



# Ventilation heat recovery jointed low-temperature heating in retrofitting—An investigation of energy conservation, environmental impacts and indoor air quality in Swedish multifamily houses



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## ABSTRACT

Sweden is actively engaged in accelerating the sustainable transformation of existing building and energy systems. Most traditional investigations of this subject have been based on final energy savings and CO<sub>2</sub> emission analysis, while most existing evaluation methods for energy-retrofitting have not accurately taken into account the influences of flow temperature patterns of different low-temperature heating (LTH) radiators to operational energy. In addition, comprehensive environmental impact analyses by energy systems, as well as the contributions to indoor air quality (IAQ), have not been fully achieved. Moreover, critical mapping of the sustainability of energy-efficient retrofitting have not yet been done. This omission leads to inaccuracies and misleading estimates of the benefits of LTH retrofitting from system and primary energy perspective. In order to fill these knowledge gaps, the present study evaluated two types of LTH systems combined with ventilation retrofitting, namely heat recovery jointed ventilation radiators (VRs) and baseboard radiators (BRs). A typical Swedish multi-family house was selected for retrofitting practice. This study aims at evaluating ventilation heat recovery jointed low temperature heating (VJLTH) retrofitting on energy conservation, environmental impacts and indoor air quality (IAQ) in typical Swedish multifamily houses. The compatibility of building performance and sustainability contributions were critically analyzed by delivered/primary energy usage, life cycle assessment (LCA), and IAQ modeling. IDA ICE (indoor climate and energy simulation program), SimaPro (LCA environmental impact modeling program), analytical model and on-site measurement data provided by both radiator and heat pump manufactures were employed. The results showed that the studied VJLTH retrofitting can save up to 55% of the final energy. And the corresponding primary energy savings are more than 25%. Compared with conventional radiators, low-temperature heating radiators can improve the COP by 12–18% for air-source heat pumps. The studied retrofit can positively contribute 11 of 16 environmental indicators, 7 of which had environmental impacts reduced by more than 50%. However, neglecting the indicators with negative impacts will increase the risk of over-representing the environmental contributions. The sustainability improvements of retrofitting, particularly for future large-scale implementation, should be critically evaluated from a broader perspective than final energy savings.

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## 1. Introduction

The building sector has become a priority area for European Union (EU) and member states in which to achieve climate and energy targets for 2020 and 2050. The development of new method-

ologies and technologies to contribute future regulations and technical solutions for cost-effective retrofitting has been promoted by the loaded EU and International Energy Agency (IEA) directives [1]. The 2010 Energy Performance Building Directive (EPBD) and the 2012 Energy Efficiency Directive (EED) required member states to implement annual energy-efficient retrofit to at least 3% of existing buildings owned and occupied by central government [2]. The directives aimed to accelerate the transformation of existing buildings towards net zero energy/emissions buildings [3]. In addition, energy performance certificates are to

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## Nomenclatures

### Acronyms

AHU	Air-handling units
ASHP	Air-source heat pump
BBR	Swedish building regulations
BR	Baseboard radiator
COP	Coefficient of performance
CR	Conventional radiator
DHW	Domestic hot water
EPBD	Energy performance of building directive
HP	Heat pump
IQA	Indoor air quality
LTH	Low-temperature heating
MB	Miljöbyggnad (Swedish building performance certificate)
MP	Miljonprogrammet (million program, 1965–1975)
PD	Percentage of dissatisfaction, %
RH	Relative humidity, %
VJLTH	Ventilation heat recovery jointed low temperature heating
VR	Ventilation radiator
C <sub>CO<sub>2</sub></sub>	Concentration of CO <sub>2</sub> , ppm

be included in all advertisements for the sale or rental of buildings [4]. With respect to the loaded policy context, Sweden has been actively engaged in accelerating the sustainable transformation of existing buildings. Swedish building regulations (BBR) were newly revised in March 2015, with operational energy usage in multi-family houses larger than 50 m<sup>2</sup> being tightened by 10% (residential buildings fall in the category of blocks of flats and premises) [5]. The current system of three climate zones for energy usage evaluations was upgraded by an additional fourth-zone system, in which original energy usage was tightened by a further 10% for all archetypes. Furthermore, the operational energy savings after retrofitting were recommended by BBR to be addressed from both delivered energy (often refereed as purchased energy) and primary energy (the total usage of up-stream fuel/resources) perspectives [5]. For existing residential buildings, the final-stage retrofit effects of space heating system commonly consist of reducing heating demand, increasing the efficiencies of room heaters, and decreasing the distribution heat loss [6]. These steps can be taken through heat recovery, well-designed piping systems, and decreased hydronic circle supply/return temperature. From an upstream primary energy perspective, retrofit effectiveness can also be achieved by more efficient heat supply system, such as increasing the electricity-to-heat ratio in a combined heat and power plant (CHP) for district heating, improved coefficient of performance (COP) of heat pumps (HP), or sharing low-exergy resources (such as a renewable energy mix). Consequently, most of the energy savings of the above-mentioned retrofits can be contributed by two key retrofit targets: the initial heating demand of the buildings, and the supply/return temperature of the hydronic circle. However, finding low-temperature heating (LTH) retrofit packages that are easy to implement has been an on-going research challenge. Existing Swedish multi-family houses have high numbers of occupants and large envelope areas. Therefore, more effective retrofit options with low impacts to the occupants and high contributions to overall building performances are needed. In addition, it remains unclear how technical guidance and a practical picture of energy retrofit benefits for stakeholders/construction industry/occupants can be provided. The present study aims at evaluating ventilation heat recovery jointed low-temperature heating (VJLTH) retrofitting on

energy conservation, environmental impacts and indoor air quality (IAQ) in typical Swedish multifamily houses.

### 1.1. Previous studies

Most of the existing studies for retrofit technologies in Swedish residential buildings, particularly for space heating, have focused on operational energy savings. Swedish industry experiences have reported that conventional envelope-based energy-retrofits have mostly been accomplished by relatively high costs, multiple visits and long operating process [7,8]. It is reported that in some archetypes, insulating external/internal walls and replacing windows may not always lead to long-term cost-effectiveness. More importantly, rather long envelope retrofitting duration and heavy impacts to the occupants raises the demand of finding an efficient alternative for future retrofitting industry. In addition, studies have offered evidence that envelope-based retrofit methods may overestimate the sustainability improvements of some measures from a life cycle perspective [9,10]. Instead, LTH and ventilation heat recovery can be installed easily without renovating the large envelope and building façade with competitive life cycle costs [11]. Studies have also shown that LTH can provide promising advantages to improve thermal comfort from both local and global perspectives due to increased heat emission efficiency of radiators [12,13]. Pilot studies have reported that combining LTH with ventilation heat recovery can save up to 30% operational energy in low-rise Swedish multifamily houses [14]. Lowered supply/return temperature in hydronic circle can further improve the efficiency and reduce the heat loss of a heat supply system, such as HP or district heating supplied by CHPs. This evidence has been reported in the literature [15–17]. Despite great efforts to promote LTH systems from a policy and industry context, the implementation of LTH systems remains limited in new buildings with relatively low heating demand. No stringent technical guidance and critical evaluations to LTH-based methods in retrofitting practice have been completed. Their applicability and sustainable contributions to major Swedish residential archetypes were not sufficiently found in the literature. The present study focused on two types of LTH radiators: ventilation radiators (VRs) and baseboard radiators (BRs). VRs and BRs are two alternative components of VJLTH system. VRs and BRs have been numerically and experimentally investigated in previous studies in both single-family and multifamily houses [12,13] and the products have been available on the market. Existing studies and measurements about the impacts on IAQ of VJLTH system were mainly focusing on selecting the optimal ventilation flow rates and controlling strategy [18,19]. Monitoring results showed negative impacts on IAQ by ventilation heat recovery were commonly caused by incorrectly usage and poorly maintenance of ventilation heat exchanger [20,21]. However, most of those studies focused on the component development of the systems in question. Evaluation methods were mainly based on the newly constructed archetypes, or idealized zone environment for numerical analysis [19,22]. These archetypes were commonly well insulated, or with existing low/nearly zero heating demand. The applicability of LTH remains unknown, as do accurate impacts on the performance of heat supply system and corresponding sustainability improvements in old residential buildings.

### 1.2. Objective

The aim of this work is to evaluate energy conservations, environmental impacts, and the corresponding IAQ contributions by VJLTH retrofitting. The focus was on mapping the influence of LTH radiators to the performance pattern of heat supply system.

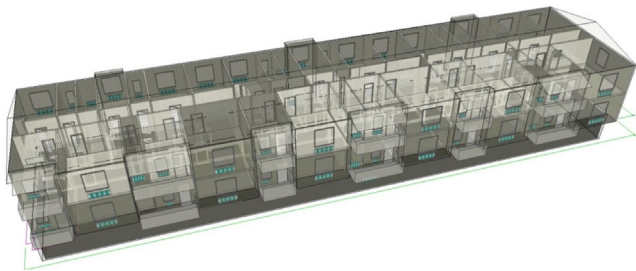


Fig. 1. Constructed building model in IDA ICE 4.6.2.

## 2. Methodology

The simulation model in this study was a combination of three tools: building performance simulation (IDA ICE 4.6.2), analytical calculation (based on manufacturers' real-life performance data of studied radiators and HP), and SimaPro v8.0.4 modeling for energy environmental impact assessment.

### 2.1. Building performance modeling and selected archetype

IDA ICE 4.6.2 (indoor climate and energy performance simulation program) was applied for the simulation of energy balance, indoor CO<sub>2</sub> concentrations, and the relative humidity (RH). IDA ICE provided annual weekly-based dynamic building energy balance modeling, as well as indoor climate estimations in all constructed zones. The accuracy of the IDA ICE code was evaluated by the IEA Solar Heating and Cooling Program, Task 22, Subtask C, in 2003 [23]. The accuracy of the IDA ICE for building energy performance simulation has been widely validated in several studies [24–26]. For multifamily houses, good agreement with measurements was found for energy balance modeling [27]. On-site measurements revealed that the maximum deviation of annual operational energy modeling in IDA ICE was below 7% in multifamily houses [24].

