3.3 °C in four hours) [40]. The reduction levels of operative temperature fluctuations were similar among the five studied retrofits. LTH-combined ventilation retrofitting (R2) and thermal bridge + air-tightness retrofitting (R1) showed slightly lower temperature fluctuations.

Fig. 13 shows the global thermal comfort before and after each LTH-combined retrofitting. The results are presented by predicted mean vote (PMV)-based mean predicted percentage of dissatisfied (PPD) level. The deviation in each retrofitting shows the maximum and minimum values (deviation) in a one-year simulation period. The mean PPD is 22% before retrofitting. Ventilation retrofitting (R2) has the highest contribution (12.3%), followed by adding insulations on external wall (R5) (13.1%). The finding shows that for the studied building, introducing pre-heated air from both heat recovery and ventilation radiator can effectively increase the thermal comfort than taking the air directly from outside. It can be observed that R2 or R5 can independently provide sufficient thermal comfort levels when combined with LTH, according to the lowest PPD limitation (15%, marked as a dashed line in Fig. 13) set by EN ISO 7730. No further renovations are needed. Other LTH-combined retrofitting can contribute 13.1–16.5% PPD level after retrofitting.

As an extension, combining the five proposed energy-demand retrofitting with LTH was performed. Carrying out this investigation aimed to:

(1) Evaluate the highest possible thermal performance contributions by LTH-combined retrofitting. This can be a pilot result to determine the best thermal performance of implementing LTH in old housing stock when they go through holistic renovation packages (which is more common than individual retrofit in MP buildings). In addition, it can indicate the performance of LTH for the future transformation toward Nearly Zero Energy Buildings in housing stock.
(2) Investigate the operational energy differences of individual retrofit option and retrofitting packages, as introduced in Section 3.2. Fig. 14a–c shows the thermal performance results of combining LTH with all five retrofit options. All red lines plotted in Fig. 14 show the thermal performance before retrofitting, while all black lines present the thermal performance after retrofitting. Fig. 14a shows the annual air temperature performance. Fig. 14b shows the annual floor surface temperature performance. Fig. 14c shows the annual operative temperature and corresponding duration curve. All results are exhibited by the "worst performance zone", same as Figs. 10–12. It can be observed that combining all energy-demand retrofitting with LTH contributes significantly to improving thermal performance, as expected. Minimum air temperature is improved to 21.6 °C. Average floor surface temperature is improved to 22.8 °C. It has been observed (from the previous results of individual retrofit options in Section 3.1) that external wall retrofitting (R5) has the largest contribution to floor surface temperature, followed by ventilation retrofitting (R2). The reason ventilation retrofit (R2) has a strong impact on the floor surface temperature lies in the location of the reference zone and its joint zone. Fig. 15 shows the zone schemes in the model. Reference zone is explored to the outdoor with both external wall and large attic. The zone below the reference zone (zone downstairs in Fig. 15) has external wall explored to the outdoor. The power of radiators in both zones were the same (P1 = P2). The introduced ventilation flow rate (from heat recovery) is the same for both zones. As a result, the mean air temperature of the zone downstairs will be largely improved than the reference zone after retrofitting, for example, either by insulations on external wall or ventilation heat recovery. Given the *U*-value of the floor slab is high and not changed after retrofitting, in other words, heat partly goes from the zone downstairs to reference zone. This results in the impacts to the floor surface temperature of reference zone. Extremely, when five retrofit options are implemented together as a package to achieve the best situation, the heat transfer from the zone downstairs to the reference zone is more distinct. This explains why the average floor temperature is slightly higher than the minimum air temperature of the reference zone when combining all the retrofit options. The whole-year mean air temperature and floor surface temperature variations (monthly-based) are kept below 1.2 °C. For operative temperature performance (Fig. 14c), it is interesting to observe that the whole-year operative temperature variations are kept below 2.7 °C.

