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Effect of passive cooling strategies on overheating in low energy residential buildings for Danish climate

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Abstract

Climate changes have progressively produced an increase of outdoors temperature resulting in tangible warmer summers even in cold climate regions. An increased interest for passive cooling strategies is rising in order to overcome the newly low energy buildings' overheating issue. The growing level of air-tightness plays in low-energy buildings a double-acting role: reduction of energy demand and lack of adequate infiltration rate. In particular, the last one combined with higher outside air temperatures brings these new concepts buildings to progressively experience higher indoor temperatures creating not negligible thermal discomfort.
In the present work the effect of passive strategies, such as solar shading and natural night-time ventilation, are evaluated through computer simulations. The analyses are performed for 1½-storey single-family house in Copenhagen's climate. The main result is that a crossed use of both strategies leads to a cooling demand reduction that varies between 98%-100% depending on the building's insulation.

Keywords: low-energy building, overheating, passive cooling strategies

1. Introduction

Climate changes have progressively produced increased outdoor temperatures resulting in warmer summers experienced also in cold climate regions. Since 1870 in Denmark the outdoor average temperature has increased approximately 1.5 ˚C and for the following 30 years it is estimated a faster increase with an average from 1 ˚C to 1.4 ˚C (DMI, 2014).

According to the EPBD Directive (2010) and its energy efficiency measures, the "Nearly/Net Zero Energy Building" are the only European target to follow in buildings´ constructions till 2020. The directive has brought to some changes in the design process mainly concentrated on an increase of buildings' airtightness, which results in reduction of energy demand but also in lack of adequate infiltration rate.

The increased buildings´ airtightness, the increase of outdoor temperatures, combined with the wider use of larger windows´ surfaces brought to a rising experience of higher indoor temperatures creating not negligible thermal discomfort.

Concerns about solutions to overcome the low energy buildings' overheating issue results today in an increased interest and new challenge for designers to be considered in providing energy efficient buildings with good indoor climate.

Orme et al (2003) found that the most important factors causing overheating in well-insulated buildings are *solar radiation* and the *ventilation rate.* The importance of solar radiation impact on eight passive houses located in Denmark has been also reported by Larsen et al (2012). They demonstrated that larger windows areas in the southern building facade increase the solar gain reducing the heating demand in winter, but on the other end bring to critical thermal condition in summer, outside of the comfort categories suggested in EN 15251 (2006). The higher solar radiation load and higher windows temperatures could generate thermal discomfort resulting as a consequence in high cooling demand.

Internal gains, like occupants and equipment, have also a relevant impact on overheating, as demonstrated in Janson´s (2010) work through the measurements performed in Swedish houses. This work showed also that tenants whom experienced an excessive indoor temperature had also considerable electricity consumption with higher appliances use. Additionally, through questionnaires, it was found that the desired indoor temperature varied between 20 ˚C to 23 ˚C and most tenants wanted 22-23 ˚C.

Passive cooling techniques and solutions, based on the interaction of the building and its surroundings, are the strategies that use climatic resources instead of electrical energy to create comfortable indoor environment. It is the strategy to be considered in order to solve overheating issue at low/zero energy cost.

It is not a new concept for buildings' cooling techniques (e.g. breezes flowing through windows, water evaporative from springs and fountains as well as large amounts of stone and earths absorbing daytime heat), but, over thousands years, it has been developed and integrated in building design. Today, called "passive cooling", it can also be seen as integration to the use of buildings´ mechanical systems with the following reduction of the pumps and/or fans energy consumption.

Solar shading and natural ventilation are the most used passive cooling strategies for decreasing the heat absorption from direct solar radiation and increasing the penetration of colder air with zero energy use.

Night-time cooling ventilation, recirculation of fresh air through windows or specific building envelope openings, is the most used cooling strategy in climatic zones with high diurnal temperature variation where as a consequence thermal discomfort can be avoided. Pearlmutter and Meir (1995) also reported that the best performance in term of less fluctuating indoor temperature is obtained in high thermal mass buildings.