One two-storey, low-rise, district-heated multifamily house was selected to present this retrofitting practice. Constructed building model (southern façade) in IDA ICE is depicted in Fig. 1. Input building parameters and technical descriptions before retrofitting (as-built situation) are shown in Appendix A. The reason for selecting this archetype was based on previous studies about the typologies of existing Swedish residential buildings [7,11]. Sweden experienced a residential building boom between 1950 and 1975 (the so-called "Record Years"), especially during the implementation of the million program (MP) between 1965 and 1975. The massive number of industrialized residential buildings met the housing demand at that time; however, after 50–60 years of usage, most of the dwellings constructed during those periods now need to be systematically renovated. The selected archetype is one of the most common multifamily houses in Swedish cities and consists the basis of the MP [28]. The building has a total heated floor area of 1580 m<sup>2</sup> and is located in the northern suburbs of Stockholm (see Appendix A). The building consists of two types of flats: a 76 m<sup>2</sup> heated floor area with two bedrooms, one living room, one kitchen, and bathroom, as shown in Fig. 2a; or a 50 m<sup>2</sup> heated floor area with one bedroom, one living room, one kitchen, and bathroom, as shown in Fig. 2b. Each flat consists of one balcony oriented to the south, and one storage room (without window and openings). These flat types were also typical in other MP houses. Four occupants were assumed for flat type 1. For flat type 2, three occupants were assumed. On basis of the different occupancies, the building was modeled by 85 zones. The zone/room-based modeling method aimed to provide more accurate simulation results and, more importantly, to find the room/zone with the highest heating demand to present the retrofitting effects; namely, heat-

ing demand reduction and IAQ improvement. Each zone presents a different room environment; namely, living room, bedroom, bathroom, kitchen, storage room, public corridor area, and basements. Three types of occupant schedule were assumed in the model based on the public holidays and average working hours in Sweden [14]: working-day schedule, holiday schedule, and DHW-usage schedule (categorized as working days and holidays). These schedules were assumed to be constant both before and after retrofitting. Outdoor temperature was based on the climate data of Stockholm/Bromma, in which the lowest design temperature is −18 °C. Operational energy calculation for space heating accounted for the assumed annual heating seasons of Stockholm. The assumption was based on statistics of average heating days of Stockholm from 1980 to 2009 [29]. Heating seasons vary from a maximum of 31 weeks to a minimum of 23 weeks. In this study, 29 weeks were selected to present the heating seasons for operational energy calculation. Weeks with heating demand lower than 50 W were excluded from the calculations.

The heating system before retrofitting was a conventional high-temperature system supported by district heating with a reference supply/return temperature of 75/50 °C based on the averaged statistics of Swedish district heating [30]. Conventional radiators (CRs) were installed under windows with the same window widths. There were six radiators in flat type 1 (Fig. 2a) and five in flat type 2 (Fig. 2b). Air-tightness level was 2 ACH under the pressure differences of ±50 Pa, calculated as wind-driven ACH. Wind profile was based on the suburban inventory, ASHRAE-1993 [31]. The ventilation system before retrofitting was decentralized exhaust ventilation. The exhaust grills were placed in both bathrooms and kitchens. Each kitchen and bathroom was equipped with fans to extract air. The flow rates in kitchens and bathrooms were 1.2 l/(s × m<sup>2</sup>) and 1.8 l/(s × m<sup>2</sup>), respectively, according to the minimum exhaust ventilation flow-rate limitation set by BBR for residential buildings. Due to the negative pressure generated by exhaust fans, fresh air was directly supplied from outside, through openings, cracks and leakages. There was no cooling installation in the building. Internal heat gains from occupants, equipment, and solar—direct and diffuse was assumed based on the living schedule and Stockholm climate data.

In the simulation, it was assumed that there were no occupancies and equipment in storage rooms and basements. Internal openings (internal doors within one flat, corridor doors) were controlled equally to the living schedule of the corresponding rooms. The openings of windows were controlled by the indoor temperature. When the indoor room temperature was above 26 °C, the windows and external openings were simulated as partly open. These assumptions were kept constant before and after retrofitting.

### 2.2. Ventilation heat recovery jointed low temperature heating (VJLTH)

As introduced in Section 1, two types of LTH radiator (VR and BR) were selected. The component layouts and displacements of radiators are shown in Fig. 3. A high-temperature conventional radiator (CR) presents the as-built situation before retrofitting. All radiators were assumed to be equipped with proportional controllers (thermostatic valves) on water flow in the IDA ICE simulation. The thermal performance of both VRs and BRs were previously investigated and experimentally tested. VRs 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 flow and thereby also the heat outputs. No additional fan (radiator booster) was equipped below/above the radiator. Outdoor air was filtered and preheated inside the radiator. Numerical analysis and experimental findings were reported

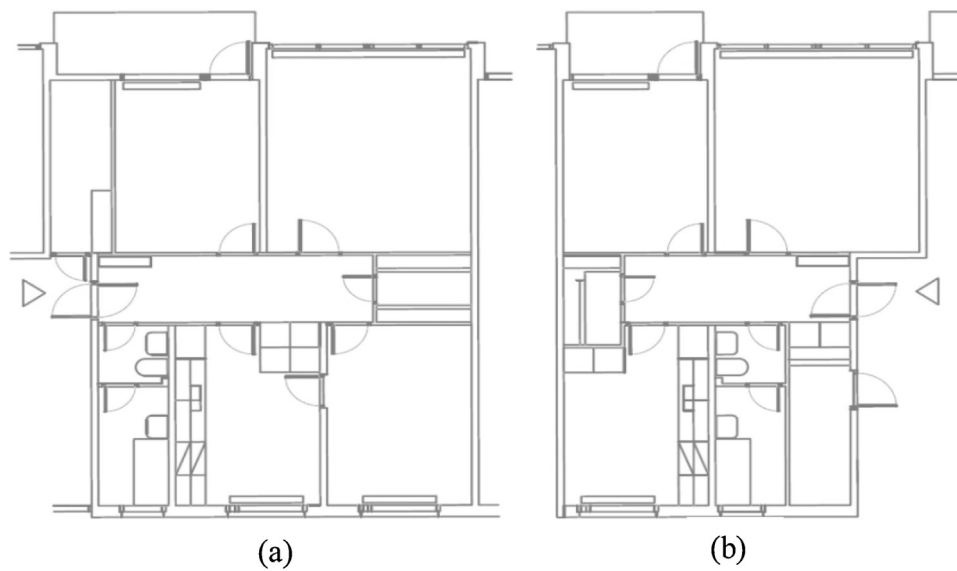


Fig. 2. Two types of flats in the studied archetype: (a) 76 m<sup>2</sup>, flat type 1, (b) 50 m<sup>2</sup>, flat type 2.

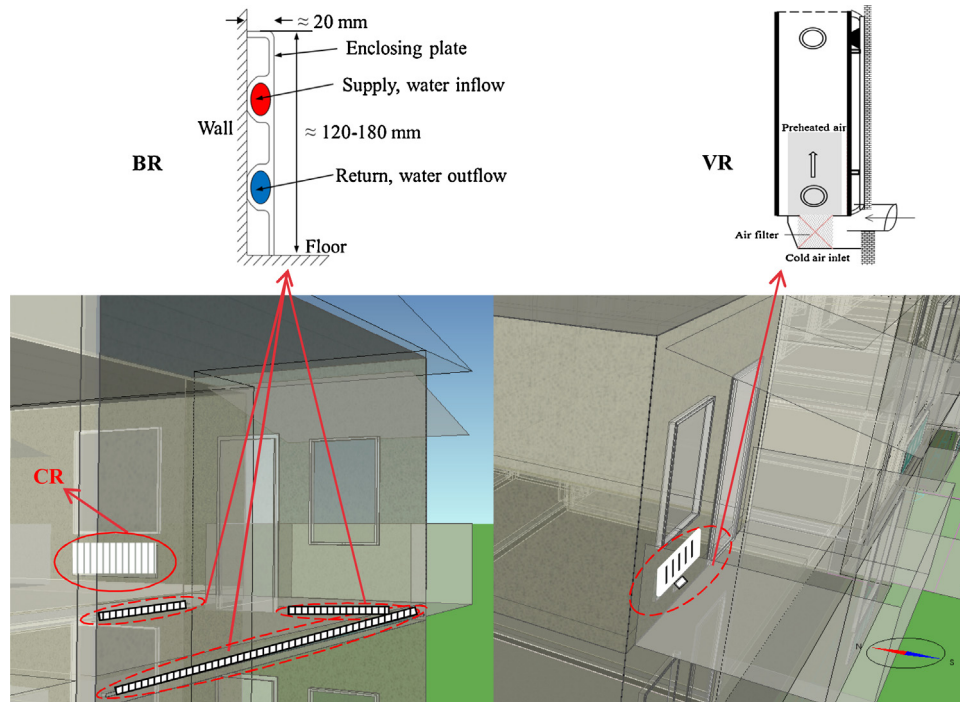


Fig. 3. The layouts of a conventional radiator (CR, left), a baseboard radiator (BR, middle) and a ventilation radiator (VR, right).

in [32,33]. VRs have already been installed in some newly constructed residential buildings in Scandinavian countries. More on the working principle of VRs can be found in [24,32]. BRs consist of low-height radiators that are placed along the inner periphery of a room. One-supply-one-return piping systems were attached to the enclosing metal plates. Typically, a BR has a height of 0.12–0.18 m and a length of 8–15 m [13]. Given the low height of a BR, convective heat flux to the room air is relatively high. In addition, the BR is exposed to colder room air along the entire length of walls. This also improves thermal gradient and gives better heat transfer from BR. The numerical and experimental analysis of the BR can be further found in [15,28]. In the present study, 8 mm heating pipes were selected, which was believed to be a realistic piping size for normal Swedish radiator systems in existing residential buildings. All three

radiators were selected as similar surface areas. The heating supply system was designed as an air-source HP (ASHP) after retrofitting. DHW was supplied by the existing district heating. Real-life COP performance was collected from over 100 HP models with respect to supply water temperature [34]. The approach sought to present the performances and differences of studied heating system as close as possible to the reality. The COP modeling of the ASHP was based on a three-step analytical model with real-life HP performance data measured by manufactures during heating seasons [35,36]:

1. Outdoor temperature was selected and heating demand was modeled by IDA ICE.
2. Supply water temperature was estimated by heating curves for HP.

