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

Qian Wang*[1], Sture Holmberg[1],

[1] *Division of Fluid and Climate Technology, Department of Civil and Architectural Engineering, Royal Institute of Technology (KTH)*

Brinellvägen 23, 100 44 Stockholm, Sweden
**Corresponding author: qianwang@kth.se*

ABSTRACT

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

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

KEYWORDS

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

Nomenclatures

Acronyms

ACH	Air changes rate, h^{-1}
BBR	Swedish building regulations
CHP	Combined heat and power
COP	Coefficient of performance
DH	District heating
DHW	Domestic hot water
FH	Floor heating (hydraulic)
HP	Heat pump
LTH	Low temperature heating
PE	Primary energy
PEF	Primary energy factor
VR	Ventilation radiator (low-temperature)
T_1	Building type 1, Swedish slab houses (low raise), before 1950
T_2	Building type 2, Swedish slab house (three- to four storeys), 1960–1975

T_3	Building type 3, Swedish slab house (high raise), 1970–1975
Symbols	
$U-value$	Heat transfer coefficient of building elements, W/m^{2}K
t_{op}	Operative temperature, ℃
t_a	Air temperature, ℃
t_r	Mean radiant temperature, ℃
$E_{F,HOB}\ (i)$	Energy for fuel type *i* during heat production provided in heat boilers
$E_{F,CHP}\ (i)$	Energy for fuel type *i* during heat production provided in CHP
$PEF_{HOB(i)}$	Primary energy factor for fuel type *i* during heat production provided in heat boilers
$PEF_{CHP(i)}$	Primary energy factor for fuel type *i* during heat production provided in CHP
$\alpha_{h,i}$	Allocation factor for on-site or off-site production for fuel type *I*
Φ_E	Total energy demand, kWh/m^2
Φ_H	Monthly heating demand, kWh/m^2
Φ_{EL}	Electricity demand, kWh/m^2
Φ_{DHW}	Domestic hot water energy demand, kWh/m^2
$\Phi_{H.T}$	Transmission heat loss, kWh/m^2

1 INTRODUCTION

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

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

2 METHODOLOGY AND SIMULATION MODEL

2.1 Energy performance model

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

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

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

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

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

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

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

2.2 Air-tightness retrofits in existing Swedish residential buildings

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

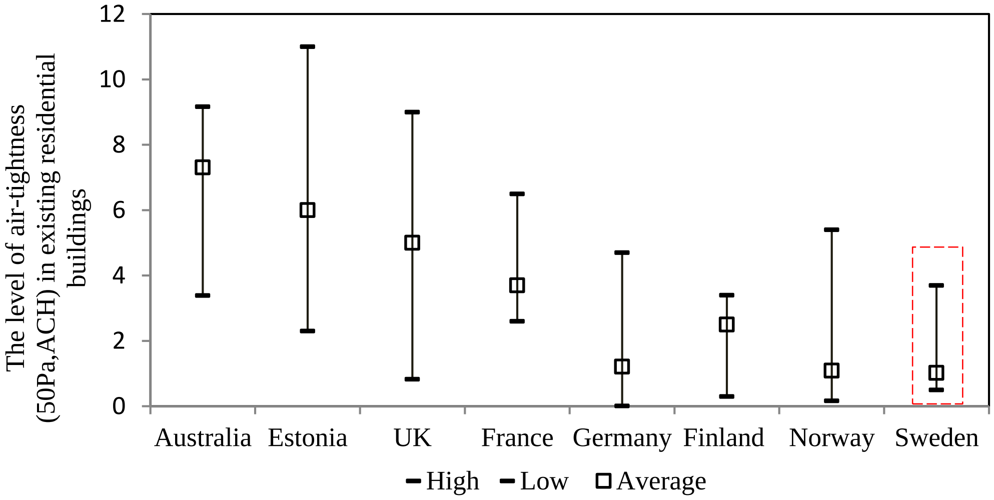

Figure 1 The air-tightness level (50 Pa) of Swedish residential buildings compared with other countries.

