Primary Energy Implication of Mechanical Ventilation with Heat Recovery in Residential Buildings

Ambrose Dodoo, Leif Gustavsson, and Roger Sathre, Mid Sweden University

ABSTRACT

In this study, we analyze the impact of mechanical ventilation with heat recovery (VHR) on the operation primary energy use in residential buildings. 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 using different heat supply systems. VHR increases the electrical energy used for ventilation and reduces the heat energy used for space heating. Significantly greater primary energy savings are achieved for VHR 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 on the electricity used for VHR and the airtightness of buildings, and strongly on the type of heat supply system. This study shows the importance of considering the interactions between heat supply systems and VHR systems to reduce primary energy use in buildings.

Introduction

Ventilation of a building provides fresh air and removes contaminants generated inside buildings to ensure healthy indoor air quality. Ventilation can be achieved naturally with extract channels or mechanically with electric-driven systems. 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. Orme (2001) studied the energy impact of ventilation and air infiltration in residential buildings in 13 OECD countries including Sweden. He found that the energy losses due to ventilation and air infiltration represent about 48% of the delivered energy for space heating. Tommerup & Svendsen (2006) reported the ventilation heat losses in typical Danish residential buildings to be 35-40 kWh/m^2-year.

Recent building standards 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. In very low energy buildings, such as passive house buildings, VHR are often equipped with additional air heater to cover the space heating demand.

Most studies on the energy impact of VHR have focused on final energy use (e.g. Hekmat, Feustel & Modera 1986; Lowe & Johnston 1997; TIP-Vent 2001; Sherman & Walker 2007). 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.

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. The outer walls of the building consist of three layers, including plaster-compatible mineral wool panels, timber studs with mineral wool between the studs, and a wiring and plumbing installation layer consisting of timber studs and mineral wool. Two-thirds of the outer façade is plastered with stucco, with the remainder covered with wood paneling. The ground floor consists of oak boarding laid on a concrete slab, expanded polystyrene and crushed stones, and the remaining floors are made of light timber joists. Persson (1998) 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 the Swedish regulation of 1994. 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 (Wahlström, Blomsterberg & Olsson 2009).

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.

Methodology

We simulate the annual final energy use of the conventional and the passive buildings, both with and without VHR, using the ENORM software (EQUA 2004). 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. We design the ventilation systems to give the airflow rates and specific fan power required by the current Swedish regulation (Boverket 2009). 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 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

We use the ENSYST software (Karlsson 2003) 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 (Gustavsson & Karlsson 2006). 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.

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 and 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/m^2-year)				
	Space heating	Ventilation electricity	Tap water heating	Household & 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/m^2-year)				
	Space heating	Ventilation electricity	Tap water heating	Household & 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 for space heating and ventilation, and to the total primary energy for operation, including space heating, ventilation electricity, tap water heating and household and facility management electricity. The VHR primary energy savings for space heating and ventilation, and the total operation energy ranges from 0-55% and 0-19%, respectively.

Table 5. Comparison of Percentage Primary Energy Savings of VHR in Relation to the Primary Energy Used for Space Heating and Ventilation, and Total Operation Energy Use

Building	Resistance heating		Heat pump		District heating, 50% CHP		District heating, 90% CHP	
	Space heating & ventilation	Total operation energy	Space heating & ventilation	Total operation energy	Space heating & ventilation	Total operation energy	Space heating & ventilation	Total operation energy
Conventional	22%	10%	12%	3%	9%	3%	0	0
Passive	55%	19%	37%	8%	32%	7%	16%	3%

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. The net savings are shown in Figure 2 for 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 are achieved when using district heating with *90% CHP*. The savings of VHR are larger for the passive building than for the conventional building.

