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# Energy efficiency of strategies to enable temperature zoning during winter in highly-insulated residential buildings equipped with balanced mechanical ventilation

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# Energy efficiency of strategies to enable temperature zoning during winter in highly-insulated residential buildings equipped with balanced mechanical ventilation

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**Abstract**. To reduce the space-heating needs, balanced mechanical ventilation equipped with a heat recovery is frequently implemented in highly-insulated residential buildings. This standard ventilation strategy tends to homogenize temperature inside the building, in other words, to reduce temperature zoning. In some countries, such as Norway, many users would like colder bedrooms. It has been proved that a significant part of the occupants in Norwegian passive houses opens bedroom windows during several hours every night during winter. Dynamic simulations have shown that it strongly increases the space-heating needs and that control only is unable to create temperature zoning in an energy-efficient way. The building concept should be changed. In the present contribution, the physical processes during temperature zoning are further explained. Detailed dynamic simulations of a detached single-family house are performed using the simulation software IDA ICE for different insulation levels, construction modes (which also influence the thermal insulation in partition walls) and control strategies. Alternative mechanical ventilation strategies are compared. They manage to reduce the influence of mechanical ventilation on the increased space-heating needs due to window opening but they cannot improve the large contribution of heat conduction through partition walls between heated areas and unheated bedrooms. Among the investigated ventilation strategies, decentralized ventilation has intrinsically the best performance.

## 1. Introduction

The necessity to drastically reduce the space-heating (SH) needs of residential buildings in Europe has prompted the emergence of building concepts based on a super-insulated building envelope, such as the passive house (PH) standard [1]. Developed for central Europe (e.g. Germany), the PH concept has been extended to Nordic countries. In particular, Norway has elaborated a national definition with the NS 3700 standard [2]. The current Norwegian building regulation, TEK17, requires comparable energy performance for the building envelope. Besides, the proposed concepts for Norwegian Zero Emission Buildings (ZEB) are most often based on super-insulated building envelopes [3]. These buildings have a building envelope that is super- or highly-insulated leading to limited heat losses. In addition, they are equipped with a balanced mechanical ventilation with an energy-efficient heat recovery (MVHR), meaning a heat exchanger with high effectiveness, $\eta$. The ventilation is most often centralized, meaning that a single air handling unit (AHU) is installed in residential buildings, such as detached and row houses. With this standard MVHR, the supply ventilation air has the same temperature for each room in the building. This is here called a one-zone MVHR. The combination of the highly-insulated building envelope with the one-zone MVHR limits the temperature differences between the rooms inside the building. This has been taken as an advantage for the simplification of the SH distribution. The number of heat emitters can be reduced compared to less-insulated buildings without impairing thermal comfort, see e.g. [1, 4-6]. However, recent research performed in Norway has shown that many occupants would like colder bedrooms (i.e. < 16°C) in combination with a higher temperature in the living areas, see e.g. [7, 8]. Berge et al. [9] investigated the user satisfaction and behavior using questionnaires distributed to the residents of 62 detached and terraced highly-insulated houses. Regarding bedrooms, 50% of occupants experience their temperature as too warm. During winter, approximately half of the respondents keep the bedroom window open at least a few hours per day. Results support the hypothesis that the dominant driver of bedroom window ventilation is temperature control. 65% of the respondents who keep the bedroom window open (all night or all day), have pre-set the supply air temperature to a level which requires post-heating during a significant portion of the winter season. Consequently, they do not operate the system coherently according to their desired indoor temperature. Berge et al. [10] performed another study combining field measurements with questionnaires on apartment buildings. This study confirmed that occupants would like colder bedrooms and use window opening to control the bedroom temperature (4h/day in average). It is worth mentioning that occupants often require a living room temperature of 22-24°C [7-9].

