Energy demand with natural ventilation in unheated bedrooms, combined with balanced ventilation.

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Abstract. In Norway, many detached houses are renovated without mechanical ventilation being installed. Many occupants prefer or accept low temperatures in bedrooms and ventilate with regular window openings all year round. In this context, a hybrid ventilation strategy combining ordinary balanced ventilation in warm zones, and natural ventilation in cooler bedrooms, could be appropriate Such a hybrid ventilation strategy might be most relevant for renovation projects where introducing ventilation ducts can be complicated and costly. The aim of this work is to investigate the energy performance using this hybrid strategy when implemented in a detached Norwegian wooden house. Detailed dynamic simulations of a case house are performed using the simulation software IDA-ICE for 2 insulation levels, and 6 different occupant behaviours. In order to reduce the uncertainty of airflow rates through open windows, simulations are done in 3 different simulation modes. Three natural ventilation strategies for bedrooms are compared to the reference with standard balanced mechanical ventilation with heat recovery. Results show that the energy performance of the investigated hybrid ventilation strategies is strongly influenced by occupant behaviour. Given an energy-conscious occupant behaviour (e.g., regarding thermal zoning), it seems possible to achieve a low energy use with natural ventilation in bedrooms. Low temperatures are frequently applied in Norwegian bedrooms so the proposed hybrid ventilation strategies could be applied to a significant share of the renovation market. However, temperature in bedrooms is strongly related to habits and culture. Therefore, the potential of hybrid ventilation can be different for other countries. With the proposed hybrid ventilation strategy, it is possible to create a night setback in the unoccupied zones with mechanical ventilation. This is a technically cheap and simple way to decrease energy use and could be investigated in further research.

Keywords. Hybrid ventilation, natural ventilation, renovation, heating demand.
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1. Introduction

More than 30% of Norwegian residential buildings are detached houses built before 1990. This building stock is reaching a stage where major renovations are needed. A recent study (1) found that 60% of the Norwegian detached households made no changes to the ventilation system when performing a renovation, while only 9% installed balanced mechanical ventilation. Renovation usually includes a substantial improvement in air tightness of the building envelope. This reduces the air change due to infiltrations, demanding systematic ventilation measures to provide sufficient indoor air quality (IAQ). The challenge is to develop ventilation concepts that provide good indoor environment and energy performance, while remaining simple and affordable enough to actually be implemented.

Standard one-zone ventilation strategies with balanced cascade ventilation tend to homogenize temperatures in highly insulated buildings. In other words, balanced ventilation reduces the possibility for temperature zoning. In Norway, many users would like colder bedrooms, and a significant part of the occupants open bedroom windows during several hours every night during winter (2-5). Dynamic simulations have shown that this window opening behaviour combined with ordinary balanced cascade ventilation strongly increases the space-heating needs. Simulations also show that control only is unable to create temperature zoning in an energy-efficient way (6, 7). This is an important research gap as it shows that existing systems still do not fully meet the occupants' satisfaction.

A large share of existing detached houses in Norway have moderate thermal insulation and use natural ventilation. Many occupants ventilate the bedrooms by opening the window when going to bed, and closing it in the morning (8-10). Many people use the bedroom only for sleeping, and keep the bedroom doors closed both day and night. Many do not use local heating in the bedrooms, or rarely. This user pattern is most common for the main bedroom (9). Partition walls in wooden buildings are usually insulated using 75 to 100 mm for acoustic reasons. This limits the heat transfer and makes bedrooms distinct thermal zones. The motivation for accepting low temperatures in bedrooms seem to be habit, reducing energy use as well as good IAQ (10). Keeping thermal comfort with low indoor temperatures is made possible by using thick duvets in beds.

In this context, a ventilation strategy combining ordinary balanced ventilation in warm zones, and natural ventilation in bedrooms, could be appropriate. A key aspect of this strategy is to utilise extensive thermal zoning, meaning lower time-averaged temperatures during the heating season in the natural ventilated rooms. Such a hybrid ventilation strategy might especially be relevant for renovation projects where introducing ventilation ducts can be complex and costly.