The minimum operative temperature is improved to 21.8 °C. Major differences with individual retrofit options lie in the operative temperature fluctuations. Retrofitting package shows much shorter temperature duration below 21 °C and above 24 °C, with the aid of the joint effects of both improved heat emissions by LTH and the building's better insulation levels after retrofitting. Air temperature is mainly impacted by the internal heat gains, heat transfer from adjacent zones, and ventilation supply temperature. Mean PMV-based PPD level after retrofitting is 6.2%, with a deviation of 8.3 to 5.0%.

3.2. Operational energy performance analysis

The required annual operational energy of space heating for the building after implementing LTH with each energy-demand retrofitting is indicated and ranked in Fig. 16. It consists of two types of operational energy criteria: delivered energy and primary energy for space heating. This heating energy is used to maintain the air temperature within the set point, in addition to the heat flows, to other adjacent zones to the outside. It is noticed that ventilation retrofitting (R2) shows the highest energy savings for both delivered energy and primary energy (80.1 and 71.3 kW h/m^2 year). The corresponding savings are of 32.4 and 38.6%, respectively. It also

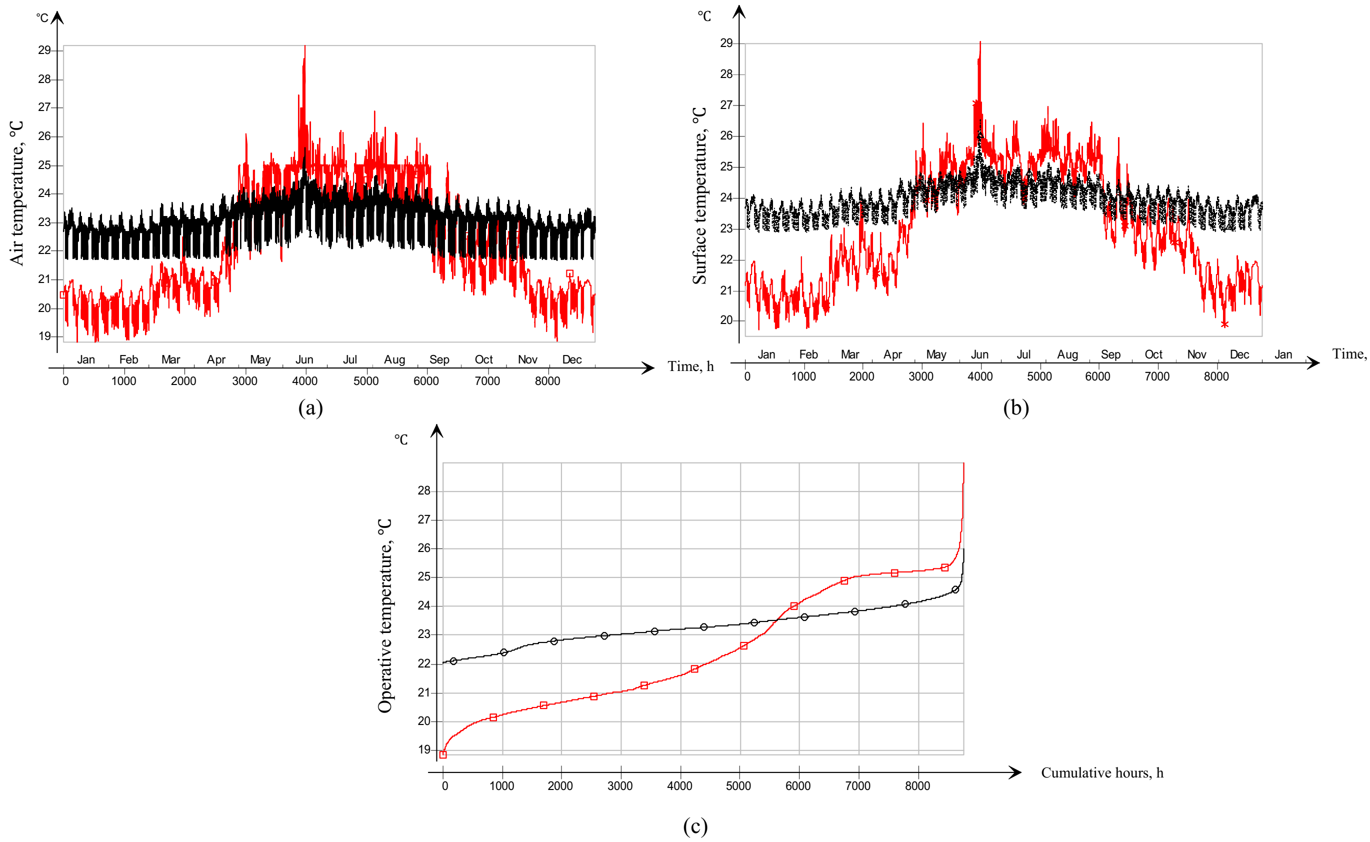

Fig. 14. Thermal performance before and after combining all energy-demand retrofitting with LTH. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

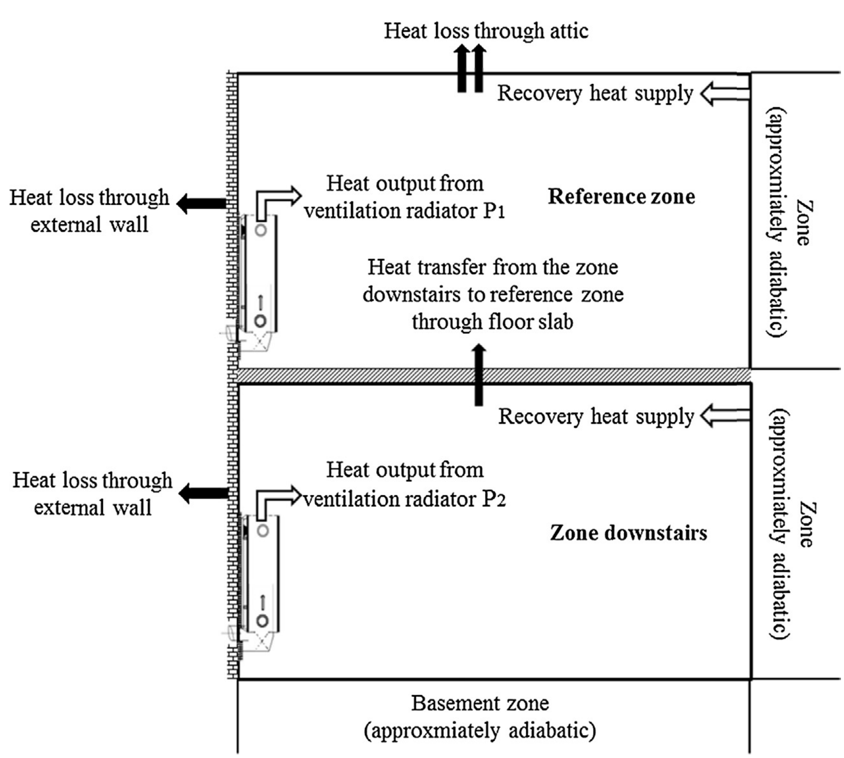

Fig. 15. The scheme of the reference zone and its joint zone.