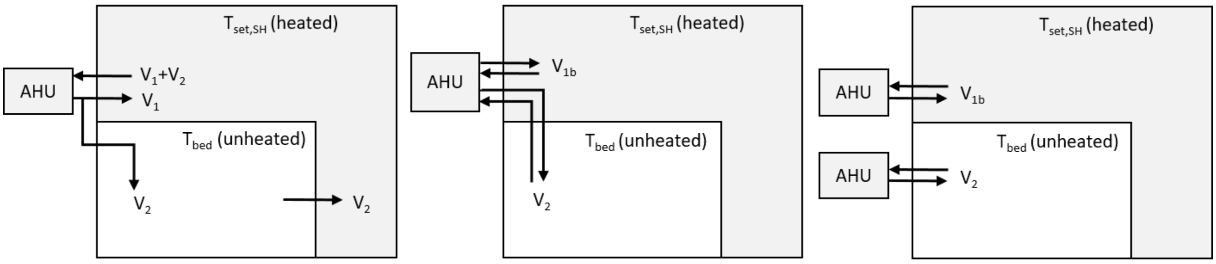
Based on these conclusions, the impact of intensive window openings on the SH needs of the building has been investigated using detailed dynamic simulations. Even though the physics to be modelled is complex, simulations suggest that opening windows to decrease bedroom temperature significantly reduce the energy efficiency [5, 6, 11]. Georges et al. [5, 6] compared different control rules for the heating and ventilation system as it has been shown that occupants do not always operate the building coherently to create the desired indoor thermal environment. None of the control strategies managed to create cold bedrooms without increasing the SH needs significantly. This suggests that this challenge cannot be addressed only using control but rather by adapting the building concept, such as the ventilation strategy. In that respect, Berge et al. [11] proposed a two-zoned ventilation concept with two distinct supply air temperatures for the living areas and bedrooms. This strategy manages to reduce the influence of window opening but the increase in SH needs is still substantial. Finally, Selvnes [12] analysed the temperature zoning in detached houses for different insulation levels and construction modes. The objective was to better understand the heat balance in the different zones and thus the physical processes explaining temperature zoning. Among other things, he showed that the phenomenon was intrinsically dynamic and cannot be fully understood using steady-state approaches. An alternative ventilation strategy based on a balanced supply and exhaust air in bedrooms was proposed as a way to reduce the influence of window opening on the SH needs. The performance of this new ventilation strategy was found to be moderate. In the remainder of the article, bedrooms will also be termed unheated zones as the local heat emission system, such as a radiator, is expected to be turned off to create lower indoor temperature. However, this is a simplified terminology as there is still active heating by the ventilation air.

As a continuation of work by Selvnes [12], the present work aims at creating at theoretical framework to understand the temperature zoning and the impact on the energy efficiency of window opening in bedrooms. It is shown that the heat conduction through the partition walls between heated and unheated areas as well as the mixing of ventilation air between zones are the two main processes of interest. Based on this framework, the influence of the construction mode can be explained and the potential of improvement using alternative ventilation strategies evaluated. In this respect, the performance of the one-zone centralized MVHR is compared with cascade ventilation and balanced airflows in bedrooms as well as with decentralized ventilation.

## 2. Methods

## 2.1. Theoretical framework

To date, most of the existing analysis about temperature zoning were based on detailed dynamic simulation (using IDA ICE) combined with parametric runs. However, a lot of the physical processes at stake occur simultaneously and are intrinsically dynamic. They are thus complex to understand so that a simplified framework of analysis would be beneficial.




(a)-(b) (c) (d)

**Figure 1.** Simplified model for the three ventilation strategies: (a) and (b) are centralized with cascade, (c) centralized with balanced airflows in bedrooms and (d) decentralized.

In this framework, the building is modelled as two isothermal zones as shown in Figure 1: one corresponding to the heated areas and one to the unheated areas (i.e. bedrooms). The temperature in the heated area is kept at a fixed set-point ($T_{set,SH}$). The temperature of bedrooms ($T_{bed}$) is free-floating and depends on the thermal characteristics of the building envelope and the ventilation system. The main idea is to evaluate the difference of SH power (ΔP) in the heated zone with and without opening of windows in bedrooms. To evaluate the SH needs of buildings, the conservation of energy is usually applied by taking all the thermal zones as the control volume, thus both heated and unheated zones. In our framework, the conservation of energy is only considered in steady-state for the heated zone and the AHU (thus excluding the unheated zone).