The aim of this work is to investigate the energy performance using this new hybrid ventilation strategy, when implemented in a typical detached Norwegian wooden house. A prerequisite for the hybrid solution to be acceptable is that the outdoor air quality (e.g., pollution) and sound levels are low at the building location. Research questions are:

- What is the energy demand for the proposed hybrid strategy compared to ordinary balanced mechanical ventilation with heat recovery?
- How do different occupant behaviour strategies affect the heating demand?
- How does the insulation level of the building envelope affect the energy performance of the hybrid strategy, relative to balanced ventilation?

As far as the authors know, the only work addressing the same questions was performed by Heide in 2013 (11). Similar simulations were done using a more generic building model and a less detailed building simulation tool SIMIEN. Results and general conclusions are similar to this study.

Temperature zoning with different rooms at several intermediate temperatures compared to the ambient are also called temperature cascade. This principle is analysed for a building with natural ventilation, by Suerich-Gulick et al (12) (ref). Results show that the use of temperature cascade can reduce energy demand by more than 50% in moderately hot or cold exterior conditions.

Some studies have analysed heating demand with natural ventilations, but then applied in all rooms. Simonson investigated energy use and heating demand in a detached low-energy house with natural ventilation and no thermal zoning in Finland (13). Calculations based on measurements showed energy demand 10 kWh/m^{2}a (10%) higher than with balanced mechanical ventilation.

An important prerequisite for the proposed hybrid ventilation strategy is sufficient air exchange rate (ACH) to ensure acceptable indoor air quality, and window opening behaviour is crucial for this. Studies from several countries find window opening more common in bedrooms than other rooms, and that habit is an important factor (14-16). Bekø et al. measured ACH in Danish detached houses with natural ventilation. They found higher ACH in summer than winter, and higher ACH when rooms were occupied, showing strong influence from the window opening behaviour (17).

One of the bedrooms monitored in (9) (room H2B2, Fig. 8) had natural ventilation, while the rest of the house had balanced ventilation with heat recovery. The measurements showed acceptable CO2 concentration and regular window opening at night, proving that the hybrid ventilation concept is worth to be investigated.

2. Method

2.1 Building model

Fig. 1 - Case house "Nanne" from Mesterhus (18).

A building test case has been defined based on the work of Selvnes and Georges et al. (7, 19). It is a typical two-storey detached house with three bedrooms located on the second floor, and a total floor area of 173.5 m^2, see Fig. 1. The building is located in Oslo. This building is representative for a great number of well-insulated wooden detached houses, not only in Norway. Thermal dynamic simulation of the case house is performed using the building performance simulation (BPS) software IDA ICE. The building as a lightweight construction in wood with a thermal inertia of 14 MJ/K. Internal gains are defined according to SN/TS 3031 (20) and space-heating is simulated using ideal heaters, as the main focus of our study is on the space-heating needs (not the energy use). The main performance indicator is the net energy demand, including appliances. This indicator enables to include the energy use for ventilation fans in the assessment.

Tab. 1 – Building thermal properties for the two building performance levels.

Insulation level	Uext.wall [W/m²K]	Uext.floor [W/m²K]	Uroof [W/m²K]	Uwindows/door [W/m²K]	n50 [h^{-1}]	Thermal bridge [W/m²K]
PASSIV (NS3700)	0.14	0.13	0.12	0.72	0.6	0.03
TEK07	0.18	0.15	0.13	1.6	4.0	0.05

Two performance levels of the building envelope is investigated: one in accordance with the Norwegian Passive House Standard (21), and one in accordance with the Norwegian building regulations of 2007 (TEK07) (22). Details are shown in Table 1. The building design is based on two occupants in the main bedroom and one occupant in the other bedrooms during the night.

The rated heat recovery efficiency used in the simulations is 70 %, as several field studies show a lower heat recovery efficiency than nominal rated values (23-26). This difference can be caused by several factors: leakages in the ducting system or the heat exchanger, imbalance of airflows, sensible heat not recovered, clogged filters, etc.