Night-time cooling ventilation can be a very powerful technique, while can also present considerable restrictions as condensation and moisture problems, privacy and/or security problems, incoming of outside air pollution, and acoustic problems. The use of this cooling technique and the evaluation of its limitative applicability are strongly associated with the specific climatic conditions.

In the cold climate region of Denmark the night cooling potential is very high, however the weather conditions, mostly rainy in summer, can be very limitative for the applicability.

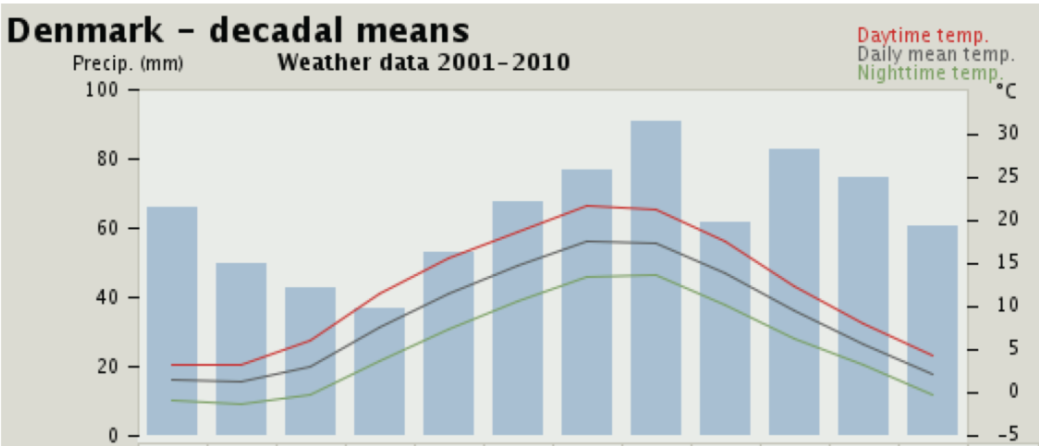
In the Danish near zero energy buildings the increase of overheating issue and the possibility of its reduction/nullification at low/zero energy cost by the use of passive strategies, solar shading and/or night cooling ventilation, is here analyzed. In particular, this study aims to evaluate the possibilities of using night cooling ventilation looking also at the restriction of its applicability; alternative solutions were also evaluated considering some users' habits.

2. Starting Consideration

When looking at the weather data over a year of Denmark, and in particular at the outside temperatures fluctuation, it is difficult to believe that overheating issue my rise in buildings located in such climate. Together with other weather data over 10 years, the monthly average of temperatures are shown in Figure 1 and the highest values were recorded in July-August, been lower than 26 ˚C (up to 21.6 ˚C).

Then, the rising question is how the low energy houses' characteristics, low air permeability and high thermal insulation, surely resulting in better energy performance could impact negatively on indoor climate.

Through building simulation program, the average monthly outside air temperatures for Copenhagen city was gathered. The temperature profiles of maximum, minimum, and average, shown in Figure 2, have the same profile of Figure 1 and the higher temperature values occurred on July and August equal to 22 ˚C.



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
Precip. (mm)	66	50	43	37	53	68	77	91	62	83	75	61	765
Rainy days	18	15	13	11	13	13	14	16	14	17	20	17	179
Daytime temp.	3.3	3.3	6.1	11.5	15.5	18.5	21.6	21.2	17.5	12.3	7.9	4.2	11.9
Daily mean t.	1.5	1.2	3.0	7.5	11.4	14.6	17.4	17.2	13.8	9.4	5.7	2.2	8.8
Night temp.	-0.8	-1.3	-0.2	3.6	7.4	10.6	13.4	13.5	10.2	6.2	3.2	-0.3	5.5
Sunshine hours	47	71	146	198	235	239	232	196	162	111	58	45	1739

Figure 1. Average of decadal weather parameters of Denmark (2001-2010) (DMI, 2014).