The standard ventilation strategy is a one-zone balanced MVHR with cascade ventilation, see Figure 1(a). This means that the ventilation air supplied in bedroom is transferred to a transition zone, such as a corridor, before being extracted in a "wet" room (typically a bathroom, the kitchen or a laundry room). In Figure 1, the direction of the airflows between zones or the AHU is show by arrows. The power of the heat exchange (P) between the heated and non-heated zones has two components: firstly, the heat transferred through the partition wall with a U-value ($U_p$) and, secondly, the power to heat the ventilation air from the colder bedroom temperature to the living room temperature. This leads to

$$P = U_p(T_{set,SH} - T_{bed}) + \dot{V}_2 C_p (T_{set,SH} - T_{bed}) \tag{1}$$

By convention, the temperature in the heated area is unchanged when the bedroom window is opened. The thermal losses to the outdoor is thus unchanged for the heated area as well as the exhaust air temperature to the AHU. The change in SH power induced by the window opening in the bedroom is only related to the increase of the heat exchange with the unheated zone, P. Making the difference with and without window opening, the change of SH power (ΔP) is simply expressed as

$$\Delta P = U_p(T_{bed,closed} - T_{bed,open}) + \dot{V}_2 C_p (T_{bed,closed} - T_{bed,open}) \tag{2}$$

Some important conclusions can already be derived from these two simple equations:

1. For a same level of thermal insulation of the building envelope, the construction mode has a direct influence on the SH power. In lightweight buildings, the partition walls are insulated for acoustic reasons unlike heavy-weight constructions. Firstly, $U_p$ is significantly lower in lightweight constructions. Secondly, the bedroom temperature with closed window ($T_{bed,closed}$) is lower in lightweight than in heavyweight constructions. For a same bedroom temperature with window

opening ($T_{bed,open}$), the influence of the window opening on P will be larger for heavy-weight buildings.

2. If the temperature in the living area is increased ($T_{set,SH}$), the bedroom temperature with closed windows will also be increased ($T_{bed,closed}$). Therefore, to reach a same bedroom temperature with open window ($T_{bed,open}$), a higher $T_{set,SH}$ will lead to a higher ΔP. From Equation (1), it is also clear that P increases with larger temperature differences between the living area and bedrooms.
3. A part of ΔP is due to the cascade ventilation. Therefore, it is meaningful to investigate alternative ventilation strategies to limit the impact of the window opening on the SH needs. The most obvious strategy would be to shut down the mechanical ventilation in bedrooms (i.e. removing the supply of ventilation air) when bedroom windows are open. The case is shown in Figure 1(b).

Point (3) suggests that an alternative ventilation strategy where an exhaust air terminal is placed in each bedroom (to balance exactly the amount of air supplied) would be beneficial, see Figure 1(c). The objective is to remove the ventilation contribution in P, the second term in Equation (1). With the adaptation of the ventilation strategy (without cascade), airflow rates should be changed to still comply to the building regulation. In practice, the updated airflow rates ($V_{1b}$) are slightly higher than the baseline value with cascade ($V_1$). By reducing the bedroom temperature, the opening of the bedroom window will decrease the average temperature of the exhaust air to the AHU. The mathematical expression of ΔP should then change to integrate the reduction of energy recovered by the AHU due to the window opening. For the sake of the conciseness, only the final equation is presented without the intermediate mathematical developments:

$$\Delta P = U_p (T_{bed,closed} - T_{bed,open}) + \eta \dot{V}_{1b} C_p \alpha (T_{bed,closed} - T_{bed,open}) \tag{3}$$

where the parameter α is defined as the ratio of $V_{1b}$ to the total ventilation airflow, $V_{1b}+V_2$. Equation 3 can be reformulated in a way that can be directly compared to Equation 2:

$$\Delta P = U_p (T_{bed,closed} - T_{bed,open}) + \eta (1-\alpha) \dot{V}_2 C_p (T_{bed,closed} - T_{bed,open}) \tag{4}$$

