Impact of ventilation heat recovery on primary energy use of apartment buildings built to conventional and passive house standard

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Abstract: In this study we analyze the primary energy implications of ventilation heat recovery (VHR) in residential buildings, considering the entire energy chains. We calculate the operation primary energy use of a case-study apartment building built to conventional and passive house standard, both with and without VHR, and heated with electric resistance heating, bedrock heat pump or district heating. VHR increases the electrical energy used for ventilation and reduces the heat energy used for space heating. The primary energy savings of VHR are greater for the passive building than for the conventional building. Significantly more primary energy is saved when VHR is used in resistance heated buildings than in district heated buildings. For district heated buildings the primary energy savings are small. VHR systems can give substantial final energy reduction, but the primary energy benefit depends strongly on the type of heat supply system, and also on the amount of electricity used for VHR and the airtightness of buildings. This study shows the importance of considering the interactions between heat supply systems, VHR systems, building thermal properties and its airtightness to reduce primary energy use in buildings.

Keywords: *Mechanical ventilation; Heat recovery; Heat supply systems; Electric resistance heating; Heat pumps; District heating; CHP plant; Primary energy.*

1. Introduction

Ventilation has a significant impact on the energy performance of buildings, accounting for 30 to 60% of the energy use in buildings [1, 2]. Energy is used to cover the heat losses due to the ventilation air and to move the ventilation air for mechanical ventilation. The ventilation system also influences the air infiltration through the building envelope.

Building regulations currently require high energy efficiency of buildings, and therefore considerable efforts have been made to improve airtightness and insulation of buildings. In such buildings mechanical ventilation with heat recovery (VHR) is often used to recover heat from exhaust air to reduce ventilation heat losses. Ventilation heat losses can be typically 35-40 kWh/m^2-year in residential buildings, and up to 90% of this can be recovered with VHR depending on airtightness and insulation of buildings [3]. VHR is therefore gaining increasing interest in low energy and retrofitted buildings. In very low energy buildings, such as passive house buildings, VHR units are often equipped with additional air heaters to cover the space heating demand.

Sweden has set targets to reduce the final energy use per heated building area by 20% and 50% by 2020 and 2050, respectively, using 1995 as the reference [4]. Heat recovery from exhaust ventilation air is considered an important means to reach this target, and increased attention is being placed on VHR. There is a technology procurement project to develop and promote VHR systems which can be adapted for existing Swedish apartment buildings [5].

Most studies on the energy impact of VHR have focused on final energy use [e.g. 6-8]. Primary energy use, in contrast to final energy use, largely determines the natural resource use and the environmental impact of end-use energy services. The concept of primary energy is used to denote the total energy needed in order to generate the final energy service, including inputs and losses along the entire supply chains. Fewer studies have analyzed the primary energy implication of VHR in buildings. In this study, we analyze the impact of VHR on the operation primary energy use for residential buildings. We determine situations where mechanical ventilation with heat recovery can reduce primary energy use for building operation.

2. Methodology

This analysis is based on simulation modeling of a case-study apartment building with mechanical ventilation. We model the primary energy use for the original and improved level of energy efficiency of the building, both with and without VHR. Next we compare the primary energy use of the buildings and calculate the net primary energy savings achieved by the VHR, taking into account the changed electricity use due to VHR, as well as the changed heat demand due to VHR and changed air infiltration.

2.1. Building description

Our case-study building is a 4-storey multi-family wood-frame building with 16 apartments and a total heated floor area of 1190 m^2. Persson [9] describes the construction and thermal characteristics of the building in detail. A new building is then modeled with thermal properties of passive house but otherwise identical to the existing building. Table 1 shows the thermal characteristics of the existing, conventional building and the new, passive building. In addition to lower U-values, the passive building is assumed to have much better airtightness than the conventional building.

Table 1. Thermal properties of the building components

Building	*U-value (W/m^2K)*					*Air leakage*
	Ground floor	External walls	Windows	Doors	Roof	l /s m^2 at 50 Pa
Conventional	0.23	0.20	1.90	1.19	0.13	0.8
Passive	0.23	0.10	0.85	0.80	0.08	0.3

For both the conventional and passive buildings, we analyze the use of mechanical ventilation with and without VHR. The designed airflow rate for the building is 0.35 l/s m^2, based on Swedish regulations [10]. For the buildings without VHR, exhaust air is extracted from the kitchens, bathrooms and closets with fan and duct system, and fresh air is supplied through slot openings under windows in the bedrooms and living rooms. For the buildings with VHR, the ventilation system provides the same airflow rate as in the buildings without VHR. For the existing, conventional building the existing ventilation system is complemented with ventilation ducts for incoming air and a heat recovery unit [5].