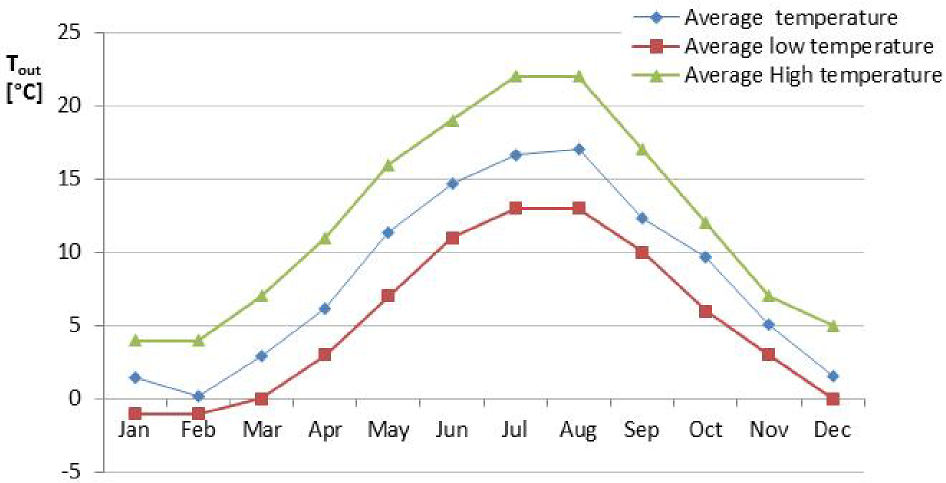


Figure 2. Monthly outside air temperatures in Copenhagen

A dynamic simulation of a typical Danish and low energy residential building, without any type of cooling systems implemented, for the climatic condition of Copenhagen was performed. The variation of the indoor temperature over all year, shown in Figure 3, reported values higher than 26 ˚C, over the recommended comfortable temperature for building category II (EN 15251, 2006). In particular those temperature data show that the issue of *overheating* needs to be considered in summer, when temperature could rise up 34 ˚C, and also in "shoulder" seasons (April, May, and September). As a consequence, cooling systems may need to be evaluated in the near future for low energy building design in order to avoid any unreasonable action that the occupants could take and which it may result in high energy consumption against the main concept of low energy buildings. So far, as prescribes by the European Directive (2010), it is necessary to exploit solutions that can grant energy saving without compromising indoor environmental quality and, for this reason, by means of dynamic simulations of Danish residential building, the effects of passive strategies, such as solar shading and natural night-time ventilation, were evaluated and analyzed.