3. The COP for the ASHP was estimated analytically by using manufacturer's data.

A combination of ventilation heat recovery with LTH can provide effective retrofitting profits for both energy conservation and thermal comfort [14]. Ventilation heat recovery is one of the most common retrofits in existing Swedish residential buildings. In the past 10 years, there has been a trend towards renovating ventilation systems from exhaust/natural ventilation to hybrid ventilation with efficient heat recovery from industry experiences [28]. The costs of ventilation retrofits are relatively low [37]. Statistics also showed evidence that installing heat recovery and centralized air-handling units (AHU) are the most common ventilation retrofits in the selected archetype [8,28,38]. In this study, the main reasons for introducing ventilation heat recovery retrofit were to reduce heating demand.

From an energy conservation perspective, heat exchangers recycle the heat from exhaust warm air and transfer it to the supply air (without mixing return and supply air streams). Cold fresh supply air is no longer continually brought directly to the room without pre-heating. As a result, the heating demand can be significantly reduced because less energy is needed to heat the intake air. From a building physics perspective, heat recovery decreases the risk of moisture condensation and mold growth inside the walls that is introduced by drawing air in through the walls, especially if there is a large temperature difference between outside and inside air in an old building. From an IAQ perspective, the supply air goes through the AHU with air filters, such as charcoal and CO<sub>2</sub> controls. This can also prevent stale air from building up and, more importantly, avoid bringing in outside pollutants such as street dust, soot, or pollen from old cracks and openings by natural air supply. Flow control is achieved either with motorized dampers or motorized supply air diffusers. However, more electricity for exhaust fans is needed to provide desired pressure drop and operate AHU. In this study, heat recovery units with air-filtering controls were selected. The supply air was modeled as return air-temperature-controlled, with a heat recovery efficiency of 80%. This heat recovery efficiency can be easily achieved from existing industry experiences [39]. The calculation of primary operational energy ( $\Phi_{\text{primary}}$ ) is obtained by Eq. (1) based on Ref. [40]. The primary energy factor has been widely recommended by EU directives to achieve sustainable energy and climate targets [40]. The primary energy factor ( $f_{\text{primary}}$ ) was selected as 0.98 for district heating by CHPs and 2.15 for electricity produced by Swedish mix [30,41].

$$\Phi_{\text{primary}} = f_{\text{primary}} \times \Phi_{\text{delivered}} \quad (1)$$

### 2.3. Environmental impact assessment of operational energy

Using the life cycle assessment (LCA) methodology, this study focused on the environmental impact assessment of operational energy before and after retrofitting. The aim is to achieve a better understanding of the overall environmental contributions of implementing VJLTH retrofitting, taking a life cycle thinking perspective. To do this, a streamlined life cycle energy analysis was carried out and employed a “cradle-to-gate” approach, accounting for all of the upstream stages before the final energy utilization phase in Sweden. It should be noted that the embodied energy of retrofitting itself was not included. The functional unit was specific operational energy (kWh/m<sup>2</sup>) or a period of one year, which was consistent with the energy conservation modeling. The LCA modeling was performed using SimaPro v8.0.4 LCA software and database. Life cycle inventory (LCI) data of relevant energy systems were taken from the Ecoinvent v3.1 database embedded in SimaPro.

The Ecoinvent database builds on the ISO 14040/44 standard for LCA, which contains both LCI datasets, data on several life

cycle impact assessment methods, and the results of applying these methods to the LCI data [42]. In the present study, two system processes served as the basis of LCA modeling. The first was electricity supplied by Swedish mix, 2014. The data calculation included Swedish electricity inputs produced and from imports and transformed to low voltage, transmission network, direct emissions to air, and electricity losses during transmission [42]. The second process was heat supplied by the CHP. This dataset shows the processing of biomass from bio-waste by combustion in a cogeneration unit with a gas engine to the final usage of district heating market. The degrees of efficiency were 0.32 for electricity and 0.55 for heat [42].

Regarding life cycle impact assessment (LCIA), there are several common ready-made methodologies, including Eco-indicator 99, EPS 2000, EDIP 2003, CML 2002, Impact 2002+, TRACI, Swiss Ecotoxicity 07, IPCC and ReCiPe. Choosing various LCIA methodologies with diverse characterization factors most commonly yields different LCIA results, which has created confusion and criticism regarding the use of LCIA and LCA in general [43]. For example, after reviewing 21 existing case studies on LCA in built environment, it concluded that LCIA methods in the previous studies were not systematically documented and selected for built environment and that LCIA methods were rather old [44]. In an effort to support the correct use of the characterization factors for environmental impact assessment, the European Commission's Joint Research Centre (EC-JRC) released the International Reference Life Cycle Data System (ILCD) in 2011. The ILCD is recommended in the ILCD guidance document “Recommendations for Life Cycle Impact Assessment in the European context—based on existing environmental impact assessment models and factors” [45]. The ILCD has been used in building sectors recently, but not widely [46,47].

LCIA was modeled using two LCIA methods embedded in SimaPro—i.e., “IPCC 2013 GWP 100a” (v1.00) and “ILCD 2011 Midpoint+” (v1.05). The first method—“IPCC 2013 GWP 100a” (v1.00) is the successor of the IPCC 2007 method, developed by IPCC [48]. The method was used to conduct carbon footprint analysis, concerning the climate change factors of IPCC with a timeframe of 100 years in this study. The second method—“ILCD 2011 Midpoint+” (v1.05)—was recommended by the European Commission's Joint Research Centre (JRC), as mentioned above [45]. The ILCD 2011 method in SimaPro includes 16 midpoint environmental categories. Impacts were evaluated by those 16 impact categories, which included climate change, acidification, terrestrial eutrophication, freshwater eutrophication, and photochemical ozone formation, etc. The descriptions of the environmental indicators are listed in Appendix B. In this study, the ILCD 2011 approach focuses on 15 material and emission flows by the studied energy systems. Regarding climate change (the 16 category), “the IPCC 2013 GWP 100a” (v1.00) method was employed, as the “ILCD 2011 Midpoint+” (v1.05) refers to the IPCC 2007 method.

### 2.4. IAQ modeling

Saving energy is not the only reason and evaluation method for effective retrofitting. Existing homes are still not air-tight, which leads to a new emphasis on the need to consider IAQ when retrofitting is implemented. On the basis of BBR and ASHRAE standard regarding thermal environmental conditions and acceptable IAQ for human occupancy, the success of retrofitting should be evaluated by providing the occupant spaces with an upgraded combination of humidity, temperature within the comfort zone, and acceptable IAQ [5,49]. The most accurate way to evaluate IAQ is by on-site measurements and monitoring for pollutants and fine particles in a long-lease term. In reality, however, annual measurements are difficult. In order to estimate IAQ by a more efficient method, CO<sub>2</sub> concentration is commonly selected as an indica-

tor. Measurements have shown that indoor concentration of rather coarse particulate matter is closely correlated to the CO<sub>2</sub> concentrations [50]. Also, the concentration of other human bio-effluents would be perceived as a nuisance [50]. In the present study, the relations between the concentrations of CO<sub>2</sub> in a space exclusively polluted by human bio-effluents and the percentage dissatisfied with air quality were calculated by Eq. (2) [50]. CO<sub>2</sub> concentration was presented as parts per million molecules (ppm). Outdoor CO<sub>2</sub> ppm was based on the inputs of annual climate data.

$$PD_{CO_2} = 395 \times \exp(-15.15 \times C_{CO_2}^{-0.25}) \quad (2)$$

By itself, CO<sub>2</sub> is not a poisoning gas to the health as other carbon monoxide; it is a naturally occurring by-product of human respiration. The safety threshold for CO<sub>2</sub> level is 5000 ppm over 8 h of exposure. At levels up to 10,000 or 20,000 ppm, more serious symptoms of CO<sub>2</sub> poisoning start to appear, including headache, lethargy, mental fogginess, confusion, irregular heartbeat, and anxiety [50]. However, CO<sub>2</sub> concentration does not usually rise up to 5000 ppm in residential buildings.