In the case study of Section 3, the heat recovery effectiveness is 85% and the ratio α is 0.33. For this case, the ventilation term in Equation (4) equals 56% of the ventilation term of Equation (2). Consequently, this new strategy roughly removes ~50% of the ventilation losses while heat transfer through partition walls is left unchanged. This most probably explains why Selvnes [12] found this new strategy to moderately improve the performance in his investigations using dynamic simulations. Equation (3) is based on the assumption that the AHU heating coil will not directly compensate for the reduced return air temperature created by the window opening. If the AHU heating is triggered, the energy savings will then be lower than ~50%.

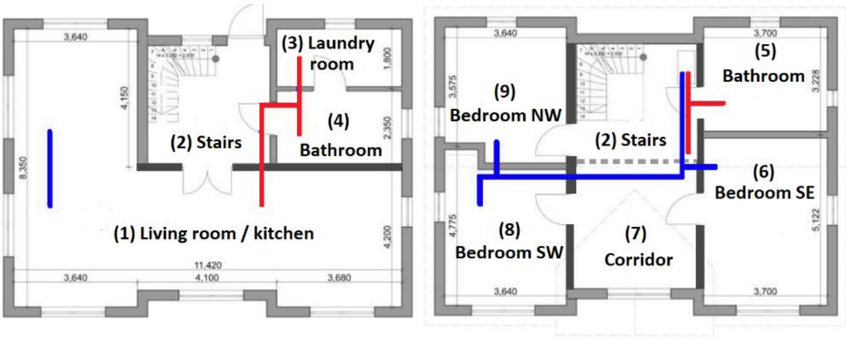
To avoid these limitations, a second AHU allocated to the unheated zones can be added, see Figure 1(d). This strategy is called decentralized ventilation. In this way, a reduction of the bedroom temperature due to window opening will not impact the ventilation heat recovery of the heated zones. The only influence of the window opening on ΔP is the heat transfer through the partition walls:

$$\Delta P = U_p (T_{bed,closed} - T_{bed,open}) \tag{5}$$

In addition, the temperature set-point of the supply ventilation air ($T_{set,AH}$) can be taken different for heated and unheated zones: it can be taken lower for bedrooms so that $T_{bed,closed}$ can be closer to the desired temperature, $T_{bed,open}$. In general, this should also decrease the need for window opening to control the bedroom temperature.

## 2.2. Case study of detached passive house

The theoretical framework will be compared to detailed dynamic simulations in IDA ICE in order to confirm whether it provides the correct conclusions and understanding of the physics. A case study is therefore necessary and has been defined based on the work of Selvnes and Georges et al. [4, 12]. This detached house of 173 m² heated area is insulated according to the Norwegian Passive House Standard [2] and located in Oslo in an open and flat terrain without obstacles, see Figure 2. The heat transfer coefficient (U-value) is 0.14 W/m².K for external walls, 0.13 W/m².K for the external floor, 0.12 W/m².K for the roof and 0.72 W/m².K for windows. The air change rate due to infiltration 0.6/h at 50 Pa while normalized thermal bridges (ψ) are taken at 0.03 W/m².K. The heat recovery effectiveness (η) is 85 %. No frost protection of the heat exchanger has been considered. The thermal properties of the different construction modes are reported in Table 1. Detailed information about the construction can be found in [4, 12]. Internal gains are taken according to TS 3031 [13] and SH is performed using ideal heaters as the main focus is on the SH needs (i.e. not the energy use).




(a) First floor (b) Second floor

**Figure 2.** Floor plan and air distribution with cascade ventilation: ductwork for supply air are coloured in blue while the exhaust air ducts are in red [12].