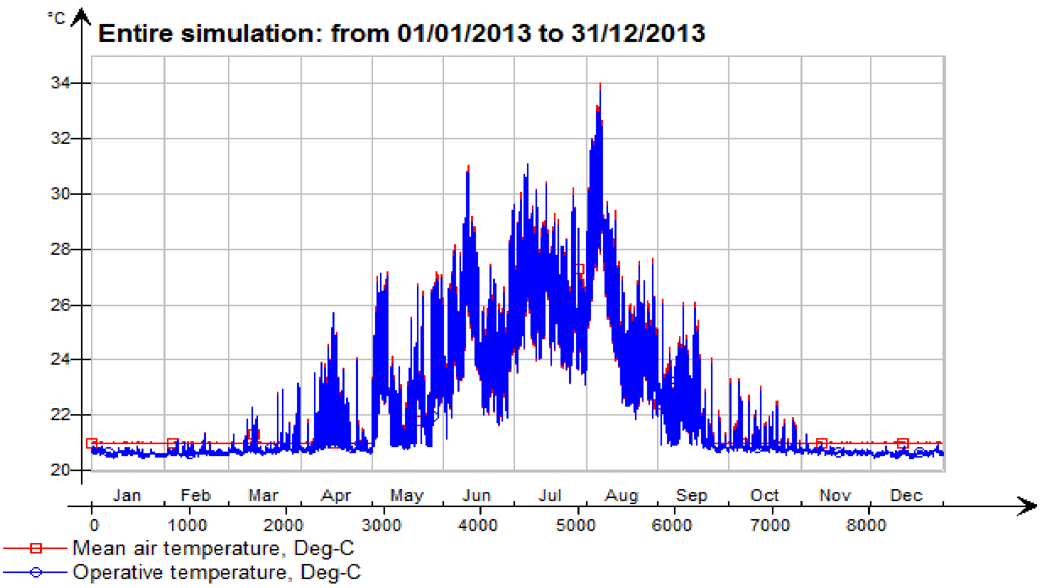


Figure 3. Operative and air temperatures hourly trend for a year of low-energy building in Copenhagen

3. Building model

A 1½-storey single-family house, earlier designed to optimize the performance of passive cooling strategies and to minimize the energy consumption in Northern European countries (Kragh et al, 2008), was chosen as building model for this study. Views of some building orientation and windows position are showed in Figure 4. A total of 23 openable windows (8 roof horizontal pivoting windows with automatic control, 8 vertical windows and 7 vertical doors), available in the marked, were positioned in the building´s model. Windows sizes and positions aimed at the reduction of electric consumption for artificial light and to increase also the cooling potential of natural ventilation techniques (Kragh et al, 2008).

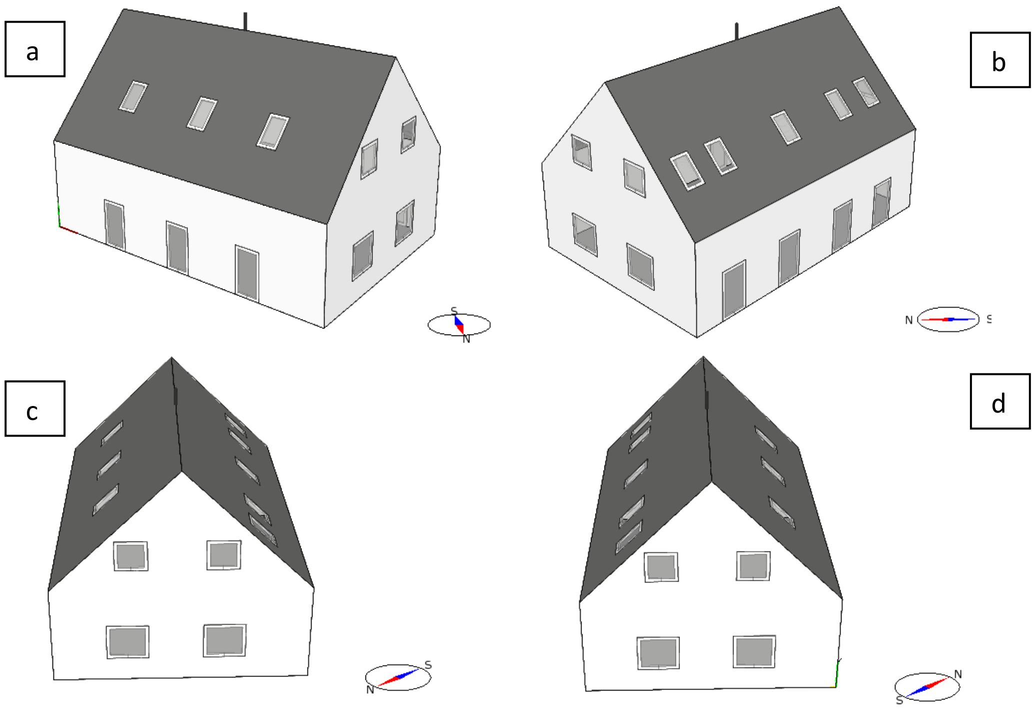


Figure 4. Visual representation of building orientation

The main characteristics of the building model are summarized in Table 1. The building is equipped with a mechanical ventilation system (M), supplying outdoor air at 16 °C minimum temperature, that guarantee 0.5 air change rate per hour during the occupancy time (not occupied from 8AM to 5PM, from Monday to Friday). A family of 4 people is assumed to be living in the building, which for the main purpose of this study is assumed to be only one zone.