2.2. Heat supply

We analyze cases where space heat is delivered by electric resistance heating, heat pump or district heating. For the electric resistance heating and heat pump we assume that the electricity is supplied from a stand-alone plant based on biomass steam turbine (BST) technology. We assume that the district heat is supplied from a combined heat and power (CHP) plant based on biomass steam turbines technology (CHP-BST). We consider scenarios where the CHP plant accounts for either *50%* or *90%* of the district heat production, with oil boilers accounting for the remainder. To show the impact of energy supply technology being developed, we also analyze a case where biomass integrated gasification combined cycle (BIGCC) technology is used instead of the BST technology for both CHP and stand-alone power production. Furthermore, Gustavsson et al. [11] explored the structure of district heat production under different environmental taxation regimes. They found that the CHP production should be 80-83% of the total district-heat production when using BST technology and 76-78% when using BIGCC technology. The difference in share of district-heat production between the technologies varies because the BIGCC technology is more efficient and capital intensive than the BST technology. To explore the implications of this for VHR, we calculate the primary energy savings when district heating is based on s uch CHP production systems.

2.3. Final energy calculations

We simulate the annual final energy use of the conventional and the passive buildings, both with and without VHR, using the ENORM software [12]. This software calculates the space heating, ventilation, domestic hot water, and household and facility management electricity use of a building based on the building's physical characteristics, internal and solar heat gains, occupancy pattern, outdoor climate, indoor temperature, heating and ventilation systems, etc. We use climate data for the city of Växjö in southern Sweden, and assume an indoor temperature of 22°C. Table 2 shows principal values used to calculate the electricity use for ventilation. Other values including fan efficiency and operation mode of the ventilation systems are based on the default assumptions of the ENORM software.

Table 2. Major ventilation input values

Description	*Value*
Air change rate (l/s m^2)	0.35
Heat recovery efficiency (%)	85
Ventilated volume (m^3)	2861
Supply air flow rate (m^3/h)	1540

2.4. Primary energy calculations

We use the ENSYST software [13] to quantify the primary energy that is used to provide the final energy use in the different cases. The software calculates primary energy use considering the entire energy chain from natural resource extraction to final energy supply. We credit the electricity cogenerated by the CHP plant to the district heat system, assuming that it replaces electricity produced by a stand-alone plant with similar technology and fuel [14]. We assume the increased electricity use due to VHR is covered by stand-alone plant with similar technology and fuel as the heat supply system used.

3. Results

Table 3 compares the annual final energy use of the conventional and the passive buildings with and without VHR. The annual total final energy use of the passive building with VHR is about 21% lower than for the alternative without VHR. The corresponding value for the conventional building with VHR is 10%. VHR decreases the final energy for space heating, but increases the electricity used to operate the ventilation system. Overall, VHR reduces the final energy for space heating and ventilation by 55 a nd 22% for the passive and the conventional building, respectively, relative to the alternatives without VHR.

Table 3. Annual final operation energy use for the building scenarios

Building	*Final energy use (kWh/m²-year)*				
	Space heating	Ventilation electricity	Tap water heating	Household and facility electricity	Total
Conventional building	70	4	40	52	166
Conventional building with VHR	50	8	40	52	150
Passive building	43	4	40	52	143
Passive building with VHR	13	8	40	52	113

Table 4 shows the annual operation primary energy use for the conventional and the passive buildings when using different end-use heating systems with energy supply based on BST technology. Ventilation accounts for 2-11% of the operation primary energy use. The primary energy for heating for the district heated buildings is low due to the high overall efficiency of district heating systems with CHP plants. The cogenerated electricity replaces electricity that otherwise would have been produced in a stand-alone plant with much lower efficiency.