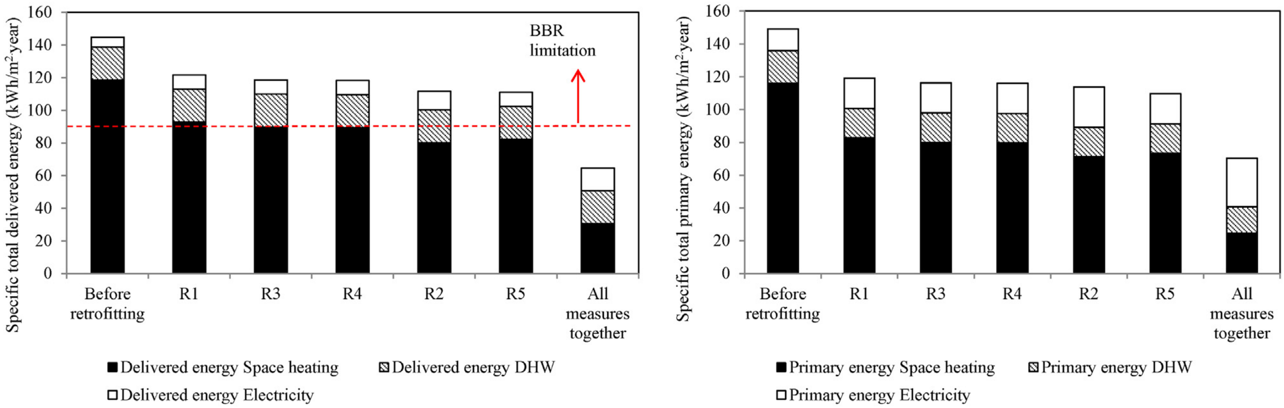

Fig. 16. Total operational energy (delivered and primary) performance before and after LTH combined with each/all retrofit options. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 4
Total operational energy performance of each LTH-combined retrofitting (R1–R5, listed in Table 2), and their combined effect.

LTH + energy-demand retrofitting	Delivered energy (kW h/(m^2 year))		Primary energy, (kW h/(m^2 year))	
	After retrofitting	Savings (%)	After retrofitting	Savings (%)
R1	121.7	16.0	119.1	20.2
R2	111.7	22.9	113.8	23.8
R3	118.6	18.2	116.4	22.0
R4	118.3	18.4	116.1	22.2
R5	111.1	23.3	109.7	26.5
Combined R1–R5	64.7	55.3	70.4	52.8

shows that for the other retrofit options, the percentage of delivered energy and primary energy savings are among 21.6–30.5% and 28.8–36.9%, respectively. It is concluded that when combining LTH with ventilation retrofitting, up to 32.4% of delivered energy can be saved, and the corresponding primary energy savings are of 38.6%. It should be noted that, in this study, the heating method in this building is district heating produced by CHP before and after retrofitting.

The increased primary energy savings are due to: When combining LTH with energy-demand savings, the supply/return temperature from district heating grids can be theoretically reduced. A decreased supply/return temperature can potentially increase the electricity-to-heat ratio of CHP. This largely reduced the primary energy factor for upstream energy mix production. A decreased return temperature can practically reduce the heat loss from district heating pipes. Fig. 16 and Table 4 show the total operational energy before and after the proposed LTH-combined retrofitting strategies. Space heating, electricity (El shows in Fig. 16's legend) and DHW contribute to the proportions of operational energy. Different to the energy for space heating results, the largest total operational energy is contributed by LTH with added insulations on external walls (R5), 23.3 and 26.5% savings to delivered and primary energy, respectively. The reason for the decreased ventilation retrofitting (R2) energy savings is the additional electricity needed to operate AHU for ventilation controls and heat recovery units. In this building, the calculated additional electricity for AHU is 2.8 kW h/(m^2 year). This further leads to a saving reduction for primary energy, because of the high primary energy factor for electricity (2.15 for Swedish mix). For the rest of the measures, savings of 16–18.4% and 20.2–22.2% regarding delivered and primary energy can be achieved, respectively. It is also observed that for LTH-combined retrofitting, there is a general increase in building electricity usage after retrofitting. The reasons for this finding can be explained by: (1) No measures that reduce public lighting, improving the fan efficiency and heating cables have been included; and (2) reduced supply/return temperatures under the designed outdoor temperature lead to an increased flow rate in hydraulic circulation, further increasing the required power for circulation pumps at the district heating substation. This additional electricity requirement for LTH-combined retrofitting was not negligible, and was calculated as a maximum additional 2.4 kW h/m^2 year. An explanation for this result is that LTH-combined retrofitting requires a correctly sized circulation pump and an increased pumping capacity that is suitable for the bypass hydraulic circuits. In this study, the circulation pumps are assumed to be the same before and after retrofitting, which limits the benefits of LTH in retrofitting practice. Fig. 16 and Table 4 also present the joint effects of LTH with all five energy-demand retrofitting. It is concluded that if combining LTH with all the proposed measures, the delivered energy and primary energy can be saved up to approximately 55.3 and 52.8%, respectively. This finding is believed to be important with regard to the Swedish national sustainability targets for existing building sectors: a 50% energy-demand saving (per heated floor area) by 2050, compared with the 1995 level. The delivered energy was further compared with BBR, which met the latest limitation for non-electric heated buildings (90 kW h/m^2 year, as shown by the red line in Fig. 16). It shall be noted that after holistic retrofitting, the ratio of energy required for DHW production and building electricity usage will be important parts to be considered, particularly from primary energy perspectives.