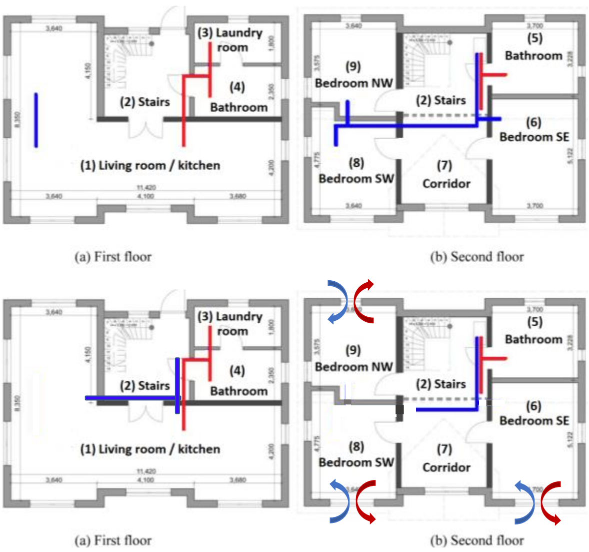

Fig. 2 – Standard balanced cascade ventilation (top), hybrid ventilation with natural ventilation in bedrooms only (lower figure). Supply air duct in blue, extract ducts in red.

2.2 Ventilation strategies

Four ventilation strategies are defined:

1. Balanced cascade ventilation covering all rooms (BAL) see Fig. 2 and 3,
2. Natural ventilation in main bedroom and balanced ventilation covering all the other rooms (MA), see Fig. 3.
3. Natural ventilation in all bedrooms, and balanced ventilation covering the rest (ALL), see Fig. 2 and 3.
4. Natural ventilation in all bedrooms, and balanced ventilation with night set-back for the other rooms (VAV), Fig. 3.

Strategy 1 (BAL) is the common in new detached houses, and serves as a reference. Measurements and surveys (10) show that main bedrooms are much less used (and heated) in daytime than the rooms of children and teenagers. Natural ventilation is less appropriate in bedrooms with occupancy during daytime. IAQ tends to be lower, as people tends to open the window when going to bed, but not before. Cold draft from the window ventilation is more perceptible when occupants are not under a warm duvet. Therefore, natural ventilation only applied in the main bedroom (MA), is explored in addition to strategy 2 with natural ventilation in all bedrooms (ALL).

The other rooms that are not bedrooms, are assumed to have low occupancy during night-time. Consequently, when natural ventilation is used in all bedrooms, the other rooms served by the balanced ventilation system have low occupancy at night. This should allow the introduction of a night set-back with lower airflow rates in these rooms, for example, by reducing the speed of the fans. This is investigated as strategy 4 (VAV). This opportunity to implement night setback is not present in the reference strategy (BAL), as the one-zone cascade ventilation couples all rooms, both the occupied bedrooms and the unoccupied rooms. The system does not allow for a change of the ventilation airflow rate by room, in a technically simple way.

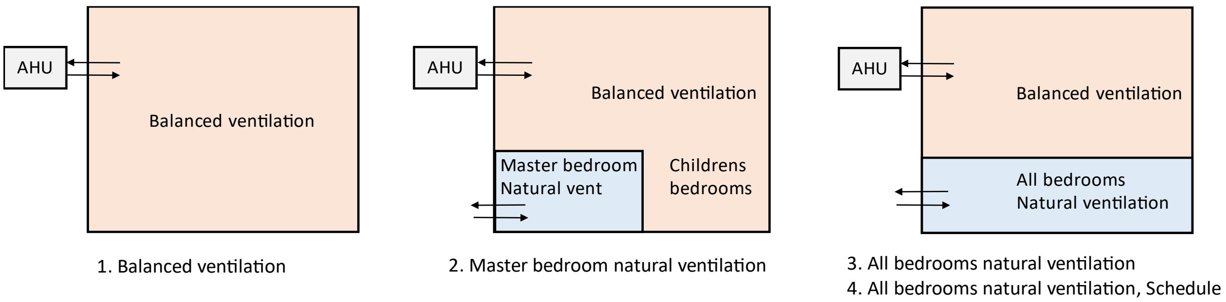

Fig. 3 - The BAL, MAL and ALL ventilation strategies: scenario VAV is equivalent to ALL but with night setback.