Figure 1. Change in Annual Primary Energy Use for Space Heating and Ventilation Electricity when Using VHR with BST or BIG/CC Energy Supply

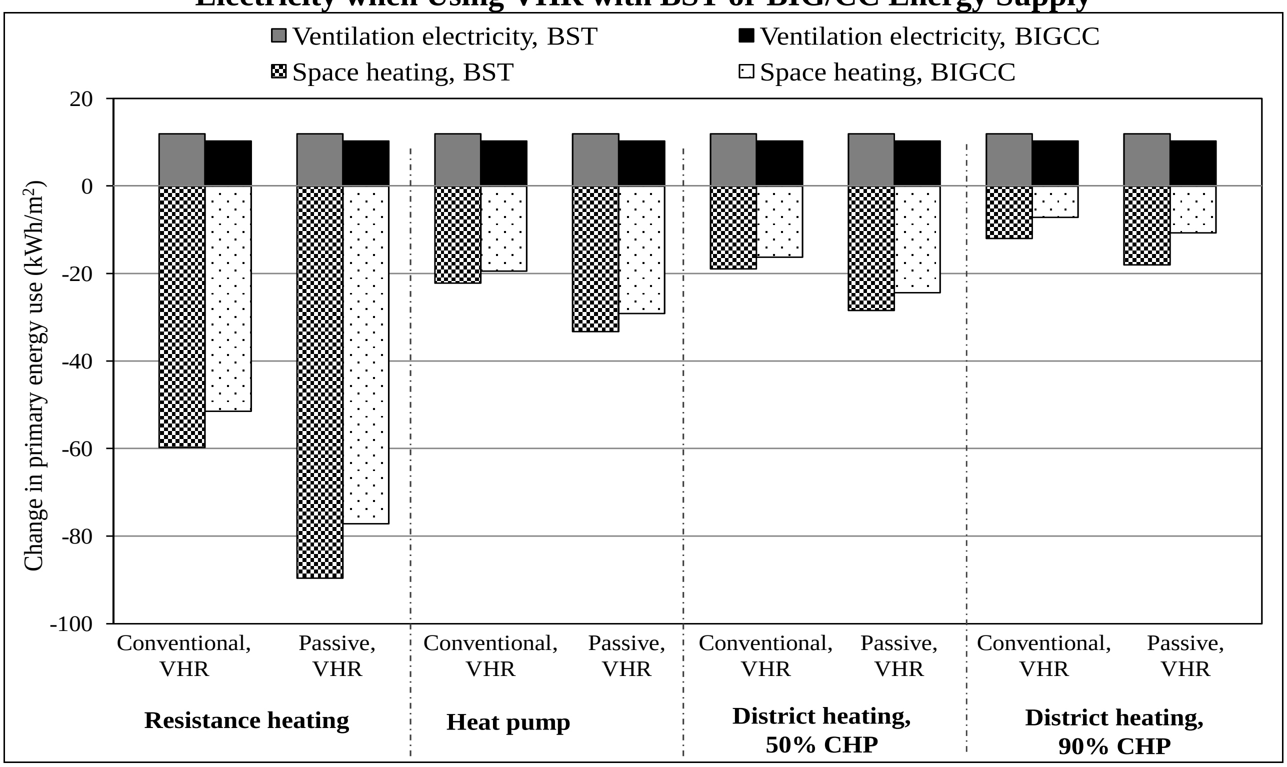
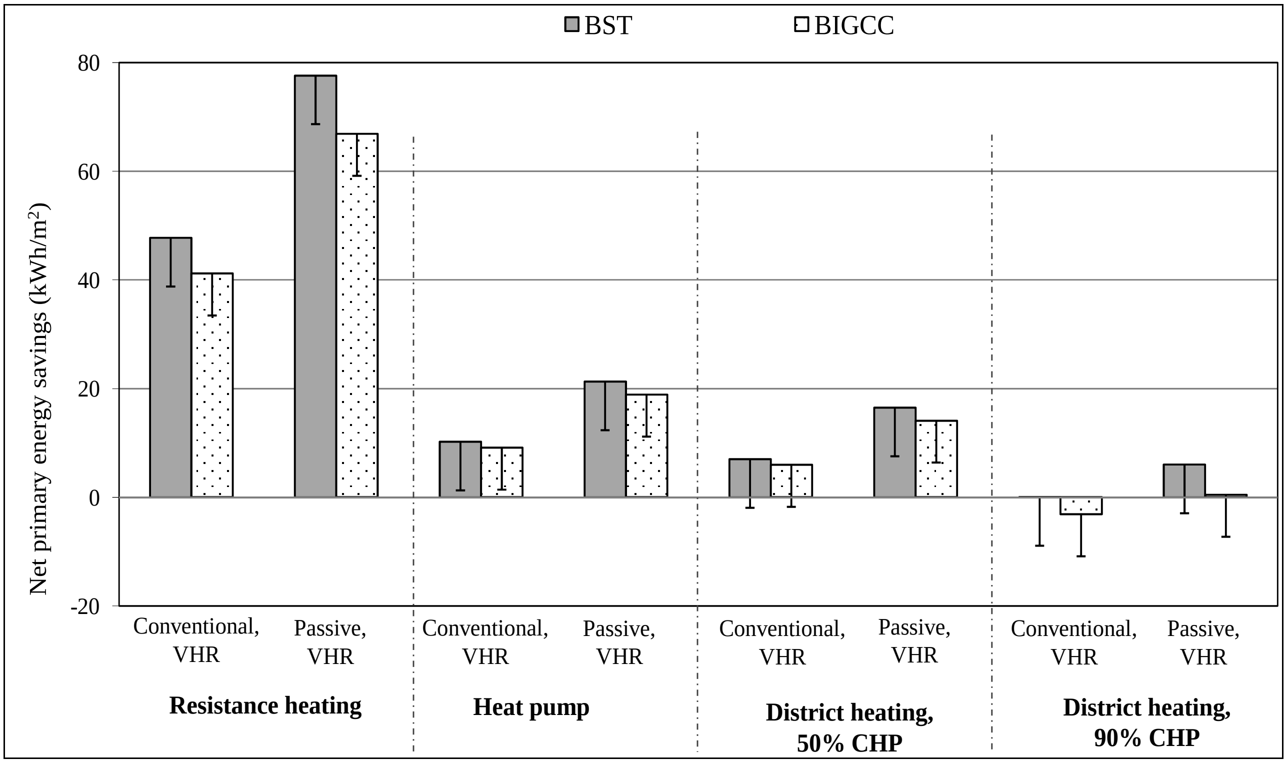