### 3. Results

#### 3.1. The energy conservation of VJLTH retrofitting

Simulations were performed with a focus on constructing the supply water temperature, evaluating the COP of the HP, and corresponding annual operational energy savings. Fig. 4 shows the constructed building model in IDA ICE. The room with the highest heating demand was found to be the room located at the most northwest position of the building, shown by the red frame in Fig. 4b. This may be caused by the outdoor temperature, orientation (solar radiation of Stockholm), and the large envelope area adjunct to outdoor environment and as-built ventilation system. This room was further selected as a reference zone for investigation. The zone has a heated floor area of 12 m<sup>2</sup>, the window size is 1.2 m × 0.8 m. For the CR before retrofitting, the size was 1 m × 0.5 m, type 11 (one-panel-one-convection fin) with total surface area of 1.54 m<sup>2</sup>. For VR after retrofitting, it was the same size and surface area as CR. For the BR, the size was 10 m × 0.15 m with a surface area of 1.5 m<sup>2</sup>. Heat balance during the annual heating seasons was modeled by IDA ICE. Internal heat gains took into account heat gains from occupancies, solar-direct and diffuse, and heat from domestic appliances. Fig. 5 presents a whole picture of retrofitting impacts to the COP on basis of outdoor temperature and heating curve of different radiators. Fig. 5a shows the modeled weekly heating demand in the reference zone before retrofitting (black solid line) and after retrofitting (green solid line) in annual heating seasons with respect to outdoor temperature (red dashed line). The heating demand varies from maximum 420/380 W before/after retrofitting (from February) to 50 W (weeks partly in April and September). The main contributor to this heating demand reduction is ventilation heat recovery, by which air-flow heat losses were largely reduced. All the heating demand in the study includes internal heat gains, which varied from 14 to 18 W/m<sup>2</sup>.

Fig. 5b shows the temperature variations as a function of time in weeks after retrofitting. The classification of low/very-low-temperature heating systems is featured by a heating curve below 45/35 °C [15]. In order to critically evaluate the energy conservation by only improving the efficiencies of radiators, the CR with reduced heating demand by ventilation retrofit is also presented as a baseline. The heating system before retrofitting was high-temperature district heating with a constructed heating curve of 75/50 °C, as introduced in Section 2.1.

The mass flow of radiators was controlled by thermostatic valves and pumping speed. The highest supply temperature for CR was

50 °C after only ventilation retrofit (with a heating demand of 30 W/m<sup>2</sup>), under the lowest averaged weekly outdoor temperature of −7 °C in February. Correspondingly, the highest supply temperatures for the VR and the BR were 43.5 °C and 40.6 °C, respectively. This result confirms that, after retrofitting, both VRs and BRs can work as low-temperature heating during the whole heating season in Stockholm. The threshold heating demand is approximately 30 W/m<sup>2</sup>. From week 17 (April) to the beginning of November, the supply temperature of CR falls below 40 °C. For VRs, the supply temperature higher than 40 °C starts with a heating demand of 22 W/m<sup>2</sup>. For BRs, the supply temperature above 40 °C starts with a heating demand of 27 W/m<sup>2</sup>. When the outdoor temperature is above approximately 4 °C and 0 °C, VRs and BRs both work with a supply temperature lower than 35 °C to provide approximately 10 W/m<sup>2</sup> heating demand. The VRs and BRs work as very-low-temperature heating (below 35 °C) for 7 and 11 weeks, respectively. It can be concluded that with a retrofitting target of approximately 10 W/m<sup>2</sup> heating demand, VRs and BRs can both work as a very low-temperature heating system. The results of the heating curve are believed to be interesting for engineering designs to provide a retrofitting threshold of heating demand in rather mild cold climate, such as Stockholm, with an annual average outdoor temperature of 6.8 °C.

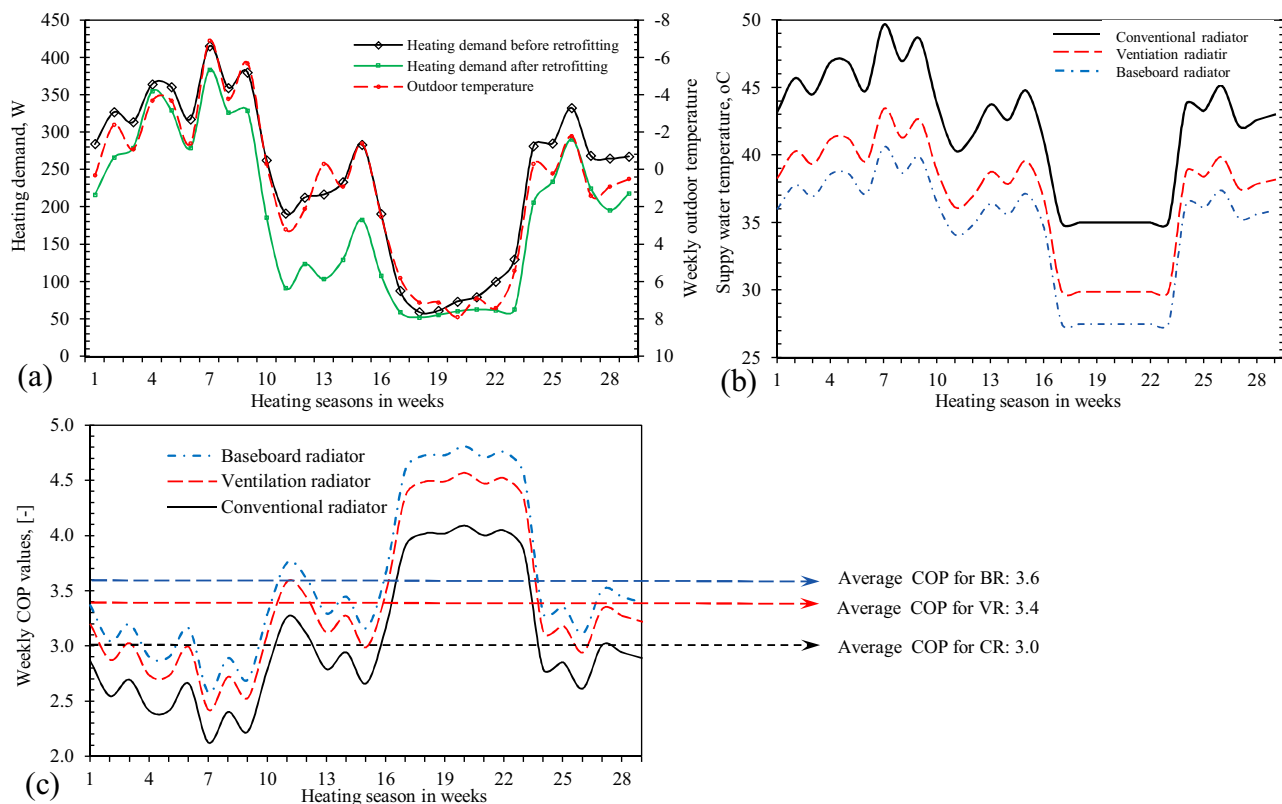
Fig. 5c shows the corresponding COP of the ASHP after retrofitting. The CR shows an averaged COP of 3.0, which improves to 3.4 for the VR and 3.6 for the BR. When the outdoor temperature is relatively mild (above 0 °C), the VR exhibits larger advantages in heat emission performance than in relatively colder outdoor temperature. This can be explained as when convection is plagued by relatively reduced temperature differences, the VR can still boost up the convection by forced ventilation channels beneath the radiators. This leads to a better performance of the VR in mild outdoor temperature. It can also be observed from Fig. 5c that great impacts of LTH to the ASHP mainly occurred in limited duration of whole heating seasons. The major contributions of LTH for the COP of the ASHP came in the weeks when the outdoor temperature was below 0 °C. The results were analysed based on real-life performance data provided by the manufacturers of the ASHP, although the result could be different if the occupants choose a particular type of ASHP.

Fig. 6 presents the result of operative temperature variations on the basis of a constructed heating curve under the design outdoor temperature. It can be observed that both the VR and the BR can reduce the fluctuations and upgrade the lowest operative temperature from 18.7 °C (before retrofitting, CR) to above approximately 20 °C (after retrofitting). The highest improvement is observed by implementing the BR with an improved average operative temperature of 20.8 °C. VR shows an improved average operative temperature of 20.2 °C. In addition, the VR shows further decreased operative temperature fluctuations compared with the BR. The CR also shows an acceptable operative temperature (20.2 °C) after ventilation heat recovery. This lies in the fact that most of the existing radiators have already been oversized. It should be noted that the contributions to operative temperature by different radiators are limited (within 1 °C). Both the VR and the BR can provide acceptable global thermal comfort during the whole heating seasons when they are implemented together with ventilation retrofitting. Local thermal comfort, such as draughts from window and claddings, was not evaluated in this study.

The specific operational energy before retrofitting (for delivered energy) was 98 kWh/(m<sup>2</sup>·year) for space heating. The total delivered operational energy was 123 kWh/(m<sup>2</sup>·year), which consisted of space heating, DHW, and electricity. The corresponding primary energy for space heating and total operational energy was 96 kWh/(m<sup>2</sup>·year) and 127 kWh/(m<sup>2</sup>·year), respectively. The contributions of different retrofit parts for space heating are shown in Fig. 7. The required annual operational energy for the build-



**Fig. 4.** Constructed building model in IDA ICE (Fig. 3b) and selected reference zone with the highest heating demand ((a), framed in red in (b)). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



**Fig. 5.** Weekly heating demand (before and after retrofitting) with respect to the outdoor temperature during the annual heating season of the selected reference zone. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

ing after implementing VJLTH is indicated and ranked in Fig. 8. It consists of two types of operational energy criteria: delivered energy and primary energy. The electricity is provided to the ASHP in order to maintain the air temperature within the set point, in addition to the heat flows, to other adjacent zones to the outside. The BR showed the highest total energy savings for both delivered energy and primary energy (52.4 and 91.4 kWh/m<sup>2</sup> year, in which space heating contribute 24 and 51.7 kWh/m<sup>2</sup> year). The corresponding total energy savings (delivered and primary) are 57 and 28%, respectively. For the VR, the percentage of delivered and primary energy savings are 56 and 26% (52.4 and 91.4 kWh/m<sup>2</sup> year, of which space heating contribute 25.4 and 54.6 kWh/m<sup>2</sup> year), respectively. It is concluded that VJLTH retrofitting can save up to 55% of delivered energy, and the corresponding primary energy savings are greater than 25%. The proposed retrofit package can reduce the operational energy of studied building below the limitation set by Swedish building regulation BBR, as indicated in Fig. 8a. No additional retrofitting is needed, such as renovations on envelope, DHW renovation, or changing the occupation behaviors. This is believed to be an interesting contribution for future large-scale

low-energy transformation of Swedish building stock in an industrialized method from the city level. The energy usage of keeping the existing CR but implementing the ASHP and ventilation heat recovery is also presented in Fig. 8. The CR requires 28.6 kWh/m<sup>2</sup> year electricity for space heating. In other words, 12% and 15% electricity for the HP can be saved by using the VR and BR. These results agree with the previous studies by [24,51], which found that the energy savings of LTH is approximately 12%, but with a more accurate indication from a building level considering different types of radiators. However, it should be noted that the primary energy factor for the HP was selected as 2.15 (Swedish mix for electricity) in this study. The total primary energy can differ on the basis of other electricity production systems in other locations/cities/countries.