Heating and cooling systems, with and without heat recovery, were integrated in the model having as set point of the indoor air temperature of 20 °C for the heating season (operating from 31st August to 6th June) and 26 °C for the activation of cooling system (operating only when needed for that particular simulated condition, later explained).

Table 1. Main characteristics of the building model

Length	Width	Floor area	Maximum height	Sloped roof	ACH	Occupants	Light	Equipment
[m]	[m]	[m^2]	[m]		[1/h]	nr.	[W/m^2]	[W/m^2]
12	8	175	7.3	45°	0.5	4	3.0	4.0

Two buildings structure, both with 20 cm of concrete thermal mass in the walls, were analyzed having different thermal property, from Building A to B, increasing the building insulation by lowering the thermal transmittance of both opaque envelope and glazed surfaces, as reported in Table 2.

Table 2. Thermal property of the two building structures

	Average U-value [W/m^2K]	
Building structure	Opaque surface	Glazed surface
A	0.30	1.127
B	0.18	0.583

4. Case studies

The Energy and Indoor Climate Visualizer (EIC Visualizer, 2012) based on IDA-ICE software was used for running all the simulations. This software was tested several times against different validation schemes. It allowed identifying the exact moment in which a change like the opening or closing of a window was occurring.

The basic building model with heating and cooling system (M_HC) was implemented with the passive strategies aiming at solving the overheating issue. Solar shading (S) and natural night ventilation (Na) were separately and coupled implemented and operated (see Table 3); so that the results obtained from the building´ simulation could be analyzed and compared.

Additionally, the building analyses with the implementation of the heat recovery ventilation (HRV) were studied. The air handling unit (AHU) was implemented with an air-to-air heat exchanger, with 0.85 efficiency, connecting the inlet and the outlet pipes to provide heat recovery reducing the energy consumption of the heating coil.

Table 3. Passive systems implemented in the building model

Case studies	Solar Shading	Natural Night Ventilation
M_HC	NO	NO
M_HC_S	YES	NO
M_HC_Na	NO	YES
M_HC_SNa	YES	YES

The automatic solar shading system was based on a PI controller activated when the increasing mean air temperature reaches the selected set point of 23°C. Sunshades were used in order to maintain the indoor air temperature by modulating the windows´ incoming solar radiation.

A nighttime schedule was implemented for controlling the natural night ventilation. Two were the set conditions determining the automated windows opening during the whole night:

1. Indoor air temperature (t_a) above the selected threshold of 23 °C (according Pellegrini (2012);
2. Indoor air temperature (t_a) higher than outdoor temperature (t_{out}).

The nighttime control conditions were both checked at 10 p.m. when it has been assumed that the occupants go to sleep. If the recorded temperatures were satisfied (t_a<23 °C and t_a>t_{out}) the windows were opened for the entire night, and the windows opening was controlled and modulated according the proportional controller:

- if t_a>23.5 °C, the windows were fully opened;
- if 23.5°C< t_a <22.5 °C, the windows opening was modulated;
- if t_a < 22.5 °C, the windows were fully closed.

Moreover, indoor air quality and thermal comfort conditions were calculated and compared according to EN 15251 (2006) categories. The total energy demand/consumption, including heating, cooling, ventilation (incl. fans and heating-coil consumption), domestic hot water and auxiliary, were calculated and reported in terms of primary energy. According to EN 15203 (2006), for the electric consumption of cooling and ventilation systems, and pumps a coefficient of 2.5 has been assumed, while 1.0 was the coefficient chosen for the heating system, AHU’s heating coil and domestic hot water.

In a second step of study, following the previously obtained results, few new simulations were performed taking into account some rescue for the occupants or their behavioral action as the daily windows opening.