Table 4. Annual operation primary energy use for the building with different end-use heating systems with energy supply based on BST technology

Description	*Primary energy use (kWh/m²-year)*				
	Space heating	Ventilation electricity	Tap water heating	Household and facility electricity	Total
Resistance heating:					
Conventional building	209	12	119	155	496
Conventional building with VHR	149	24	119	155	448
Passive building	128	12	119	155	415
Passive building with VHR	39	24	119	155	337
Heat pump:					
Conventional building	78	12	45	155	290
Conventional building with VHR	55	24	45	155	280
Passive building	48	12	45	155	260
Passive building with VHR	14	24	45	155	239
District heating, 50% CHP:					
Conventional building	66	12	38	155	271
Conventional building with VHR	47	24	38	155	264
Passive building	41	12	38	155	246
Passive building with VHR	12	24	38	155	229
District heating, 90% CHP:					
Conventional building	42	12	24	155	233
Conventional building with VHR	30	24	24	155	233
Passive building	26	12	24	155	217
Passive building with VHR	8	24	24	155	211

Table 5 compares the percentage primary energy savings of VHR in relation to the primary energy use for space heating and ventilation, and to the total primary energy use for operation, including space heating, ventilation electricity, tap water heating and household and facility management electricity. The VHR primary energy savings ranges from 0-55% of space heating and ventilation primary energy use.

Table 5. Percentage primary energy savings of VHR, in relation to the primary energy used for space heating and ventilation for the different end-use heating systems with BST energy supply technology

Building	*Relative primary energy savings*			
	Resistance heating	Heat pump	District heating, 50% CHP	District heating, 90% CHP
Conventional	22%	12%	9%	0
Passive	55%	37%	32%	16%

The change in annual primary energy use for space heating and ventilation electricity when using VHR with different end-use heating system with BST or BIGCC energy supply are shown in Figure 1. T he net savings are shown in Figure 2 f or both BST and BIGCC technologies. The primary energy savings of VHR is significantly greater when using resistance heating, followed by heat pump and district heating with *50% CHP*. However, much smaller or no primary energy savings is achieved when using district heating with *90% CHP*. The savings of VHR are larger for the passive building than for the conventional building. The BIGCC technology gives similar results as the BST technology, but the net primary energy savings are lower compared to the case of BST.

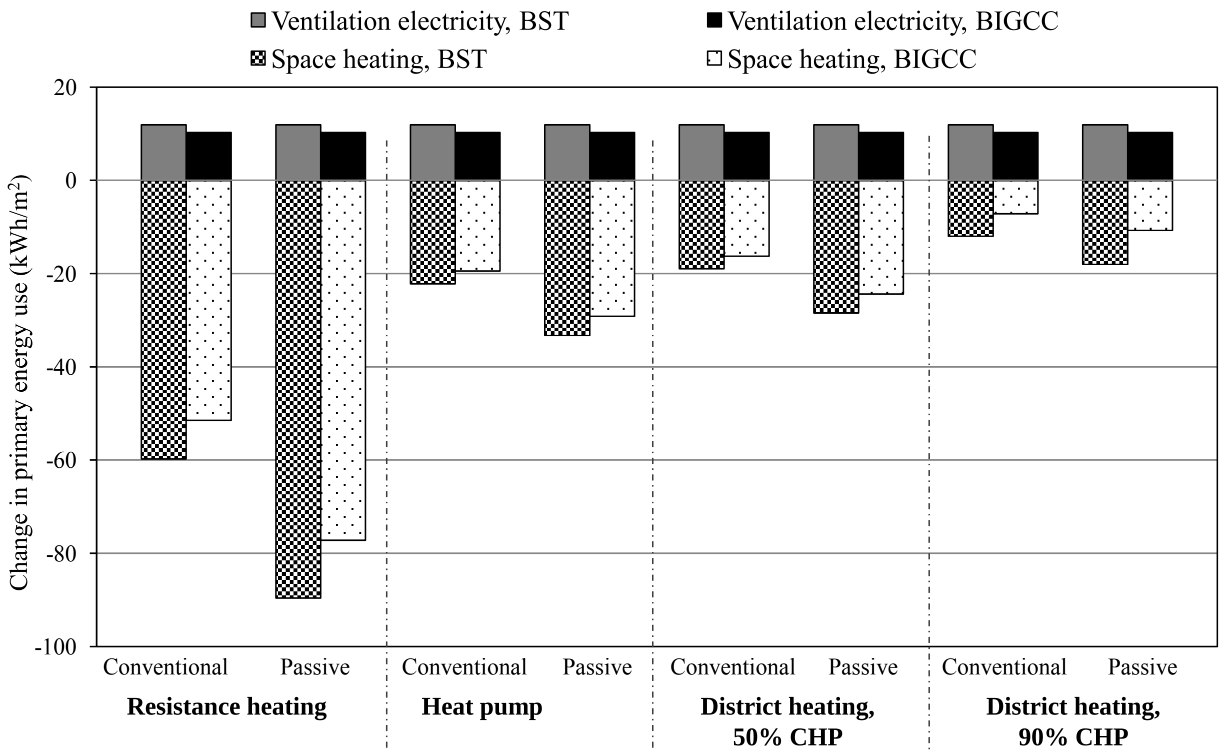

Figure 1. Change in annual primary energy use for space heating and ventilation electricity when using VHR with BST or BIG/CC energy supply