Figure 2. Net Annual Primary Energy Savings for VHR when using BST or BIGCC Energy Supply; the Error Bars Show the Savings when Electricity Use by the VHR is 7 kWh/m²



The BIGCC technology gives similar results as the BST technology, but the net primary energy savings are lower compared to the case of BST.

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 (Kragh et al. 2007). 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 & Svendsen (2006) 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. 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 a 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 even be counterproductive.

Discussion

In this study we explore the primary energy implications of VHR in residential buildings. Our results show that primary energy savings of VHR can be very significant, depending on the type of heat supply system and the airtightness of buildings, besides the increase use of electricity to operate the VHR system. The biggest savings are achieved when VHR is installed in a resistance heated building. However, small primary energy savings are 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, Gustavsson & Sathre (2010) and Gustavsson et al. (2010). For district heating systems mainly based on CHP, the reduced heat demand reduces the potential to cogenerate electricity and is more if BIGCC technology is used instead BST technology. Gustavsson et al. (2010) analyzed the effects on district heating systems of reduced heat demand from various end-use energy efficiency measures, including VHR, and discussed this issue further.

The primary energy savings of VHR were greater for the more airtight passive building than for the conventional building, confirming that VHR systems perform better in airtight buildings (Tommerup & Svendsen 2006; Hekmat, Feustel & Modera 1986). We found that the greatest primary energy savings are achieved when VHR is incorporated in resistance heated passive building.

The primary energy savings of VHR depend on the electricity use to operate the VHR system. Therefore the amount of electricity required to operate VHR system should be minimized.

VHR is often used in passive houses (Feist et al. 2005). Our results show that VHR can give low primary energy savings also in such 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 installing VHR, attention should therefore be given to the interaction between the electricity use for VHR, airtightness of the building and the type of heat supply system, in particular district heating with a large share of CHP production, as suggested by Dodoo, Gustavsson & Sathre (2010) and Gustavsson & Joelsson (2010).