**Table 1.** Construction modes: building thermal inertia (EN 13790), U-value of internal construction.

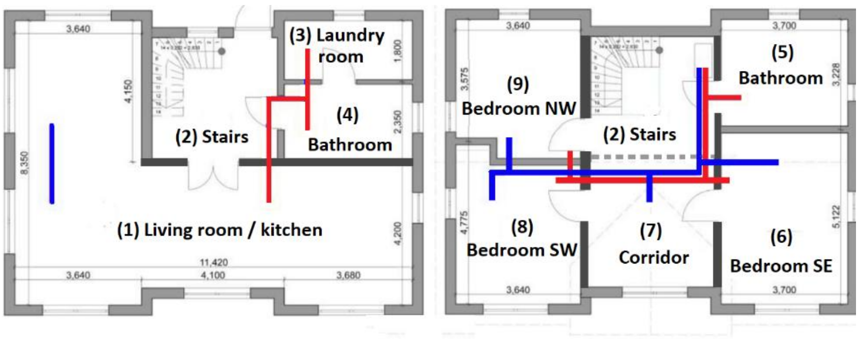
| Construction type | Inertia level | Inertia [MJ/K] | $U_{floor}$ [W/m².K] | $U_{part}$ [W/m².K] | $U_{bearing}$ [W/m².K] |
|---|---|---|---|---|---|
| Masonry heavy (CM1) | *Very-heavy* | 86 | 1.6 | 3.2 | 2.8 |
| Wood-masonry (CM2) | *Heavy* | 41 | 1.6 | 0.33 | 2.8 |
| Wooden heavy (CM3) | *Medium* | 35 | 0.23 | 0.33 | 2.8 |
| Masonry light (CM4) | *Light* | 26 | 0.21 | 0.33 | 1.1 |
| Wooden light (CM5) | *Very-light* | 14 | 0.21 | 0.33 | 0.25 |

The building has MVHR with constant air volumes (CAV). Airflows are described for the different ventilation strategies in Table 2 and have been defined in order to comply with the Norwegian building regulation, TEK 17. The strategy (a) is the standard ventilation with the airflow cascade principle. The strategy (b) is a small adjustment of strategy (a) where the supply air to bedrooms is stopped when the bedroom windows are open. Then, the equivalent amount of air is injected in the corridor of the second floor. The strategy (c) is the one-zone MVHR but with balanced supply and exhaust airflows in bedrooms. This lead to a new layout for the ventilation ducts, see Figure (3), that is not significantly more complex than the baseline, see Figure (2). Finally, strategy (d) is the decentralized ventilation where two AHU have a heat exchange with a same η. For ventilation strategies with balanced airflows in bedrooms, meaning (c) and (d), the gap below the bedroom doors necessary for the cascade ventilation has been removed. With cascade ventilation, the value of airflow rates is dominated by the minimum amount of supply air so that the minimum amount of extracted air should be increased to comply to TEK 17. On the contrary, with balanced airflows in bedrooms (strategies c and d), the dominant airflows are the minimum amount of extracted air so the amount of supply air should be increased compared to the minimum values. This leads to a total amount of ventilation air that is about 40% higher. In this study, the electricity use for fans is not considered.

**Table 2.** Ventilation airflow rates for the different ventilation strategies [12].

| Zone | Room | With cascade (baseline) | | Without cascade** | |
|---|---|---|---|---|---|
| | | Supply [$m^3/h$] | Return [$m^3/h$] | Supply [$m^3/h$] | Return [$m^3/h$] |
| 1 | Kitchen and Living | 104 | 40 | 126 | 36 |
| 2 | Stairs | 0 | 0 | 0 | 0 |
| 3 | Technical/Laundry | 0 | 40 | 0 | 36 |
| 4 | Bathroom 1st floor | 0 | 64 | 0 | 54 |
| 5 | Bathroom 2nd floor | 0 | 64 | 0 | 54 |
| 6 | Bedroom SE | 52 | 0 | 52 | 52 |
| 7 | Corridor 2nd floor | 0* | 0 | 54 | 0 |
| 8 | Bedroom SW | 26 | 0 | 26 | 26 |
| 9 | Bedroom NW | 26 | 0 | 26 | 26 |
| Total | | 208 | 208 | 284 | 284 |

* In strategy (b), this airflow is 104 $m^3/h$ if the supply ventilation air in bedrooms is stopped.
** This corresponds to the strategy (c) and decentralized ventilation (d).