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

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

- Insulate the ventilation studs and piping systems.

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

2.3 LTH retrofits and selected archetypes

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

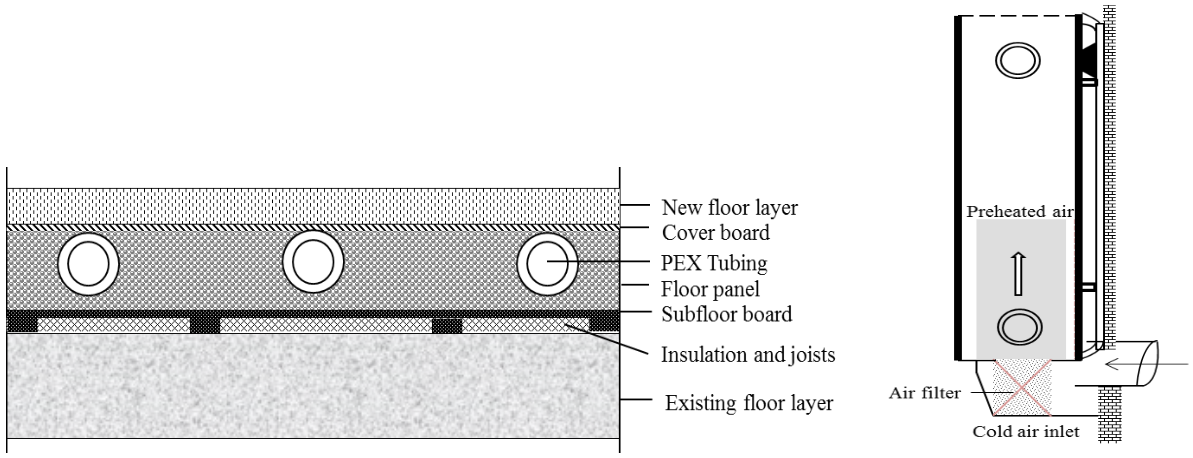

Figure 2 Left, The principle of overlay FH, floor panel units embedded with PEX tubing and, Right, VR, designed as preheated air and low-temperature radiator

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

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

Table 1: LTH retrofitting designs

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

Table 2: Selected archetypes and energy systems for retrofitting analysis

	T1	**T2**	**T3**
Archetypes			
Dwelling types	Single family house	Multi-family house	Apartment block
Age	Before 1950	1960-1975	1970-1975
Foundation	Lightweight concrete	Concrete slab	Polished concrete
External wall	10 cm mineral wool insulation	13 cm mineral wool insulation	15 cm mineral wool insulation
Window	Double glazing, aluminium frame	Double glazing, timber frame with ventilation fan	Double glazing, aluminium frame with one-side ventilation fan
Roof /ceiling	Brick and cutter coke ash insulation	Flat roof covered with cardboard and mineral wool	Concrete foundation with galvanized sheet metals, mineral wool insulation
Ground floor	Linoleum and coke ash	Slab covered with linoleum mats or plastic board	Slab covered with mineral wool or linoleum
Heating	Furnaces /electricity	District heating	District heating
Radiator	Furnaces/electricity	Single-pipe hydraulic radiator	Two-pipe hydraulic radiator
Ventilation	Natural ventilation	Exhaust ventilation	Exhaust ventilation
Energy mix	Gas/oil/partly el.	CHP	CHP
Air-tightness	2 ACH	2 ACH	5 ACH