### 3.2. Environmental impacts

Fig. 9a–p provides results regarding the release of thousands of chemicals, radiations, and resource usage associated with the energy producing, transportation, transformation, and usage. The background data (e.g., data for the production of Swedish mix)

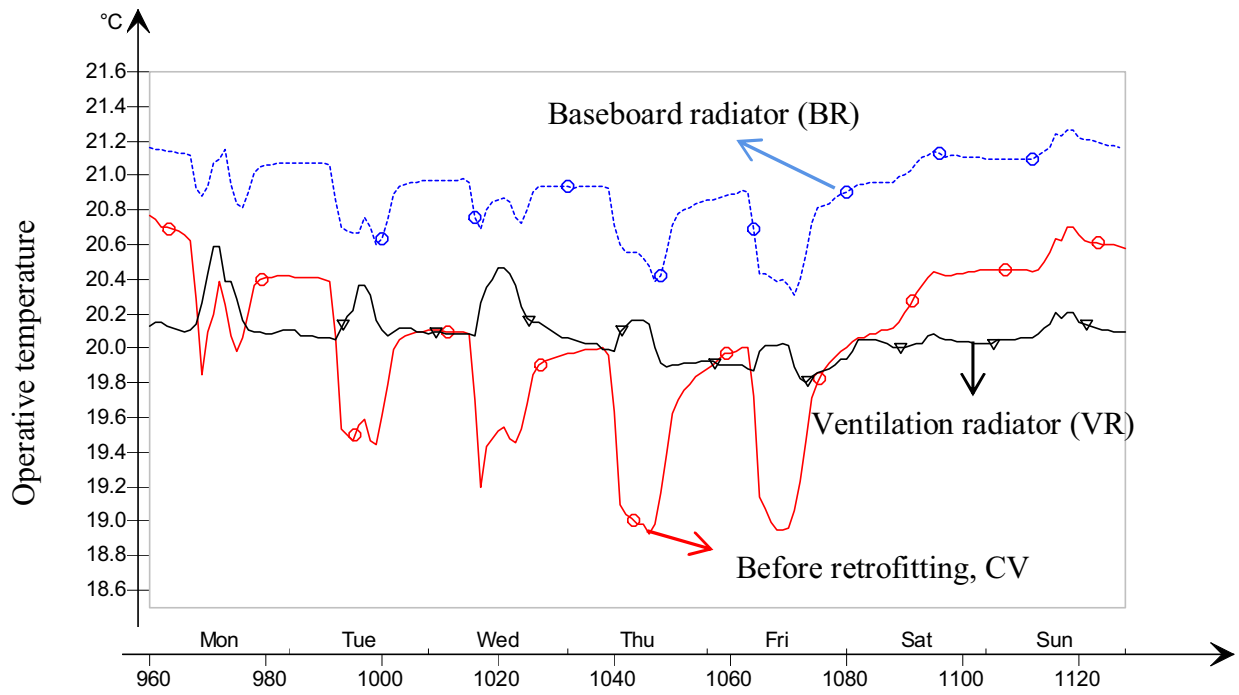


Fig. 6. Operative temperature of the CR, VR, and BR under the design outdoor temperature in the selected reference zone.

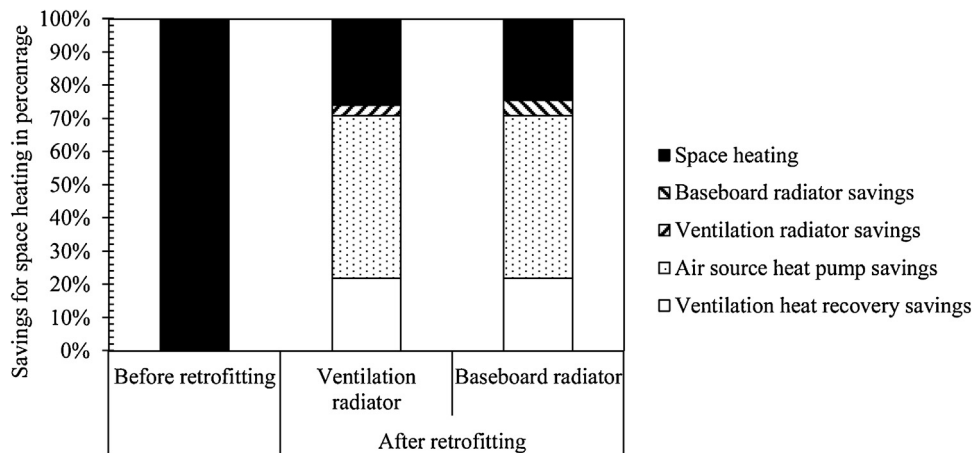


Fig. 7. Contributions of energy savings for space heating.

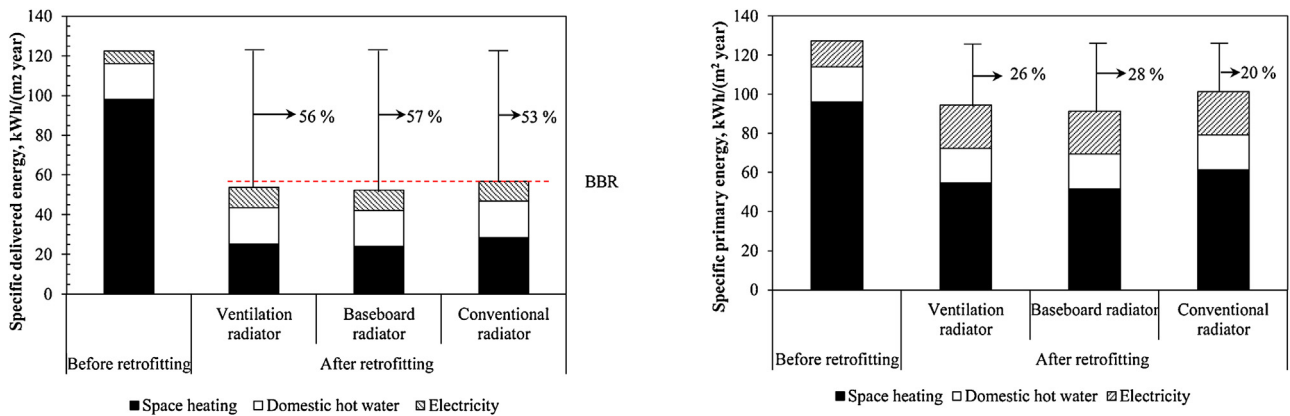


Fig. 8. Total operational energy (delivered, left figure, and primary, right figure) performance before and after VJ LTH retrofitting.