When some drawbacks in connection with the use of natural night ventilation through the windows´ opening, e.g. security reasons, raining season, and/or outside noise, were considered an alternative use of the colder outside air was evaluated. The use of the mechanical ventilation system during the night as variable air volume for bringing inside the outside air with the support only of a fan, and so the increase of air change rate was considered. Then the energy consumption and the resulting indoor temperatures for providing thermal comfort were calculated and compared between the windows´ natural ventilation (Na) and the mechanical ventilation implemented by the night use for bringing inside the colder outside air (MNa).

To make comparable the two simulation models using the outside air for cooling, the same setting of the night natural ventilation (Na) earlier explained, were adopted to the mechanical ventilation system. Therefore, when at 10 p.m. the inside temperature is higher than 23˚C the supply air flow was automatically increased up to 1 ach.

The two models were applied and compared for the period of time from May 1th till September 30th.

5. Results

The simulated results evaluating two near zero energy buildings show that, by improving the insulation and airtightness of the building, from structure A to B, the total energy demand decrease from 128 kWh/m^2 per year to 96 kWh/m^2 per year, resulting in 21% of total energy saving (see Table 4). A further 21% and 27%, for the same building´s structure A and B respectively, was saved when the heat recovery unit was implemented in the systems, of which 70-73% of energy savings were achieved by the ventilation system.

Looking more in details through the energy demand of different systems, it can be noted that the heating demand went from 58 to 18 kWh/m^2 per year resulting in 69% of energy saving on heating; while, on the other hand, the increased insulation and air tightness (building B) caused an increase of cooling need (up to 60%), bringing the energy demand for cooling from 13.3 to 21.4 kWh/m^2 per year (see Figure 5). It indicates the rising of overheating issue, with expected indoor temperatures distribution reaching even 34 ˚C and, as shown in Figure 6, with an extended overheating period till the end of September.

Those results suggested that actions need to be taken in order to avoid future increase of energy consumption, to control the energy use for satisfying the cooling demand, and to maintain indoor thermal comfort conditions.

Clearly the combination of the combined passive strategies, solar shading and natural night ventilation, applied in the simulated model with the heat recovery unit (M_HC_SNa_HRV) were the best energy saving applications. Those strategies applied to the higher insulated building B resulted in only 47 kWh/m^2 year of energy demand (see Table 1) and permitted to reach the goal of zero energy cooling demand (see Figure 5b).

Can also be noted that the application of only one of the two passive strategies helped substantially on decreasing the cooling demand, to 0.6 or 0.4 kWh/m^2 year with the solar shading, and to 7.1 or 0.1 kWh/m^2 year with the night-time ventilation (see Figure 5), which is very low but still accounted.

However, the performed simulations showed that with higher building insulation (building structure B) and ventilation with heat recovery, the only use of natural night ventilation permit to achieve the lowest total energy consumption (46.3 kWh/m^2 year) having only 0.1 kWh/m^2 year of cooling demand.

Table 1 Total energy demand of two buildings structure

CASE STUDIES	Total energy demand [kWh/m^2 year]		Energy Savings [%]
	Structure A	Structure B	From A to B
M_HC	127.7	95.9	24
M_HC_HRV	101.3	69.5	31
M_HC_S	116.4	75.0	36
M_HC_S_HRV	90	48.6	46
M_HC_Na	118.7	70.5	41
M_HC_Na_HRV	93.8	**46.3**	**51**
M_HC_SNa	115.1	72.4	37
M_HC_SNa_HRV	**89**	46.9	47