2.3 Modelling of natural ventilation

The simplifications for the modelling of airflow rates in BPS should be taken into account. This strongly affects airflow rates through windows and other openings, like infiltrations. Zhai et al. reviewed computational simulation models for natural ventilation (ref). They found that the current airflow network models typically used in BPS tools (like IDA-ICE) can be used to model natural ventilation but it shows low accuracy for single-sided wind-driven ventilation (27). Uncertainty on the computed airflow rates through open windows is to be expected. One way to reduce this uncertainty is to compare different simulation scenarios based on different modelling strategies. Three simulation modes were defined for this purpose:

A. Fixed ventilation airflow rates. ("AHU").
B. Automatic CO_2-controlled window opening (AutW).
C. Fixed window opening size during night-time (FixW).

In simulation mode A, air change rates are fixed and modelled using a decentralized mechanical ventilation (i.e., an additional air handling unit in IDA ICE) with the heat recovery efficiency set to zero. In reality, the airflow will be affected by the wind, the time-varying stack effect as well as the user behaviour. Therefore, real airflows will not be equal to the idealized case A with controlled airflow rates. To evaluate this impact on results, a 50% increase of the overall airflow rate is also briefly analysed (see section 2.6).

In simulation mode B, automatic window opening with a PI-control tracking the CO_2 concentration in the bedrooms was simulated. The setpoint maximum CO_2 concentration in bedrooms is 920 ppm. This is also an idealized model as windows are almost always controlled manually.

In simulation mode C, a constant window opening area was set during night-time. The opening area has been calibrated to reach acceptable maximum CO_2 concentration in the bedrooms. It resulted in a window openings of 90 cm x 9.5 cm for the main bedroom with a maximum CO_2 concentration of 1100 ppm, and an opening of 90 cm x 5 cm in single bedrooms with a maximum CO_2 concentration of 900 ppm. To ensure a minimum ventilation outside occupancy periods (i.e., windows and doors closed), there are also ventilation valves with a constant opening size of 0.005 m^2 in each bedroom, in mode C. The gaps in lower part of the doors of bedrooms with natural ventilation are reduced from 0.01 m^2 to 0.0001 m^2. Windows are generally open during nigh-time and closed during the day. A time schedule is thus defined for window openings where the night was defined from 23:00 to 07:00.

2.4 Mechanical ventilation airflow rates

Ventilation airflow rates using mechanical ventilation are in compliance with the Norwegian Standard SN/TS 3031 (20), adjusted to follow the requirements in the Norwegian building regulations. These airflows are also used in the natural ventilation using simulation mode A. In bedrooms, it corresponds to ventilation airflow rates of 26 m^3/h per bed. During daytime, these bedrooms with natural ventilation were simulated with the general 1.2 m^3/h pr. m^2 floor area, as they were not assumed to be continuously occupied. In ventilation scenario 4 (VAV), the mechanical ventilation is simulated with a reduction of the ventilation airflow rate during the night of 58% compared to the nominal daytime rate (i.e., 1.2 m^3/m^2*h in daytime, 0.7 m^3/m^2*h during night-time).

Tab. 2 – Definition of the occupant behaviour scenarios and resulting control strategies.

	Warm	Basic	Econ+	Economic	Frugal	Frugal Corr
Other rooms heater setpoint temp.	24	21	21	21	21	21
Bedroom heater setpoint temperature	21	21	10	10	5	No heater
Supply air setpoint temperature	18	16	16	16	16	16
Heat recovery setpoint temperature	20	18	18	18	18	18
Heater in corridor	Yes	Yes	Yes	Yes	Yes	No
Doors open every morning and evening	Yes	Yes	Yes	No	No	No

2.5 Occupant behaviour and control

It is known that the occupant behaviour has a strong influence on the indoor environment and energy use. Occupants define the set-point temperatures (e.g., for the local heaters) and the window and door openings in bedrooms. Consequently, six occupant behaviours are defined in Table 2. Bedroom doors are generally closed, but in the Warm, Basic and Econ+ scenarios they are open half an hour every morning and night. A constant set-point temperature during day and night is applied to the bedroom heater. The set-point supply air temperature defined in Table 2 is only for the mechanical ventilation.