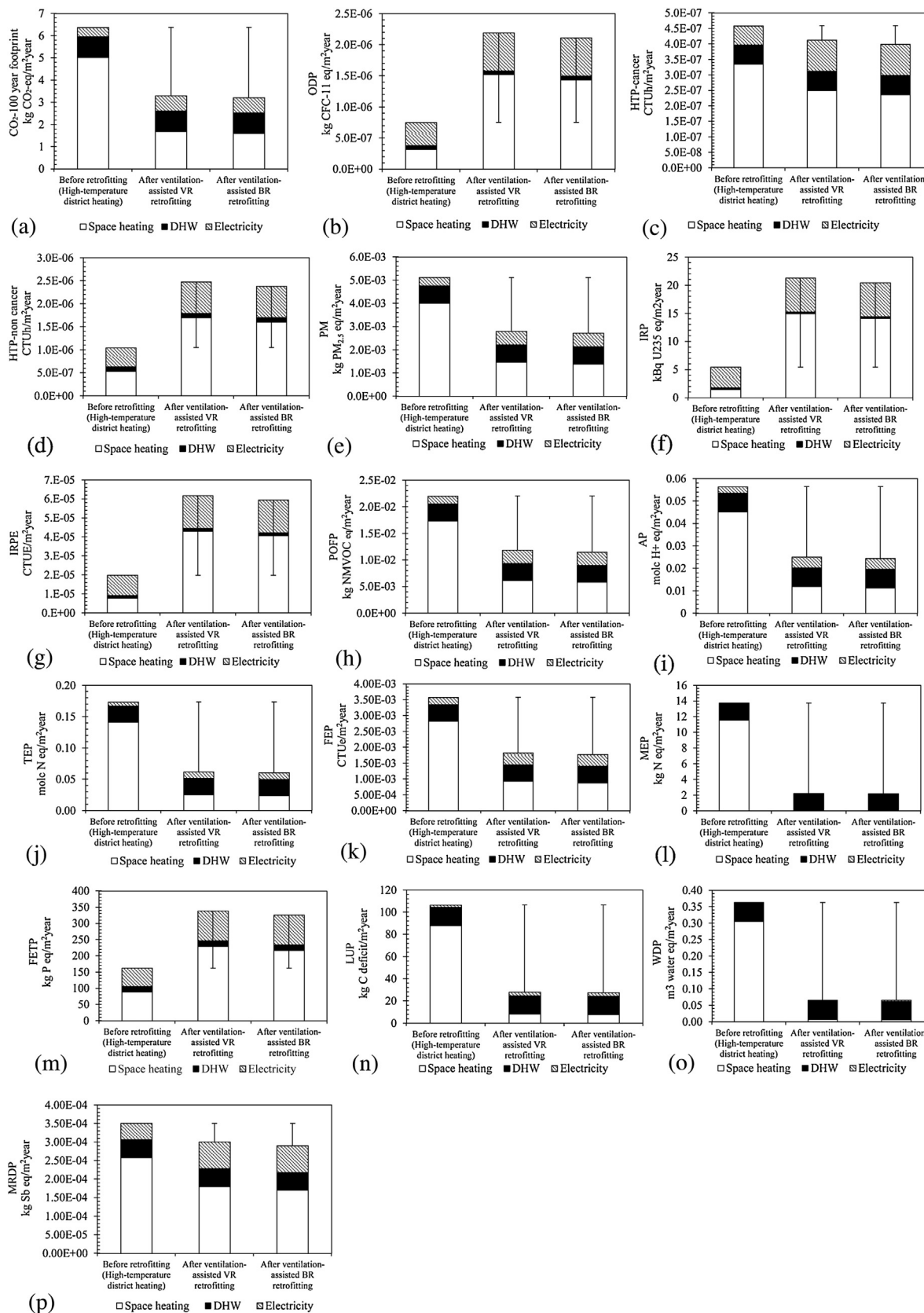


Fig. 9. (a–p) Quantified environmental impacts before and after retrofitting (per function unit) concerning the studied 16 indicators \*P in each acronym refers to potential, deviation bars show the impacts.

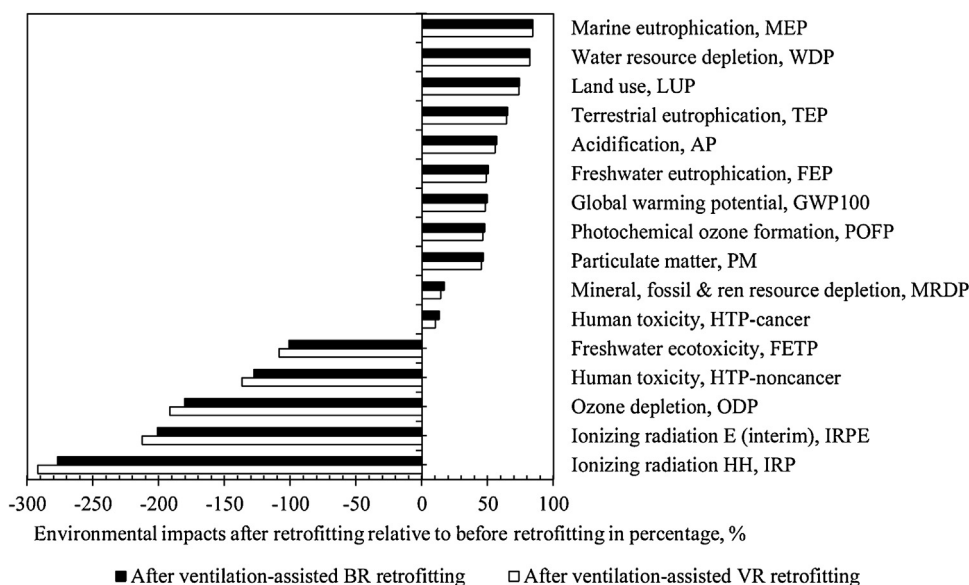


Fig. 10. Environmental impacts by VJLTH retrofitting relative to before retrofitting, as percentage.

is taken from the Ecoinvent database [42]. The life cycle impact assessment results, represented in Fig. 9a–p, are based on the SimaPro calculation results [45]. Quantified environmental impacts per function unit are presented on the basis of 16 environmental indicators. The study does not aim to compare one environmental indicator with another, or weight the importance of collective pollutants to the environmental impacts. Also, the results do not aim to present the total environmental impacts of the selected case building. Instead, the study focuses on addressing the positive/negative environmental impacts by the proposed retrofit package before and after retrofitting, and further quantifying them from a comprehensive LCA perspective. The results are presented to be repeatable for similar archetypes that are expected to implement VJLTH retrofitting in the future. Therefore, the results of 16 environmental indicators are all presented without neglecting or omitting those that have relatively low overall impacts or quantities. This method has also been pointed out by the employed environmental modelling methods and environmental scientists [45]. Based on the results of Fig. 9a–p, Fig. 10 presents the corresponding environmental impacts after retrofitting relative to before retrofitting, expressed as a percentage. Most of the environmental indicators (11 of 16) were positively impacted by implementing VJLTH retrofitting. In general, the BR has higher contributions than the VR because less operational energy is needed for BR. However, the differences between the BR and the VR are small.

7 of the 11 positively impacted environmental indicators have approximately 50% (or more) positive impacts, which were mainly caused by reduced emissions from greenhouse/toxic gases to the air, pollutants to the aquatic, and solid environment by less final energy demand. These indicators are marine eutrophication (MEP, Fig. 9l), water resource depletion (WDP, Fig. 9o), land use (LUP, Fig. 9n), terrestrial eutrophication (TEP, Fig. 9j), acidification (AP, Fig. 9i), freshwater eutrophication (FEP, Fig. 9k), and global warming potential (GWP100, Fig. 9a). The highest contributions are observed for marine eutrophication, or water resource depletion. Notably, the key driver for biogas production (which is the main resource of the CHP for district heating)—GWP 100—is reduced by approximately 50% after retrofitting (by using a LTH ASHP) compared with before retrofitting (high-temperature district heating). In summary, replacing the existing high-temperature district heating system to ASHP-supported LTH with improved efficiency can reduce eutrophication, acidification, and most toxic/greenhouse

gas emissions, such as photochemical ozone formulation, particulate matter, and CO<sub>2</sub> footprint. The results can be explained by the current Swedish energy supply systems in residential sectors. The Swedish energy system is partly based on renewables (such as water, wind, and biofuels). It has become increasingly common to produce district heating in CHPs, which is notably biomass-based. In 2011, wood fuels accounted for 38% of the input energy used to produce district heating in Sweden, followed by waste for 19%, peat for 4% and waste heat for 6%. Biogas production is an important contributor to acidification, eutrophication, and certain toxic gases, largely because of the emissions from digested storage [52]. Instead, Swedish electricity production is composed of 48% hydro-power, 38% nuclear power and 4% wind power (data of 2012). The remaining 10% was combustion-based production, mainly from CHPs and industry [53]. When the proposed retrofitting was implemented, the total operational energy (final stage) was greatly reduced and the energy supply system (secondary energy) was transformed from a high-temperature-based CHP to an electricity-based ASHP. As a result, certain environmental indicators, which are more considerable in biogas-based district heating production, reduced notably due to the use of highly efficient heat pumps after retrofitting. However, it is risky to conclude that the proposed retrofit – or, in other words, HP is the most optimistic sustainable solution to the environment in Sweden, even though the electricity demand is largely reduced by energy-efficient measures. It can be observed from Fig. 10 that 5 of 16 indicators are significantly negatively impacted after retrofitting; these including ionizing radiation (Fig. 9f–g), ozone depletion (ODP, Fig. 9b), human toxicity (non-cancer, Fig. 9d), and freshwater ecotoxicity (FETP, Fig. 9m). The relative increased impacts are high—up to almost 2–3 times more than before retrofitting—although the total impact quantities are still small after retrofitting, such as ionizing radiation and ozone depletion. This can be explained by the primary energy of electricity in Sweden. A large proportion of electricity is dependent on nuclear fuels and hydro-power. The fact that ionizing radiation can severely damage human health has been widely pointed out and is known to the nuclear power industry. The ozone depletion is mainly caused by chlorofluorocarbons (CFCs), Halons, and Freons, which are common in aerosol cans and are released by electronic appliances. CFCs account for approximately 80% of ozone depletion. Nuclear power itself does not produce CFCs. However, as a main source of nuclear reactor uranium, from which mining and pro-

cessing inevitably emit CFCs, tailings dams cause pollution through leakage. In addition, uranium refining facilities commonly rely on fossil fuels to provide electricity. These joint factors resulted in negative impacts by the proposed retrofitting, even though the final energy savings are up to more than 50%.

### 3.3. Indoor air quality

The IAQ of the building is simulated based on the recommendations of Swedish building certificate tool [54]. The indicators include both CO<sub>2</sub> concentrations and relative humidity (RH), before and after retrofitting, as introduced in Section 2.4. Fig. 11 presents the results of a bedroom that had the highest CO<sub>2</sub> concentration and the corresponding percentage of dissatisfaction (PD) in the building. The results present the simulation for an entire year, including both heating and non-heating seasons. According to the requirement of IAQ levels by [5], relative humidity is also presented within the same period. The calculated averaged IAQ levels were not largely improved by VJLTH retrofitting. The CO<sub>2</sub> concentrations were improved from an averaged level of 898 ppm (before retrofitting, solid red line) to 840 ppm (after retrofitting, solid black line). The corresponding annual averaged PD levels were improved from an averaged level of 16.2% (before retrofitting, red dashed line) to 14.5% (after retrofitting, black dashed line). The CO<sub>2</sub> concentration has an acceptable IAQ both before and after retrofitting, according to the requirements (within 700 ppm above outdoor CO<sub>2</sub> concentration/below 20% PD, annual outdoor CO<sub>2</sub> concentration is approximately 370–400 ppm in Stockholm [55]). Specifically, the CO<sub>2</sub> concentration after retrofitting is below 1100 ppm throughout the entire year. The maximum CO<sub>2</sub> concentration was reduced from 1240 ppm before retrofitting to 1100 ppm after retrofitting. The higher CO<sub>2</sub> concentration level is observed mainly during the heating seasons in winter time. In summer time (non-heating seasons), the CO<sub>2</sub> concentration is commonly low. This is explained by the parameters set in the model. In the simulation when outdoor temperature is above 26 °C, the windows and external openings were modeled as partly open in order to have more natural ventilation and the ventilation flow rate was not largely changed by retrofitting. The impact of the proposed retrofit to the RH is limited. The averaged RH was reduced from 32% before retrofitting (solid red line) to 30% (black dashed line). According to the requirement of ASHARE, RH above 70% for normal living may cause condensation on cold surface, which increases the risk of mold growth, corrosion, and moisture-related deterioration. RH above 60% feels uncomfortably wet for humans. Too low RH below 25% may cause bad IAQ with static electricity. Based on the simulation results, RH shows similar results of CO<sub>2</sub> concentrations that the RH falls in the acceptable category for IAQ (25–60% RH) both before and after retrofitting. During weeks 7–13 (partly in February and March), three weeks have RH below 25% because of the cold and dry outdoor temperature in Stockholm. One can conclude that the studied VJLTH retrofitting can improve the CO<sub>2</sub> concentrations by 11% on an annual average basis. The impacts to the RH are limited. The IAQ before and after retrofitting fell into the acceptable level. This agrees with the measurements that the current requirement for ventilation flow rate of Swedish building codes BBR is large enough to support acceptable IAQ [18].