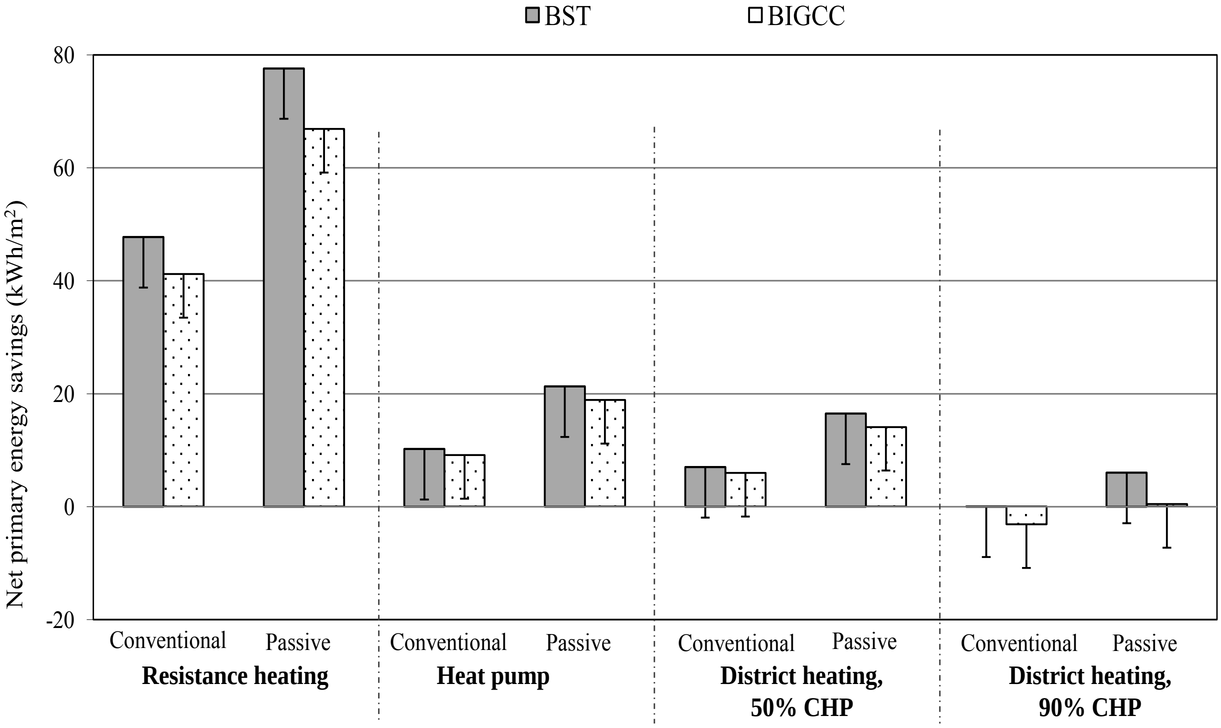

Figure 2. Net annual primary energy savings for VHR when using BST or BIGCC energy supply. The error bars show the savings when electricity use by the VHR is 7 kWh/m^2

In cold climatic regions VHR systems usually encounter frost during severe winters, and additional energy may be needed for defrosting. VHR systems may be fitted with additional preheating device to overcome this problem, increasing the electricity use for VHR [15]. Our base calculations are based on electricity use of 4 kWh/m^2 for the VHR and do not include electricity to defrost the system. Tommerup and Svendsen [3] reported that electricity use in VHR system of 80-90% efficiency is typically 7 kWh/m^2 under Danish conditions, and suggested this might be reduced to 3 kWh/m^2 with more efficient systems. In Figure 2 the error bars show the change in net primary energy savings for VHR, when the electricity use for VHR is 7 kWh/m^2 instead of 4 kWh/m^2. The higher electricity use for operating VHR reduces the net primary energy savings, in particular for the district heated buildings. In fact, a ventilation electricity use of 7 kWh/m^2 increases the net primary energy use for the buildings with district heating based on *90% CHP*. Hence low electricity use for VHR is important. For the conventional building with lower airtightness together with district heating based on a large share of CHP production, VHR may be counterproductive and increase primary energy use.