2.6 Sensitivity analysis

In addition, a sensitivity analysis is done to evaluate the influence of the parameter uncertainty. Firstly, the rated efficiency of the ventilation heat recovery is increased from 70% to 80%. Secondly, the influence of bedrooms doors that are always open during daytime is evaluated. Finally, a 50% increase of the airflow rates for the natural ventilation in simulation mode A is analysed.

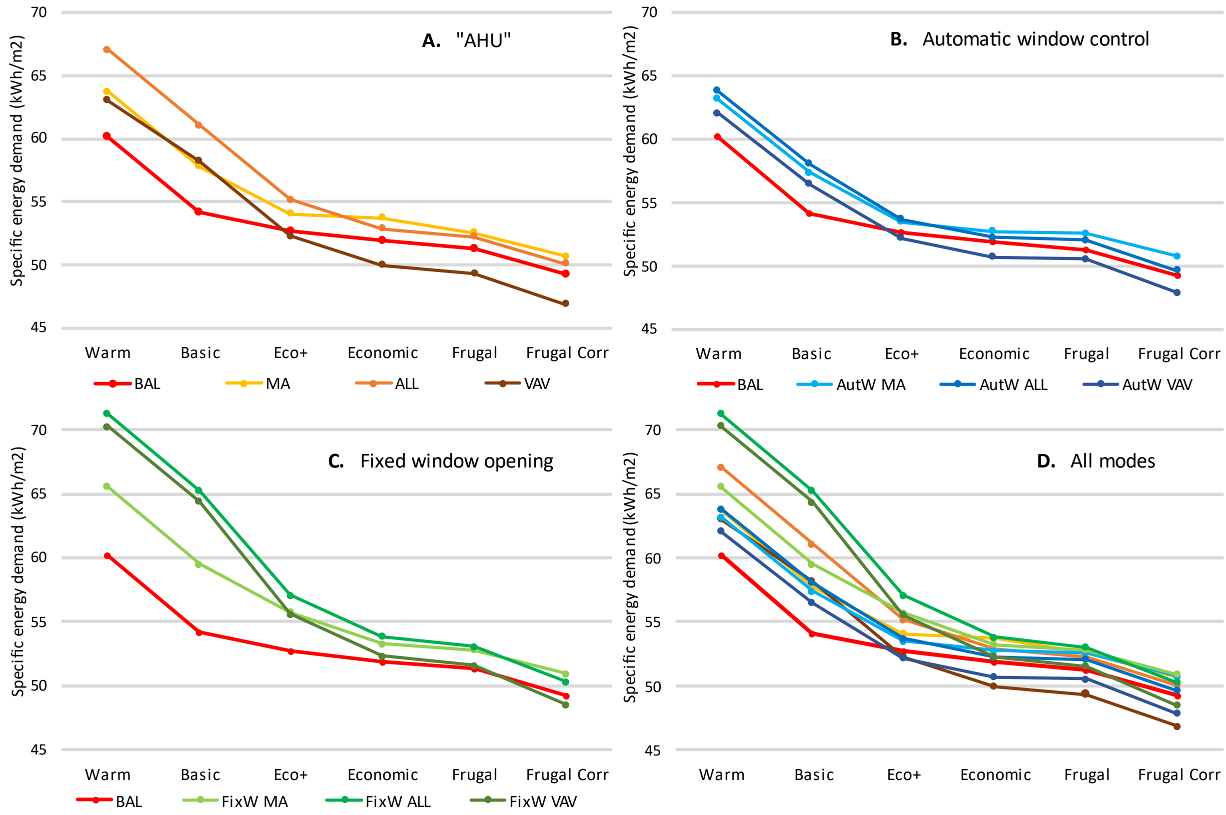

Fig. 4 - Specific energy demand for the Passive building: the figures are grouped by different simulation modes, but all modes are merged in the figure in the bottom right.