## 4. Discussion

### 4.1. Application of VJLTH

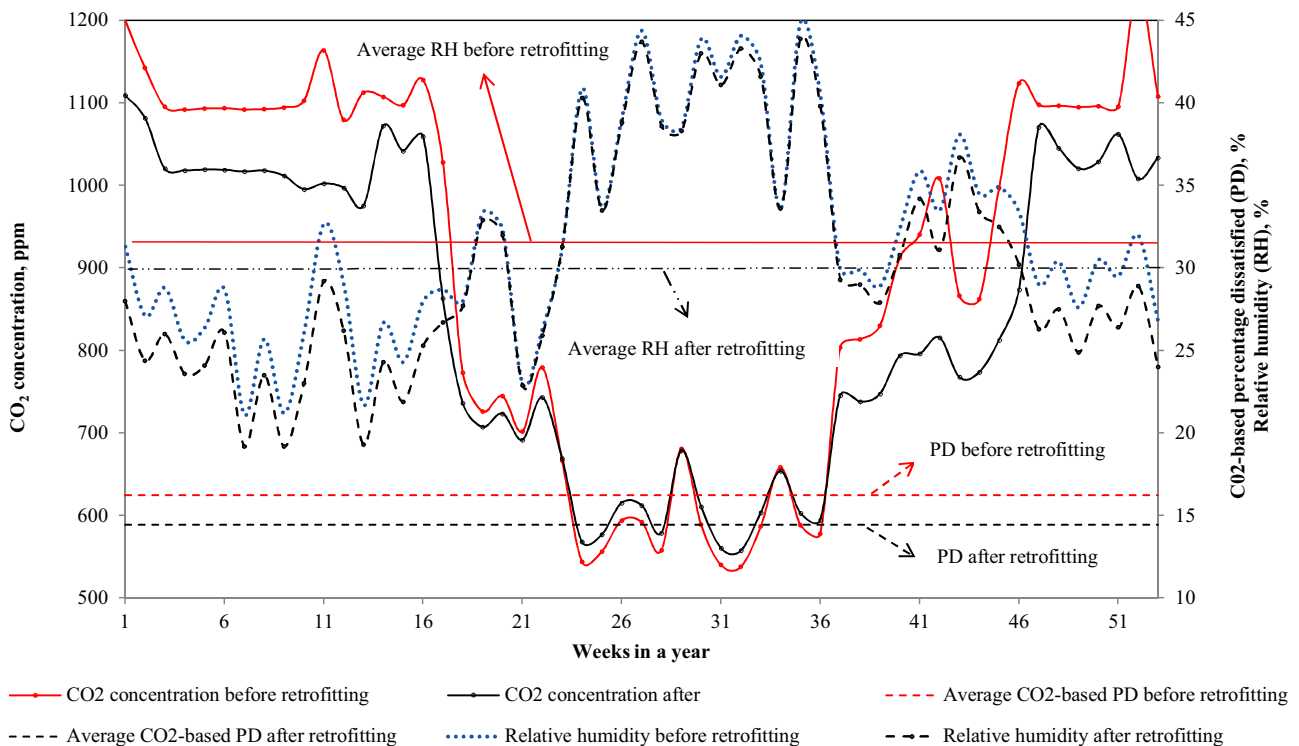
ASHPs and district heating are both widely used heating systems in Swedish multifamily houses. However, ventilation heat recovery with LTH in retrofitting has not been widely implemented

in Swedish housing stock. The processes are mainly plagued by the ways of selecting the suitable renovation measures from the demand side; more specifically, of renovating the existing buildings to a condition that is suitable for LTH. On the basis of operational energy results, it can be concluded that VJLTH can reduce the final energy by more than 55%. These energy conservations are contributed by the joint effect of reduced heating demand (ventilation retrofit), the improved performance of the HP, and the improved efficiency of radiators.

Fig. 5 has shown that when a building is renovated to 10 W/m<sup>2</sup> heating demand (including internal heat gains), both the VR and the BR work below 35 °C. This indicates that the heating system will work/classified as “very low-temperature heating” [15,56]. When a building is renovated to 30 W/m<sup>2</sup> heating demand, the VR and BR both work as low-temperature heating (below 45 °C). They are interesting threshold values for engineers looking to design and target the heating demand in future retrofitting practice. However, Fig. 8 also shows that the CR can save up to 50% of the final energy. The profits of implementing more energy-efficient radiators (VRs and BRs) are approximately 5% more than for CRs, with respect to the total delivered energy savings. The corresponding improvements of VRs and BRs to the COP (compared with CR) are approximately 12% and 18%, respectively. Compared with pilot retrofitting studies on this archetype without LTH [51], the simulated delivered energy was not greatly reduced by having only LTH radiators. VJLTH retrofitting shows a high ability to reduce heating demand; however, the additional electricity needed for AHU and pumps after retrofitting (approximately 4 kWh/(m<sup>2</sup>/year))—which shows similar results with previous analytical models [9]—shall be critically considered. This raises the future research demand that the full profits of LTH shall be explored by combining efficient heat emission components with optimistic system designs (piping, pumping, heating demand, and ventilation system), which are well-designed for LTH. A further study regarding how to select different ventilation systems with more effective, pre-heated supply air with LTH shall be investigated. Other ventilation systems, such as demand-control ventilation, have been reported as being able to provide good combinations with LTH and operational energy savings [19]. Fig. 8 shows that the largest contributions of VRs and BRs than CRs lie in the savings to primary energy, which are approximately 6–8% than for CRs, with respect to total primary energy. This is because of the high primary energy factor of electricity, which is the energy supplier to operate the compressor of ASHP after retrofitting. The BR has the highest primary energy saving—up to 28% but this is based on the assumptions that baseboard can be well designed and placed. Results show that there was no negative impact of thermal comforts after retrofitting. Fig. 6 also reveals that the main contributions of LTH radiators to operative temperature are the reduced temperature fluctuations. The main operative temperature can be improved by LTH radiators, but this does not vary significantly among CRs, VRs and BRs. The size of LTH radiators are designed as the same as CRs before retrofitting. This confirms previous findings that increasing the heat convection of radiators is more effective than enlarging the radiators to improve the heat emission efficiency in retrofitting [27,14].

### 4.2. Accuracy of modeling

Accurate operational energy modeling was challenging, due to inconsistencies varying from actual engineering work to the impact of occupant behaviors. First, uncertainties emerged from the energy balance modeling of IDA ICE. The study was based on the modeling results and parametric analysis; no questionnaires and communications with occupants were carried out. In addition, the internal heat gains were based on the assumptions of average occupants, equipment, and controls from statistics [53,55]. In reality, the occu-



**Fig. 11.** Weekly CO<sub>2</sub> concentration, percentage dissatisfied (PD), and relative humidity (RH) in the worst apartment before and after retrofitting. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

pants can vary from 1 to 5. Various living schedules and occupancies in the studied zones show differences in energy balance modeling, which has been widely pointed out in the literature [23]. The studied archetype is not low-energy/net zero building. As a result, the randomness and behaviors of occupancies to the internal heat gains were not studied in detail. However, this should be further improved in future studies. Second, there are uncertainties in modeling VRs, BRs, and ASHPs, all of which are partly dependent on how the technicians choose the components, and may vary largely from actual operation and controls by the occupants. The present study is based on the measured data from real-life performance of ASHPs. However, different ASHPs provided by manufactures perform in very different ways. Therefore, the results do not aim to provide recommendations for one or two particular parameters that influence the COP of an ASHP; instead, they seek to generate findings how energy efficiency (LTH radiators) can impact ASHPs in general. Third, the study only focuses on the energy conservations of LTH radiators and ventilation; some practical drawbacks of proposed retrofit were not fully covered in this study, such as noise. Heat emissions from BRs were calculated using equations based on laboratory measures and the assumptions that the components can be well placed. However, the heat transfer of a BR can be influenced largely by the occupants, such as the place of furniture. The distance between a BR and furniture can block the heat transfer or, in another way around, create a heat-chimney effect to improve heat transfer. This will increase the uncertainties of the studied system. In addition, the maintenance of ventilation vents and the AHU of introduced ventilation retrofit were not studied. It has been pointed out by industry that ventilation with heat recovery units usually requires more maintenance than exhaust ventilation. The performance also drops dramatically without maintenance within a short life-span, which further increases the life-cycle costs. Fourth, the primary energy factor is applied in the model. However, different methods lead to large variations of primary energy factor values in energy accounting. The shortages of applying primary energy

factors for primary energy estimations have been reported in previous studies [9,14]. Furthermore, integrating renewables with LTH should be further explored in order to accelerate the retrofitting efficiencies from primary perspective. If the retrofitting target is a nearly/net-zero building, additional retrofits on DHW and energy savings for electricity-based fittings are required. After retrofitting, the final stage energy by DHW and the building's electricity usage will be equally important to space heating. More importantly, it will be increasingly demanding to correctly size the suitable piping system, valve controls, circulation pumps and choose highly-efficient fans to meet the flow rate of LTH. In other words, provide favorable conditions that can cope with LTH. This raises the question of how low-temperature heating systems for existing buildings should be practically designed from an engineering point of view. However, on-site measurements and controlling of the system has not yet been sufficiently studied.