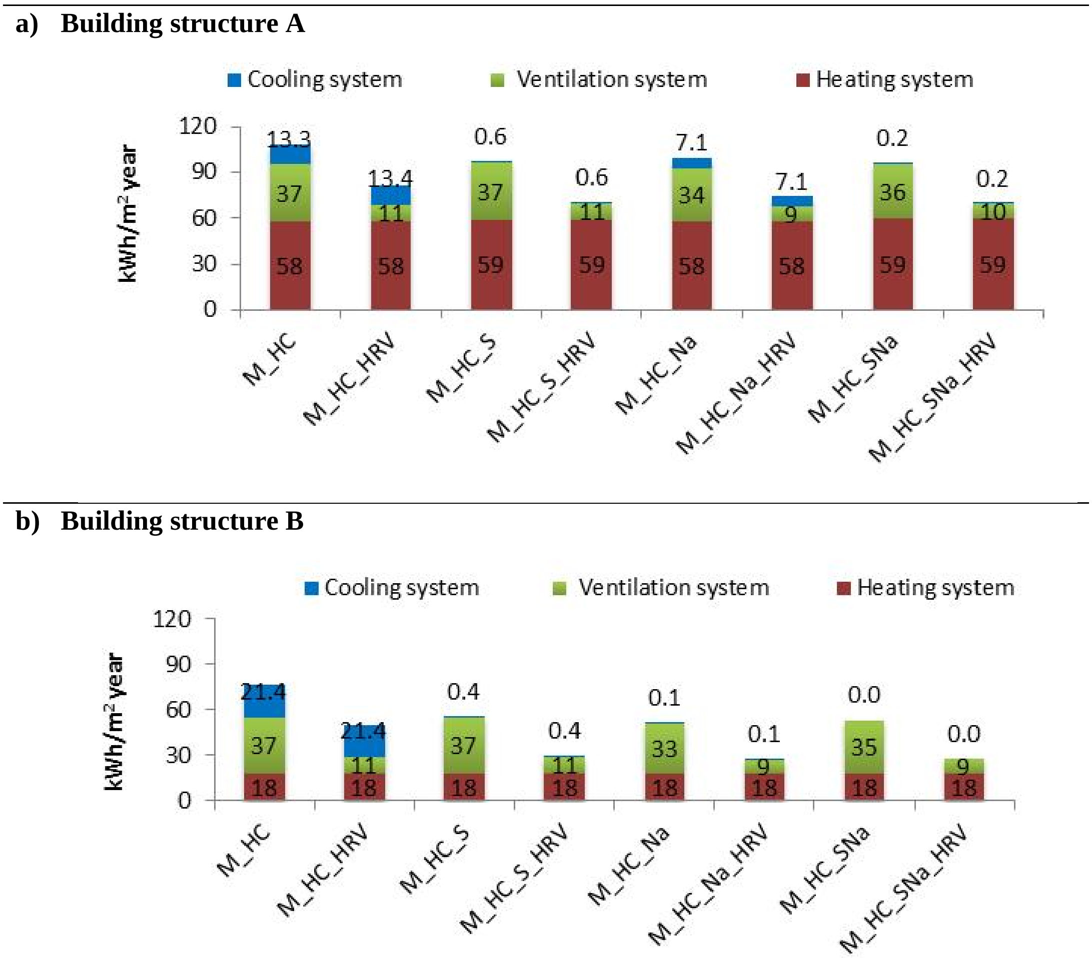


Figure 5. Energy demand divided by the three systems for M_HC_HRV and M_HC_SNa_HRV models for both structure A and B.