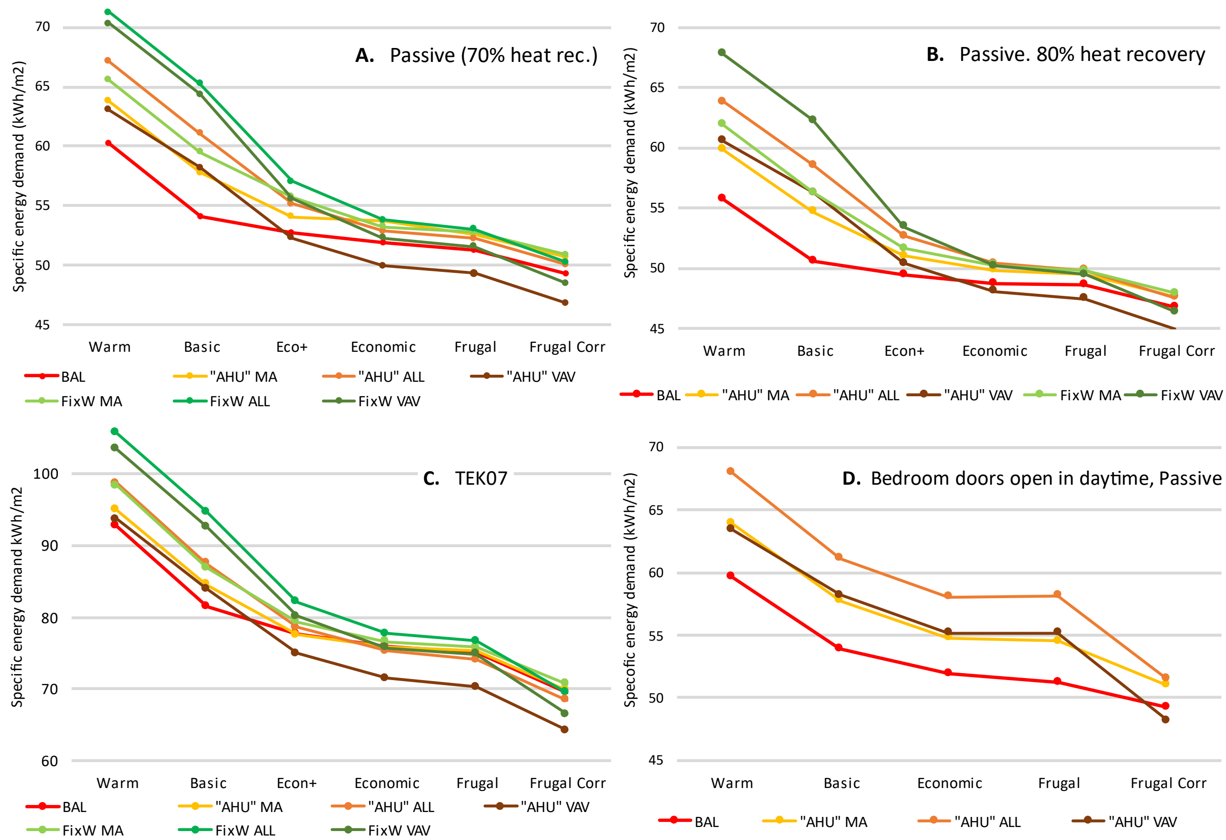

Fig. 5 – Specific energy demand for the total building for several occupant behaviours and simulation modes: different building envelope levels on the left figures, 70% and 80% heat recovery efficiency compared on the top figures while the effect of keeping the bedroom doors open all day is shown by comparing (d) and (a).

3. Results and discussion

Results are presented in Fig. 4 and 5.

The general trend shows a progressive decline in space-heating needs when moving towards occupant behaviours with lower indoor temperatures (meaning more economic behaviour). As expected, strategies using natural ventilation show large space-heating needs when high temperatures are preferred in bedrooms. For the occupant behaviour strategies Warm and Basic, ordinary balanced ventilation clearly shows lower space-heating needs, while the differences with the occupant behaviour Economic and Frugal are much smaller. In other words, the energy performance of the mechanical ventilation (BAL) is more robust regarding the user behaviour.