#### 4.3. Challenge of analyzing environmental impact

Environmental impact analysis with respect to the energy conservations is challenging because of the large boundaries of the system. Figs. 9 and 10 reveal some interesting findings regarding the environmental impacts by the studied retrofit. The results show that VJLTH retrofitting can contribute 11 indicators, in which the impacts to eutrophication, acidification, air pollutants and greenhouse emissions are reduced by up to 50% compared to before retrofitting. Therefore, it is safe to conclude that the studied retrofit can benefit the three Swedish national environmental and climate strategies by 2020: more efficient energy use; non-toxic, resource-saving environmental life cycles; and management of land, water and the built environment [58]. This technology is also beneficial for reducing the emissions of supplied energy. The stable and relatively low primary energy production of electricity by Swedish mix further extends the possibility of applying HPs from a national level for future LTH-based heating method [12]. However, it is still too

early to conclude that the studied retrofit is completely sustainable, from a life-cycle assessment perspective. Figs. 9 and 10 also reveal that 5 environmental indicators were negatively impacted by changing high-temperature district heating to low-temperature HPs, even though final energy use was reduced by more than 50% and the overall quantities of these negative indicators (absolute values) are still low. It has been reported that the use of biofuels for electricity and heating has been constantly rising in Sweden [49]. However, the electricity is still dominated by nuclear power and hydro-power production. Given that the decay and cumulative effects of toxic chemicals and radiations is extremely complex in nature-secondary energy-building system, the current focus on greenhouse gas emissions (or, in other words, low-carbon technologies in buildings) may have unintended consequences with regard to those impacts that show harmful effects in a long-lease term to human health and ecological system. This point has also been made by researchers who have focused on the LCA of different energy systems, such as fossil fuels, biomass-based CHPs, and renewable heat incentive schemes [52]. This study also provides evidence that it is arbitrary to evaluate the sustainability of energy-saving measures only by carbon emissions, particularly in retrofitting buildings/building clusters, which commonly extend the life of a building by more than 50 years. Reducing environmental impacts by final energy savings should not be sacrificed in the race to reduce greenhouse gas emissions. This finding agrees with the reports of the Swedish Environmental Objective Council that 9 of the 16 Swedish environmental quality objectives will be difficult or impossible to achieve by the target date, with the trends pointing in the wrong direction despite a fall in Swedish emissions [58]. Some studies have pointed out that on-site energy producing systems, such as an optimistic combination of solar collectors with photovoltaic and low temperature heating systems, may lead to both energy conservation and reduced environmental impacts. However, critical reviews regarding the sustainability of retrofitting should also take into account the embodied energy of the renovation measures themselves, which is not covered in this study.

## 5. Conclusion

In this paper, the authors have investigated the possibility and evaluated the impacts of implementing ventilation heat recovery

jointed low-temperature heating system (VJLTH) in retrofitting low-rise Swedish multifamily houses. The studied building was renovated from high-temperature district heating to VJLTH system. Three criteria were presented to assess the retrofit contributions to sustainability: energy conservation, environmental impacts, and indoor air quality. Based on the obtained results the following conclusions are drawn:

- After retrofitting (below 30 W/m<sup>2</sup> heating demand), both ventilation radiators and baseboard radiator could work as low-temperature heating. They serve as very-low-temperature heating with a heating demand of 10 W/m<sup>2</sup> (including internal heat gains).
- During the annual heating seasons, ventilation radiator and baseboard radiator could improve the COP of air-source heat pump by approximately 12% and 18%, respectively, compared to conventional radiators with the same surface area.
- Ventilation heat recovery jointed low-temperature heating retrofitting can save total final and primary energy up to 55% and 25%, respectively, compared with before retrofitting.
- 11 of 16 environmental indicators were positively impacted by the retrofit, with 7 of 16 environmental impacts being reduced by 50% compared with before retrofitting. The largest contribution of the studied retrofitting is to emissions, such as eutrophication, acidification, and greenhouse gases.
- 5 of 16 environmental indicators were negatively impacted by the retrofit, which shall not be omitted. It is risky to solve one environmental and climate target that policy is currently promoting—namely, climate change—at the expense of other environmental impacts.
- The studied retrofit can improve the indoor air quality, but not largely. The percentage of dissatisfaction was reduced from 16.2% before retrofitting to 14.5% after retrofitting.

## Acknowledgments

The authors are grateful to Formas in Nordic Built, Nordic Innovation, and the Swedish Energy Agency for providing financial support, and to the building owners and industries that contributed valuable information and empirical documents for this project.

## Appendix A. Building parameters and technical descriptions before retrofitting.

Building parameters	Technical description
Archetype	12 flats per storey, 24 flats in total
Location	Stockholm, Sweden
Storey/heated floor areas	1600 m <sup>2</sup>
Orientation	South–north
Occupants	3–4 in each flat
Living schedule (including DHW)	Swedish public holidays
Attic/roof, materials	Two-storey, designed as parallel or perpendicular with basements (flat height: 2.71 m),
Wall and external/internal insulation, materials	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
Windows	Double glazing window with aluminum cladding and natural ventilation openings (with windcatcher)
Ground floor, materials/U-value	Concrete slab covered by linoleum or plastic mats on surface of fiberboard
Shadings	No
Basement	Concrete slab, directly on gravels. 20 × 40 cm insulation layers are placed on the edge between foundation slab edge and joists
Air-leakage level	2 ACH under the pressure differences ±50 Pa
Balcony/terrace	Suspended 10 cm precast slab concrete foundation covered by 1.2 cm healed asfboard; concrete studs
Heating design temperature	18 °C
Heating seasons	29 weeks
Reference supply/return temperature of heating system (before retrofitting)	75/50 °C
Reference ventilation system (before retrofitting)	Decentralized exhaust ventilation
Reference ventilation grille locations (before retrofitting)	Kitchens and bathrooms

## Appendix B. Environmental impact indicators included in the analysis (adapted from Simapro v8.0.4).

Impact category	Acronym	Unit	Description
Global warming	GWP100	kg CO <sub>2</sub> -eq	Global warming potential calculating the radiative forcing over a time horizon of 100 years.
Ozone depletion	ODP	kg CFC-11 <sub>-eq</sub>	Ozone Depletion Potential (ODP) calculating the destructive effects on the stratospheric ozone layer over a time horizon of 100 years
Human toxicity, cancer effects	HTP <sub>-cancer</sub>	CTUh	Comparative Toxic Unit for humans (CTUh) expressing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogram).
Human toxicity, non-cancer effects	HTP <sub>-noncancer</sub>	CTUh	Comparative Toxic Unit for humans (CTUh), expressed as above
Particulate matter	PM	kg PM <sub>2.5</sub> -eq	Quantification of the impact of premature death or disability that particulates/respiratory inorganics have on the population, compared to PM <sub>2.5</sub> . It includes the assessment of primary (PM <sub>10</sub> and PM <sub>2.5</sub> ) and secondary PM (including creation of secondary PM due to SO <sub>x</sub> , NO <sub>x</sub> and NH <sub>3</sub> emissions) and CO
Ionizing radiation HH	IRP	kBq U <sub>235</sub> -eq	Quantification of the impact of ionizing radiation on the population, compared to Uranium 235
Ionizing radiation E (interim)	IRPE	CTUe	Comparative Toxic Unit for ecosystems (CTUe) expressing an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a radionuclide emitted (PAF m <sup>3</sup> year/kg). Fate of radionuclide based on USEtox consensus model (multimedia model)
Photochemical ozone formation	POFP	kg NMVOC <sub>-eq</sub>	Expression of the potential contribution to photochemical ozone formation
Acidification	AP	molc H <sup>+</sup> <sub>-eq</sub>	Accumulated Exceedance (AE) characterizing the change in critical load exceedance of the sensitive area in terrestrial and main freshwater ecosystems, to which acidifying substances deposit
Terrestrial eutrophication	TEP	molc N <sub>-eq</sub>	Accumulated Exceedance (AE) characterizing the change in critical load exceedance of the sensitive area, to which eutrophying substances deposit
Freshwater eutrophication	FEP	CTUe	Expression of the degree to which the emitted nutrients reaches the freshwater end compartment (phosphorus considered as limiting factor in freshwater)
Marine eutrophication	MEP	kg N <sub>-eq</sub>	Expression of the degree to which the emitted nutrients reach the marine end compartment (nitrogen considered as limiting factor in marine water)
Freshwater ecotoxicity	FETP	kg P <sub>-eq</sub>	Comparative Toxic Unit for ecosystems (CTUe) expressing an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a chemical emitted (PAF m <sup>3</sup> year/kg)
Land use	LUP	kg C <sub>-deficit</sub>	Soil Organic Matter (SOM) based on changes in SOM, measured in (kg C/m <sup>2</sup> /a)
Water resource depletion	WDP	m <sup>3</sup> water <sub>-eq</sub>	Freshwater scarcity: scarcity-adjusted amount of water used
Mineral, fossil & renewable resource depletion	MRDP	kg Sb <sub>-eq</sub>	Scarcity of mineral resource with the scarcity calculated as “reserve base”. It refers to identified resources that meet specified minimum physical and chemical criteria related to current mining practice

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