4. Discussion

Low-temperature heating in retrofitting has not been widely tested in Swedish housing stock. The processes are mainly plagued by the ways to select corresponding renovation measures from the demand side and reducing the impacts to the occupants. On the basis of thermal performance results, it can be concluded that LTH can provide improved air temperature up to 21 °C when it is individually combined with each energy-demand saving measure. Changing exhaust ventilation to 80% heat recovery efficiency, and adding insulations on external walls show high thermal performance contributions when combined with LTH. However, ventilation retrofitting is more recommended than external wall renovation for the following reasons: (1) External wall retrofitting has much larger impacts and longer renovation duration than ventilation retrofitting, according to the Swedish industry standards [41]; and (2) From a sustainability perspective, the embodied energy in external wall retrofitting is much higher [42]. Pilot studies have shown evidence that the cost effectiveness of external wall retrofitting is relatively lower in this archetype [31]. Results show that there was no shortage of heat supply because of the reduced operating temperature after retrofitting. Fig. 12b also reveals that the improvements in mean operative temperature are the effects of LTH and energy-demand renovation. However, the levels of reduced operative temperature fluctuations do not vary significantly between different energy-demand retrofitting. The sizing of LTH radiators were designed as the same with conventional radiators before retrofitting. This confirms the previous findings that increasing the heat convection of radiators is more effective than enlarging the radiators to improve the heat emission efficiency in retrofitting [10]. This is partly because radiators have been commonly oversized to cover the window width and overcome cold draught from poor insulations. Therefore, it can be summarized that from a thermal performance perspective, either small-scale renovations (such as improving the air-tightness and thermal bridges) or relatively large-scale renovations (such as replacing windows and external wall retrofitting) can provide an acceptable operative temperature after retrofitting when they are combined with LTH. The optimal selection of these measures is mainly dependent on their abilities to save operational energy.

Compared with pilot retrofitting studies on this archetype without LTH, the simulated delivered energy was not largely reduced when combining retrofitting with LTH [31]. Ventilation retrofitting shows the highest space heating energy savings. However, the additional electricity needed for AHU after retrofitting – which shows similar results with previous analytical models [42] – shall be critically considered. The difference in the energy required by AHU is also related to exhaust air temperature: the higher the exhaust air from the zone, the less energy needed for space heating. In this study, heat from exhaust air was recovered by a centralized rotating heat exchanger. The ventilation supply temperature was modeled as 16 °C. However, a further study regarding how to optimize different ventilation systems with more effective, pre-heated supply air with LTH shall be investigated. More energy-saving ventilation systems, such as demand-control ventilation, have been reported as able to provide both good indoor air quality and operational energy savings [43].