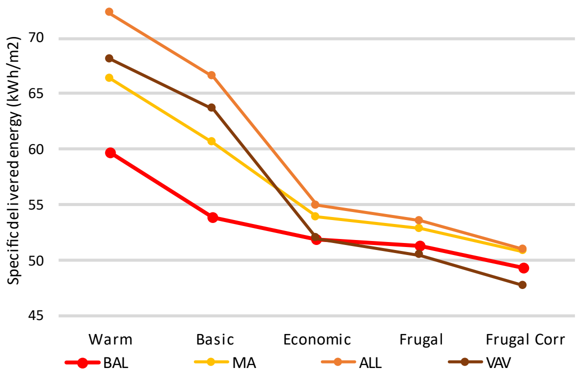

Fig. 6 – Specific energy demand with 50% increased natural ventilation air flow. "AHU" simulating mode, in Passive building.

3.1 Influence of simulation modes

The computed energy needs for the different natural ventilation simulation modes shows similar values. The exception is mode C, with fixed window opening. This mode shows approximately 5% higher energy demand than the other two modes, for occupant behaviour Warm and Basic., When simulating with a fixed night-time opening area all year, it is indeed expected that the airflow rates through the window to be higher than needed (for acceptable IAQ). This is confirmed by a detailed analysis of the output data from the simulations. Fig. 6 shows the influence of an increase of 50% of the airflow rates in simulation mode A and can be compared to Fig. 4(a). Even though this increase of airflow rates is large, the space-heating needs using the natural ventilation in simulation mode A with the occupant behaviour Frugal, is comparable to the balanced ventilation with the user behaviour Basic.

3.2 Bedroom doors

The opening of the bedroom doors influences the energy performance. This is reflected in some of the occupant behaviour modes. In the Warm, Basic and Econ+ scenarios, bedroom doors are opened half an hour every morning and night while the other doors remain closed. The only difference between Econ+ and Economic is the door opening status. The difference in energy demand between these two modes shows that these two short opening events have a significant impact. The effect of having the bedroom doors open all day is shown by comparing Fig 5(a) and 5(d) and in Fig. 7. We can see the impact is substantial: for the mode Frugal the annual specific energy demand increases with 6-7 kWh/m^2.

In Norway, many bedrooms are only used for sleeping (and storing clothes), especially rooms for grown-ups, as reported by Heide et al (9). If the hybrid ventilation strategy was implemented in real houses, one could imagine adapting the building layout to match the ventilation system. Using small bedrooms purely used for sleeping, and other rooms designated for playing and office activities would seem advantageous.

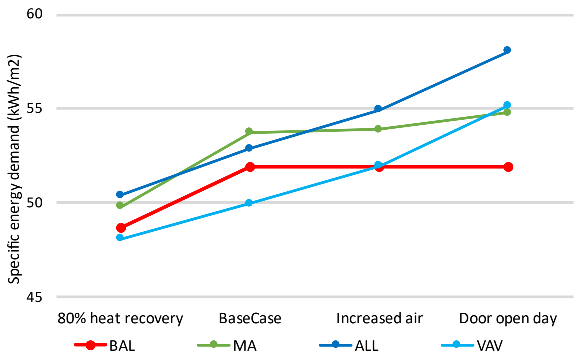

Fig. 7 – Sensitivity analysis on the specific energy demand with the Economic behaviour strategy, in the Passive building.

3.3 Thermal comfort in bedrooms

What are the lowest temperatures in bedrooms with natural ventilation during cold nights? In most of the occupant behaviour scenarios, the minimum temperature in the bedrooms is defined by the set-point temperature applied to the local bedroom heater. Only in the Frugal Corr scenario (with no local heater), the bedroom temperature is free-floating. The resulting minimum temperature here is -0.8°C in the main bedroom, and 3°C in the single bedrooms. This only happens during the coldest nights. When measuring bedrooms with natural ventilation in the field, Heide et al. found temperatures from -2°C to 23°C (9). In the behaviour mode Economic, bedrooms are heated to 10°C, and in Frugal, to 5°C. The annual energy consumption for one of these local heaters is only 80 kWh, and 5 kWh, respectively. This indicates that the number of cold nights is low. According to the authors, a common habit for the coldest or windiest nights, is to close the windows but keep the bedroom door open. In this way the bedrooms are connected to the ventilation of the rest of the house. This can result in less privacy, but this may be acceptable for a few days.