In our base case calculations, the CHP production accounts for 50 and 90% of the total district heat production [16]. In this section, we show the net primary energy savings for VHR when more optimally designed CHP production systems are used. Figure 3 shows the net primary energy savings for VHR when district heating is based on the lower and upper optimal CHP productions according to Gustavsson et al. [11]. VHR increases net primary energy use for all buildings when the electricity use for VHR is 7 kWh/m^2. The net savings is positive, but very low, for the conventional buildings with VHR systems using 4 kWh/m^2.

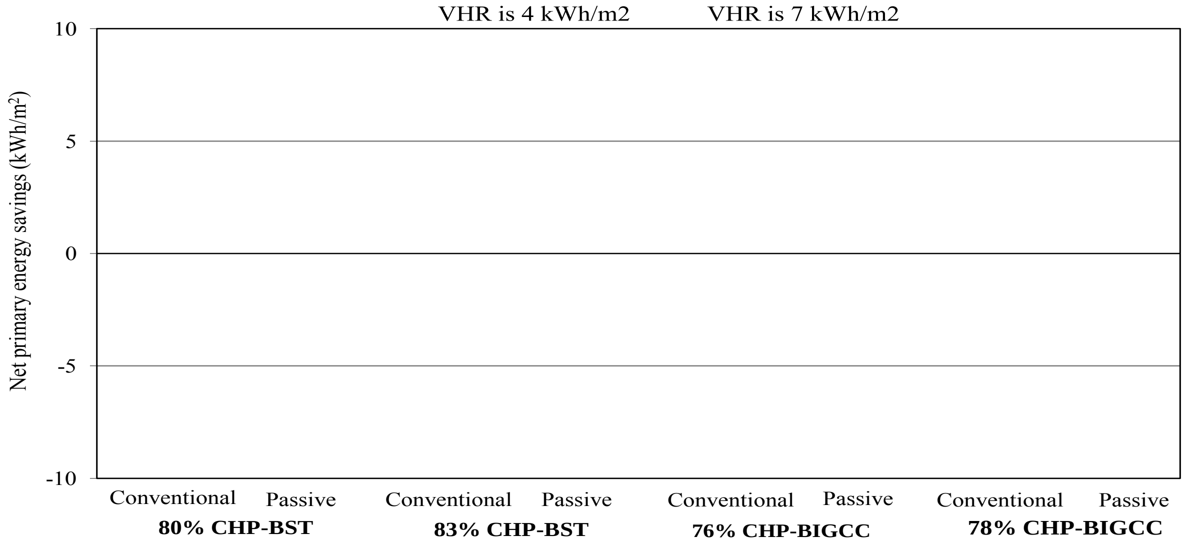

Figure 3. Net annual primary energy savings for VHR when more optimally designed CHP production systems are used

4. Discussion and conclusions

Our results show that primary energy savings of VHR can be very significant, depending on the type of heat supply system, the airtightness and thermal properties of buildings, and the amount of increased electricity used to operate the VHR system. The biggest savings is achieved when VHR is installed in a resistance heated building. However, small primary energy savings is achieved when the VHR is installed in CHP-based district heated buildings. VHR gives much smaller primary energy savings for the district heating with 90% CHP than with 50% CHP, supporting the findings of Dodoo et al. [16] and Gustavsson et al. [11]. For district heating systems mainly based on CHP, the reduced heat demand reduces the potential to cogenerate electricity, and is more significant if BIGCC technology is used instead BST technology.

The primary energy savings of VHR are greater for the passive building than for the conventional building, confirming that VHR systems perform better with improved airtightness [3, 6]. Hence, the air-tightness of buildings should be in the range as for newly constructed passive houses to minimize primary energy use when using VHR systems. We found that the greatest primary energy savings is achieved when VHR is incorporated in resistance heated passive building. The primary energy savings of VHR depend on t he electricity use to operate the VHR system. Therefore the amount of electricity required to operate VHR system should be minimized.

Our results show that VHR may give low or negative primary energy savings in passive house buildings when combined with energy-efficient heat supply systems. For example, the case-study passive building with VHR in some cases uses greater primary energy than the same building without VHR. It is important to build houses with airtightness comparable to that of passive houses but such houses need to be ventilated using strategies that minimize primary energy use.

When deciding on i nstalling VHR, attention should therefore be given to the interaction between the electricity use for VHR, the airtightness of the building and the type of heat supply system. This is particularly important when using district heating with a large share of

CHP production, as suggested by Dodoo et al. [16]. A primary energy analysis is necessary to evaluate the energy benefits of VHR in residential buildings.

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