(a) First floor (b) Second floor

**Figure 3.** Floor plan and air distribution with balanced supply and exhaust airflows in bedrooms (strategy c) [12]: ductwork for supply air are coloured in blue while the exhaust air ducts are in red.

**Table 3.** Definition of the different control strategies for SH and ventilation.

| Cases | Living areas | AHU | Bedrooms | Windows | Windows | Door |
|---|---|---|---|---|---|---|
| | $T_{set,SH}$ | $T_{set,AH}$ | $T_{set,bed}$ | Schedule | $T_{set,win}$ | Schedule |
| 1 | 21 or 24°C | $T_{set,SH}$-3 | $T_{set,SH}$ | Closed | - | Closed |
| 2 | 21 or 24°C | $T_{set,SH}$-3 | None | Closed | - | Closed |
| 3 | 21 or 24°C | 16°C | None | Closed | - | Closed |
| 4 | 21 or 24°C | 14°C | None | Closed | - | Closed |
| 5 | 21 or 24°C | $T_{set,SH}$-3 | None | Open (Night) | 16°C | Closed |
| 6 | 21 or 24°C | 16°C | None | Open (Night) | 16°C | Closed |
| 7 | 21 or 24°C | 14°C | None | Open (Night) | 16°C | Closed |
| 8 | 21 or 24°C | $T_{set,SH}$-3 | None | Open (Night) | 16°C | Open (Day) |

In Table 3, the different control strategies of the SH and ventilation systems are described. Different temperature set-points are applied for the SH in the heated area ($T_{set,SH}$), in bedrooms ($T_{set,bed}$) and the supply ventilation after the heating battery ($T_{set,AH}$). The area of the window opening in bedrooms is adjusted using a proportional-integral (PI) control with a cooling temperature set-point ($T_{set,win}$). This is an idealization of window control. Firstly, this removes the influence of the user behaviour as windows are here controlled automatically and, secondly, the uncertainty regarding the modelling of bi-directional airflows through windows is removed. If applied, this PI control is implemented for all the three bedrooms. Regarding time schedules, the temperature set-points are constant and windows are opened only during night-time (defined between 10 PM to 7 AM). If internal doors between bedrooms and living areas are opened, it is done during daytime (between 7 AM and 10 PM). The first strategy is the reference scenario to evaluate the SH needs. It assumes a uniform temperature for all the zones in the building. Strategies 2 to 8 try to generate colder bedroom. Strategy 2 just removes SH in bedrooms. Strategies 3 to 4 aim at decreasing bedroom temperature by reducing the temperature of the supply ventilation air but keeping windows closed. Strategies 5 to 7 resort to window opening with different temperature for the ventilation supply air. Finally, strategy 8 imposes large daily fluctuations of the bedroom temperature by opening windows during night-time and by heating bedroom during daytime using internal door opening.

## 3. Results

### 3.1. Heat balance during steady-state boundary conditions

The simplified framework of Section 2 assumes that the temperature in the living area is strictly constant with and without opening of windows. With a yearly simulation using a typical meteorological year (TMY), some periods with high solar and internal gains would lead the air temperature to exceed the set-point. Therefore, in order to be consistent with the proposed framework, the case study is first analysed with steady-state boundary conditions, meaning with a constant outdoor temperature and with constantly overcast sky. This guarantees a constant temperature in the heated zones. 30 days are used to initialize simulations corresponding to one day. It has been previously said that the physics of temperature zoning was intrinsically transient. An outdoor temperature of 5°C has been here selected to generate comparable temperature differences between the living areas and bedrooms than fully dynamic simulations.