3.4 Sensitivity to the user behaviour

According to the simulation results, the energy performance seems strongly influenced by the occupant behaviour. A technology that is dependent on certain skills, habits or cultural patterns is user sensitive, and may not fit all occupants. As long as the occupants prefer a cool or cold bedroom, performance of the investigated hybrid strategy may be acceptable. However, if occupants prefer warm bedrooms, the hybrid strategies do not perform as well as a standard balance mechanical ventilation. If they open windows to have acceptable IAQ, with the local heaters on, high space-heating needs is a likely result. Alternatively, if these occupants keep the windows closed at night, in order to keep higher bedroom temperatures, this will result in low air change rates and low IAQ.

3.5 Insulation level of the building envelope

When comparing the two performance levels of the building envelope, the trend shows that the reference (balanced ventilation), shows slightly better performance compared to the hybrid ventilation, with the highest insulation level, see Fig. 5(a) and 5(c). One of the advantages of the hybrid system is the extensive thermal zoning. The lower bedroom temperatures reduce the transmission losses through the external walls of bedrooms. This advantage decreases when the building envelope has better insulation.

3.6 Energy savings using the VAV strategy

The ventilation strategy VAV (with reduced mechanical ventilation airflow rates during night-time) generally shows the lowest energy demand among the natural strategies. For the most energy efficient occupant behaviours, the space-heating needs with this strategy can even be lower than the standard one-zone balanced mechanical ventilation with efficient heat recovery (BAL). This possibility for creating a night set-back is technically cheap and simple. It might be seen as an opportunity provided by the proposed hybrid ventilation strategy. This deserves to be investigated in more details in further work.

3.7 Generalization to other countries

In this study, the simulations are done for a single building. The building test case is however representative for a large number of well-insulated wooden detached houses, also outside Norway. The author has also performed similar but less detailed simulation on a more generic building model, using the BPS software SIMIEN (11). The results and conclusions were in general similar.

An important prerequisite for the proposed hybrid ventilation strategy with extensive thermal zoning, is the use of warm, high-quality duvets and bed clothing. This seems to be important for the acceptance and preference of low bedroom temperatures. Cold bedrooms are not acceptable in all countries, for instance due to the habits related to bedclothes. However, some studies indicate acceptance or tolerance of cold bedrooms is other countries than Norway, like Denmark and China (28-30). The bedroom habits are not frequently reported in the literature so cold bedrooms could in fact be in use in several places in the world. Another important prerequisite for the hybrid solution to be acceptable is that the outdoor air quality (e.g., pollution) and sound levels are low at the building location. This is more challenging in urban areas.

4. Conclusions

The modelling of natural ventilation is based on simplifications in building performance simulation (BPS). Significant uncertainty is expected for window airflow computed using BPS. However, using sensitivity analysis based on different modelling assumptions and different model input parameters, the influence of these uncertainties can be quantified, and the results enable to formulate some general trends.

The energy performance of the investigated hybrid ventilation strategies is strongly influenced by the occupant behaviour. When occupants prefer bedroom temperatures at about 20°C, the investigated hybrid ventilation strategies lead to significantly higher space-heating needs compared to a standard balanced mechanical ventilation with efficient heat recovery unit. When bedrooms are used by occupants accepting (or preferring), low temperatures in bedrooms, and if these rooms are not heated during daytime, the computed space-heating needs are almost as low as standard balanced mechanical ventilation. Given an energy-conscious occupant behaviour (e.g., regarding thermal zoning), it seems possible to achieve a low energy use with natural ventilation in bedrooms. Low temperature in bedroom is frequently applied in Norwegian bedrooms so that the proposed hybrid ventilation strategies could be implemented into a significant share of the renovation market. However, temperature in bedrooms is strongly related to habits and culture. Therefore, the potential of this hybrid ventilation can be different for other countries.

Finally, for the hybrid ventilation strategy where all bedrooms are naturally ventilated, it is possible to create a night setback in the unoccupied zones served by the mechanical ventilation. It is a technically cheap and simple way to decrease energy use. This could be investigated in more details in further research.

5. Acknowledgement

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The datasets generated and analysed during the current study are not publicly available because significant pre-processing and structuring of data is required to make it open-access, but will be available upon request.

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