Table 3: PEF modeling of LTH retrofits

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

3 REUSLTS AND DISCUSSION

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

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

4 CONCLUSIONS

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

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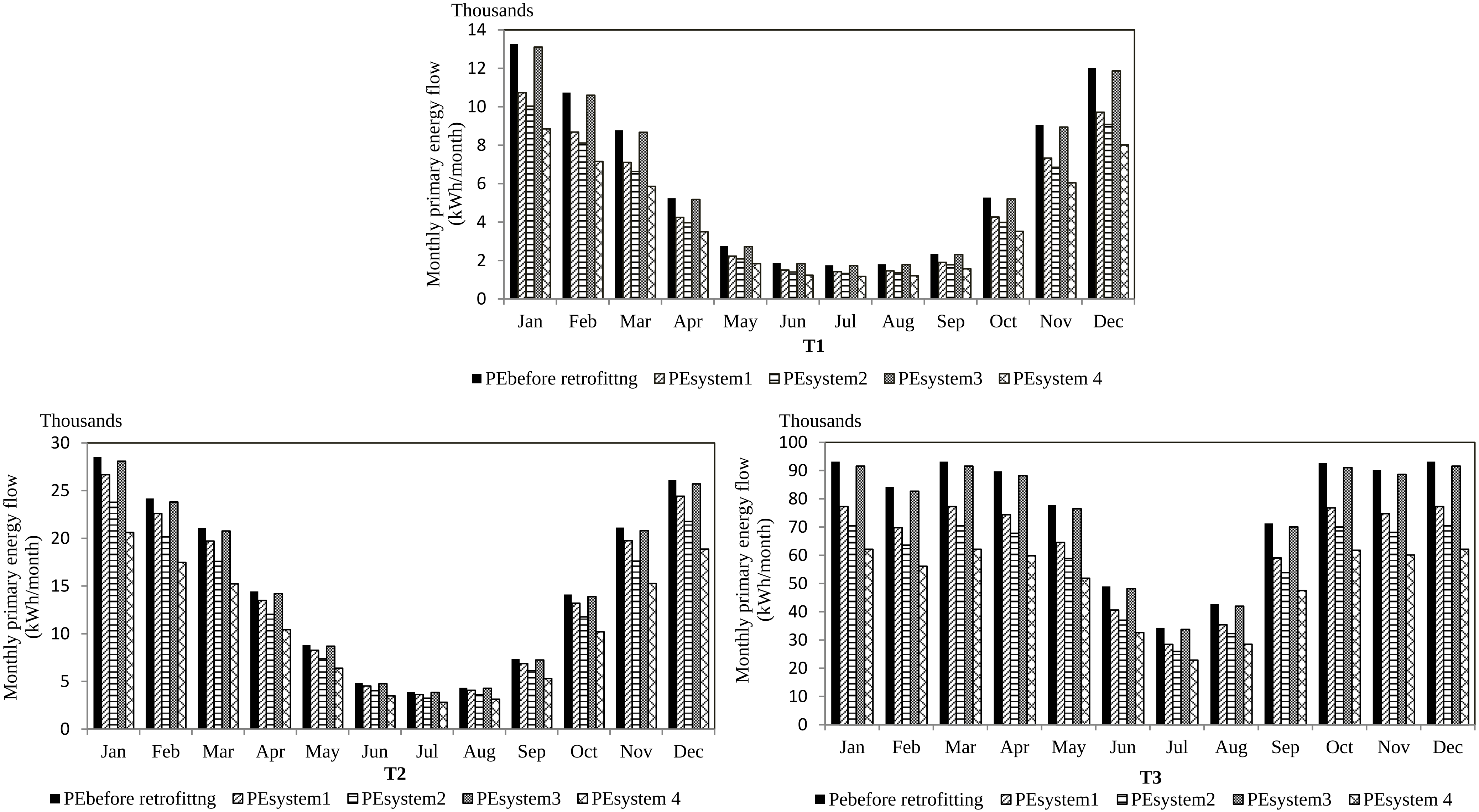

Figure 3 Energy monthly flow of the archetypes installed with LTH systems before and after retrofitting