Accurate thermal performance simulation on retrofitting options was challenging, due to inconsistencies varying from actual engineering work in the whole renovation process to impact by occupants. First, uncertainties emerged from the internal heat gains. The study was based on the modeling results and parametric analysis; no questionnaires and communications with occupants have been carried out. Various living schedules and occupancies in the studied zones show differences in modeling both thermal performance and operational energy usage, which has been widely pointed out in the literature [10]. Second, there are uncertainties in modeling ventilation radiators, which are partly dependent on how the technician chooses the radiators and may vary largely from actual operation and controlling by the occupants. Third, although the five selected energy-demand retrofitting are based on the statistics and standard reference from the local building industry [41], spare renovation measures may be requested according to the particular retrofitting priorities for the archetype. Fourth, primary energy factor is applied in the model. However, different methods lead to large variations of primary energy factor values in energy accounting. Lacking of consistent statistics leads to inaccuracies, which can be district-to-district, city-to-city, or country-to-country dependent. In this study, primary energy factors were selected based on the energy systems of major electricity and heat suppliers for the Stockholm region [5,38]. The primary energy results may vary for other cities/regions. Renewable energy mix was not included in this study. However, integrating renewables into LTH should be further explored to accelerate the retrofitting efficiencies from an energy perspective. This raises the demand for splitting primary energy calculation into renewable and non-renewable categories, particularly when a method based on primary energy factor is adopted. This demand has also been currently indicated in EU directives for future implementation of primary energy calculation methods and policies [37]. Another topic to explore is how to avoid hygiene problems in domestic hot water (DHW) when the supply temperature is reduced below 50 °C after retrofitting.

If the retrofitting target is a nearly net-zero building, additional retrofits on DHW distribution energy losses, energy savings for public lighting fittings are needed. It can be observed that after combing LTH with all energy-demand retrofit options, the primary energy required by DHW and the building's electricity will be equally important to space heating. More importantly, correctly sizing the circulation pumps and choosing highly-efficient district heating substations to meet the flow rate of LTH must be critically calculated. This raises a question concerning how low-temperature district heating systems for existing buildings should be practically implemented at district or city levels. Some studies have reported certain pilot recommendations such as installing secondary circuits with a mixing valve to lower the operating temperature, or DHW is secondary heated by a micro-heat pump supplied by heat from district heating girds [10,18]. However, controlling of the system and on-site measurements have not been sufficiently regarded.

5. Conclusion

One typical Swedish residential building stock – low-rise, multi-family concrete slab house – was selected to represent the retrofitting simulation. Ventilation radiators were selected as low-temperature heating (LTH) components after retrofitting.

The simulation results indicate that combining LTH with each energy-demand retrofitting can provide improved temperature and acceptable thermal performance in the representative building.

It is concluded that LTH can contribute to reduced temperature fluctuations and primary energy savings. When LTH is combined with energy-demand retrofitting, mean operative temperature and delivered energy savings can be further improved.

Combining LTH with ventilation retrofitting shows the largest contribution to air temperature, PPD, and energy required for space heating. This measure is recommended as the preferable first option to combine with LTH. However, it should be noted that the total operational energy savings are limited by the additional electricity required for AHU.

Combining LTH with external walls shows the highest contribution in operative temperature and total operational energy savings. However, pilot studies have given evidence that this measure is not in relative terms cost-effective and influences occupants in the studied archetype.

Adding insulations on attic/roof, replacing windows, improving air-tightness levels and thermal bridges show similar effects, individually, in improving thermal performance. The total delivered and primary energy savings of these three measures are between the range of 16–18.4% and 20.2–22.2%, respectively. However, it should be highlighted that additional electricity usage for circulation pumps will occur due to increased flow rates for LTH-combined hydronic circuits. This part of energy should be further considered by additional district heating substation renovations.

When combining LTH with all five energy-demand retrofit options as a package, 6.2% of PPD can be achieved. More importantly, 55.3% and 52.8% of total delivered energy and primary energy can be achieved in this archetype, respectively. This can effectively assist the transition of Swedish housing stock toward the national target in the building sector: 50% energy-demand saving (per heated floor area) by 2050, compared with the 1995 level. This study provides a pilot modeling investigation on which energy-demand saving measures should be selected as 'pre-retrofit', and the performance of the building after the implementation of LTH-combined retrofitting in Swedish low-rise multi-family houses. Findings show reference baselines for further on-site implementations and measurements.

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