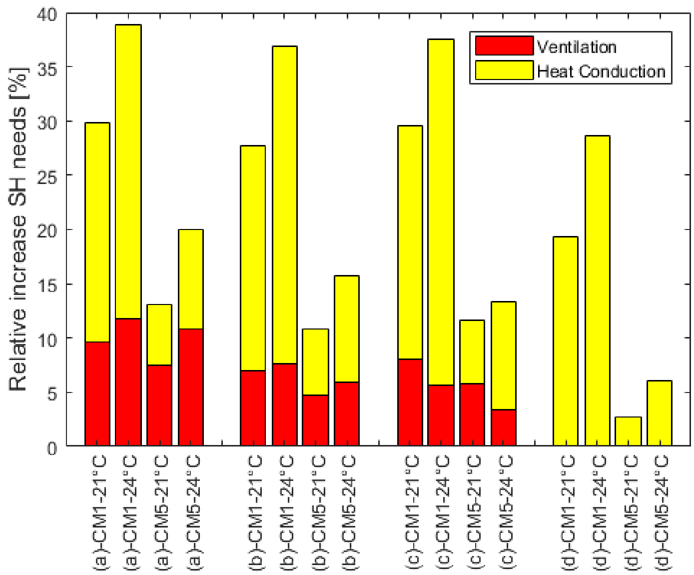
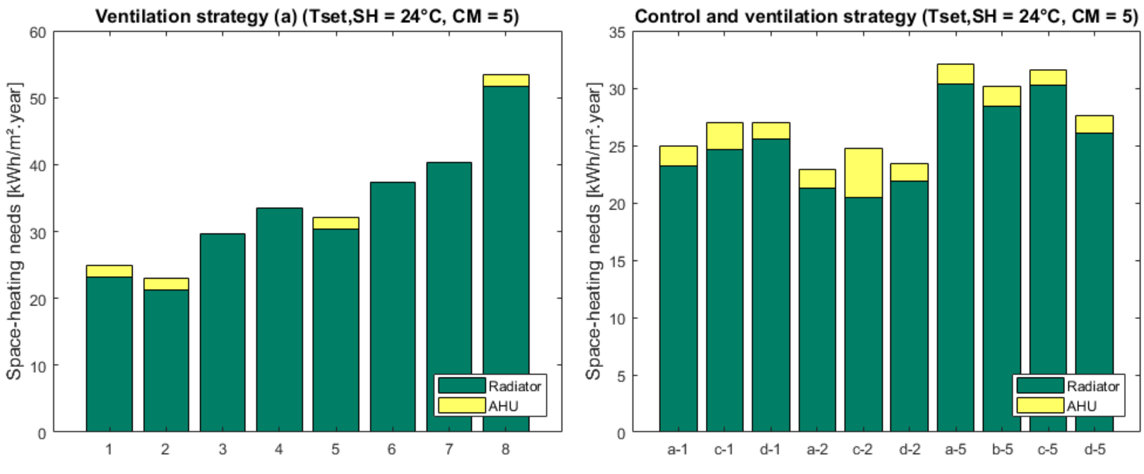



**Figure 4.** Relative increase of the SH needs (ΔE in [%]) when bedroom windows are open: strategy 5 compared to strategy 2 for all ventilation strategies (a to d), two construction modes (CM) and $T_{set,SH}$.