Conclusions

This study shows that VHR systems can give substantial final energy reduction, but the primary energy benefit depends on the electricity used for VHR and the airtightness of buildings, and strongly on the type of heat supply system. A primary energy analysis is necessary to evaluate the energy benefits of VHR in residential buildings.

References

Boverkets. 2009. "**Byggregler: Boverkets Författningssamling**". (The Swedish building regulations): Karlskrona: The National Board of Housing, Building and planning.

Dodoo, A., L. Gustavsson, and R. Sathre. 2010. "**Life Cycle Primary Energy Implication of Retrofitting a Swedish Apartment Building to Passive House Standard**". *Resources, Conservation and Recycling* (In Press).

EQUA, 2004. "**ENORM, Version 1000**". Stockholm: EQUA Simulation AB.

Feist, W., J. Schnieders, V. Dorer, and A. Haas. 2005. "**Re-Inventing Air Heating: Convenient and Comfortable within the Frame of the Passive House Concept**". *Energy and Building* 37 (11): 1186-1203.

Gustavsson, L. and A. Joelsson. 2010. "**Life Cycle Primary Energy Analysis of Residential Buildings**". *Energy and Buildings* 42 (2): 210-220.

Gustavsson, L. and Å. Karlsson. 2006. "**CO_2 Mitigation: On Methods and Parameters for Comparison of Fossil-Fuel and Biofuel Systems**". *Mitigation and Adaptation Strategies for Global Change* 11(5-6): 935-959.

Gustavsson, L., A. Dodoo, N. L. Truong, and I. Danielski. 2010. "**Primary Energy Implications of End-Use Energy Efficiency Measures in District Heated Buildings**". *Journal article manuscript*.

Hekmat, D., H. E. Feustel, and M. P. Modera. 1986. "**Impacts Of Ventilation Strategies On Energy Consumption And Indoor Air Quality In Single-Family Residences**". *Energy and Buildings* 9 (3): 239-251.

Karlsson, Å. 2003. "**ENSYST, Version 1.2**". Lund: Lund University.

Kragh, J., J. Rose, T.R. Nielsen and S. Svendsen. 2007. "**New Counter Flow Heat Exchanger Designed For Ventilation Systems In Cold Climates**". *Energy and Buildings* 39 (11): 1151-1158.

Orme, M. 2001. "**Estimates Of The Energy Impact Of Ventilation And Associated Financial Expenditures**". *Energy and Buildings* 33 (3): 199-205.

Lowe, R. and D. Johnston. 1997. **Mechanical Ventilation with Heat Recovery in Local Authority, Low-Rise Housing: Final Report on the Derwentside Field Trial**. Leeds: Leeds Metropolitan University.

Persson, S. 1998. **Wälludden Trähus i Fem Våningar: Erfarenheter Och Lärdomar** *(Wälludden wooden building with five stories: Experiences and knowledge acquired)*. Report TVBK-3032. Lund: Lund Institute of Technology.

Sherman, M. H. and I. S. Walker. 2007**. Energy Impact of Residential Ventilation Norms in the United States**. LBNL Paper LBNL-62341. Berkeley, California: Lawrence Berkeley National Laboratory.

TIP-Vent. 2001. **Towards Improved Performances of Mechanical Ventilation Systems**. http://www.inive.org/Documents/Tip-Vent_Source_Book.pdf on March 1, 2010.

Tommerup, H. and S. Svendsen. 2006. "**Energy Savings In Danish Residential Building Stock**". *Energy and Buildings* 38 (6): 618-626.

Wahlström, Å., Å. Blomsterberg, and D. Olsson. 2009. **Värmeåtervinningssystem för Befintliga Flerbostadshus. Förstudie inför Teknikupphandling** (*Ventilation heat recovery system for the existing multi-residential buildings. Feasibility study for technology procurement*). Gothenburg: BeBo.