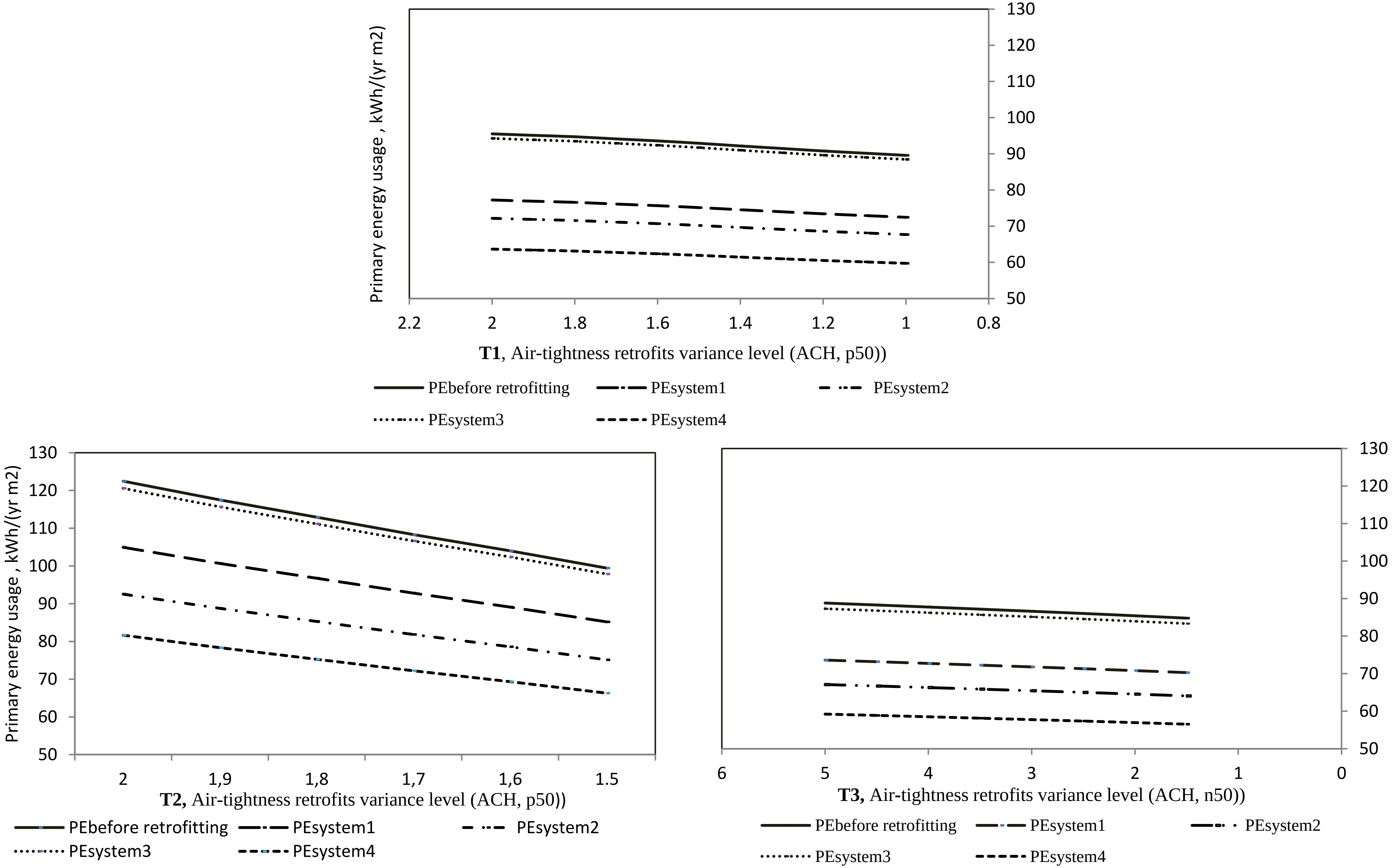

Figure 4 The impact of air-tightness variance levels to the primary energy usage of studied archetypes (kWh/yr m^2)

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