Results are shown in Figure 4 where the respective contribution of ventilation and heat conduction through partition walls are distinguished (using the heat balance of zones in IDA ICE). Starting from ventilation strategy (a), the increase of SH needs (ΔE) due to window opening strongly depends on the construction mode. The ventilation contribution is left unchanged but the heat conduction through partition walls increases significantly with higher thermal masses. The second factor of influence is the $T_{set,SH}$ as a larger temperature difference inside the building leads to a higher influence of window opening. As expected, the ventilation strategy (b) manages to reduces the ventilation losses compared to strategy (a) while the contribution from heat conduction is left almost unchanged. This reduction of the ventilation contribution is limited because the strategy (b) differs from strategy (a) only during night-time. In line with the theoretical framework, the strategy (c) only leads to a slight reduction of the ventilation component compared to the baseline strategy (a). Finally, the strategy (d) based on decentralized ventilation has only a contribution from the heat conduction. This one is lower than for the other cases because the bedroom temperature with window closed ($T_{bed,closed}$) can already be reduced compared to centralized approaches by a proper control of the AHU dedicated to bedrooms. As shown in Equation 5, this directly reduces ΔP. In conclusion, these results are in line with the simplified theoretical framework. In addition, it shows that heat conduction has a large contribution that cannot be reduced by a change of ventilation strategy. Finally, the ventilation contribution to ΔE is only slightly decreased by the alternative strategies (b) an (c). Only, the decentralized ventilation manages to remove completely the influence of mechanical ventilation on ΔE.

### 3.2. Yearly dynamic simulations

The analysis can now be extended to yearly dynamic simulations. For the sake of the conciseness, only the case of a lightweight building (CM5) is shown as it is most representative for Norway. In addition, a living room temperature ($T_{set,SH}$) of 24°C is assumed as it is a common temperature set-point in passive houses, see Introduction Section.




(a) (b)

**Figure 5.** SH needs for the baseline ventilation strategy (a) with alternative controls (left figure) and for the different ventilation strategies (right figure).

Results are shown in Figure 5. The baseline SH needs are as high as 24 kWh/m².year due to a higher indoor temperature of 24°C compared to the 21°C used by the NS3700 standard. Figure 5(a) considers the baseline ventilation strategy (a) but with different controls. Decreasing the supply air temperature leads to significantly increased SH needs while bedroom temperatures will be decreased but not up to 16°C (figure not shown here). Window opening (i.e. strategy 5) leads to an increase of 10 kWh/m².year.

This increase can be much more drastic if the bedroom is re-heated during daytime (i.e. strategy 8) leading to large temperature differences between daytime and night-time. The thermal energy stored in the building is flushed during each night and can lead to increased SH needs of 30 kWh.m².year. In conclusion, the increased of SH needs due to window opening is influenced by two user-dependant parameters: the temperature differences imposed inside the building but also the daily variations of indoor temperatures imposed to bedrooms. Figure 5(b) compares the different ventilation strategies and confirms the findings of the previous Section. Comparing control 5 between strategies (a) to (d), ventilation strategies (b) and (c) lead to a moderated improvement as they only focus on decreasing the ventilation contribution and not the heat conduction through partition walls. Unlike the theoretical framework, the energy performance of strategy (c) depends on the temperature set-point to the AHU heating coil. The decentralized ventilation, i.e. strategy (d), completely removes this ventilation contribution and gives the best performance. This work has the merit to show the relative contribution of ventilation and heat conduction through partition walls on the increase of SH needs induced by window openings. Considering alternative ventilation strategies only improves one aspect while the heat conduction remains an important factor that is left almost unchanged.

## 4. Conclusion

This article gave a theoretical framework to understand the increase of SH needs due to window opening in bedrooms during the SH season. Two separate effects should be considered: the effect of mechanical ventilation and the heat conduction through partition walls separating heated zones and unheated bedrooms. The influence of heat conduction is dominant for heavyweight buildings while it is comparable to mechanical ventilation for lightweight buildings (with insulated partition walls). The final increase of SH needs is strongly user-dependant. It depends on the temperature difference between heated areas and bedrooms, the daily temperature fluctuations imposed to bedrooms and the number of bedrooms where windows are opened. Alternative ventilation strategies to reduce the impact of mechanical ventilation leave the influence of heat conduction through partition walls almost unchanged. The alternative centralized ventilation strategies investigated here moderately limit the influence of ventilation. Only the decentralized ventilation completely removes the effect of ventilation on the increase of SH needs. In addition, using decentralized ventilation, the supply air temperature to bedrooms can be adjusted specifically for bedrooms and limit the need for intensive window openings in bedrooms.

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