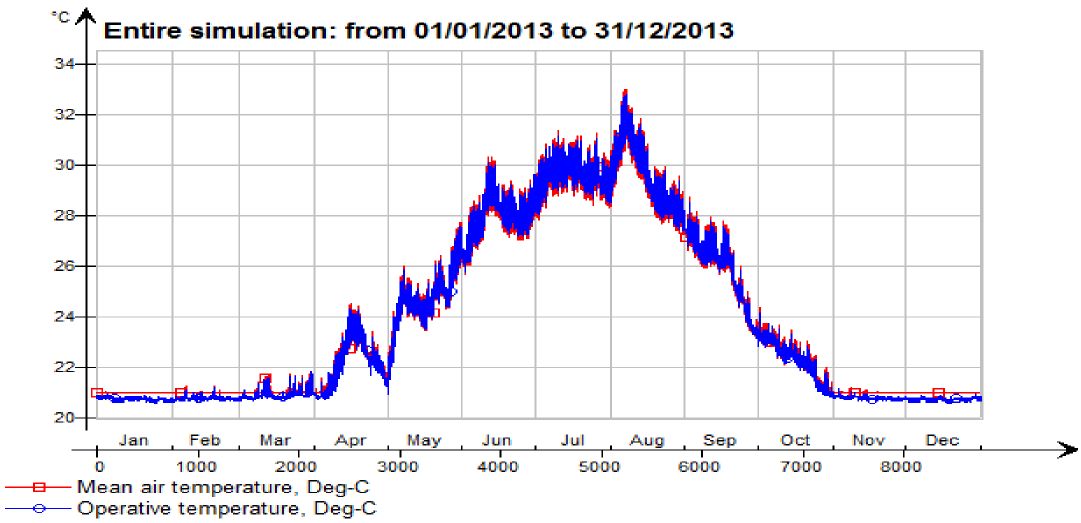
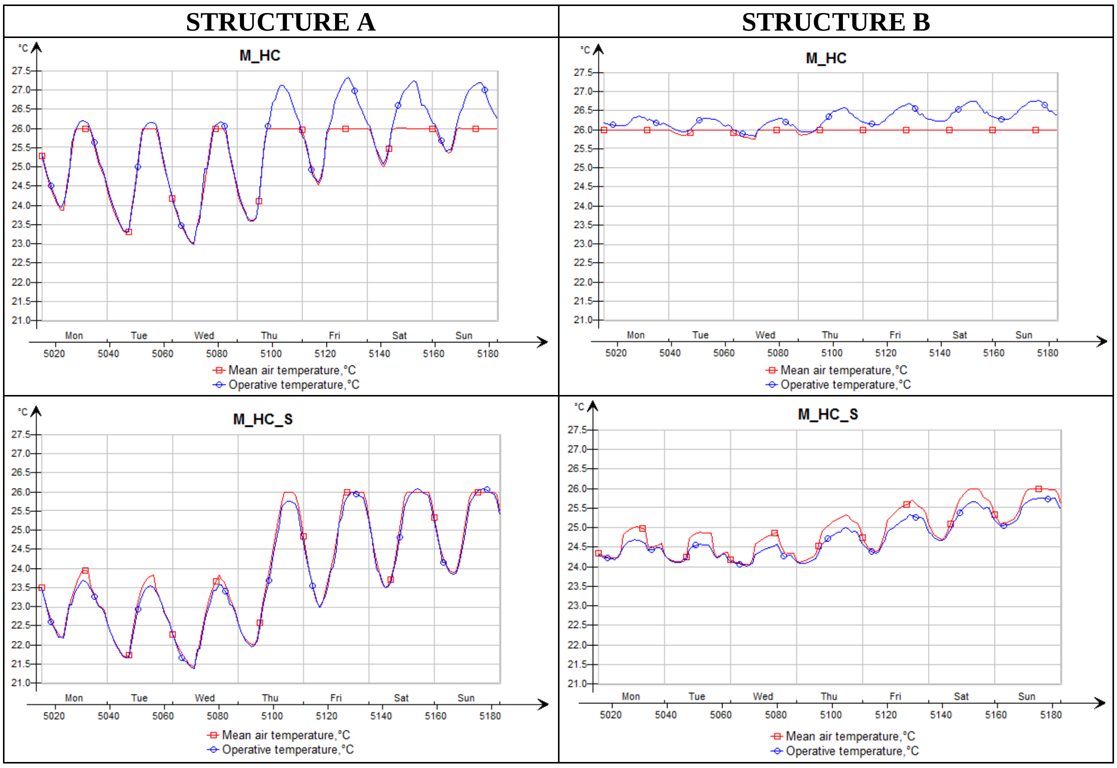


Figure 6. Indoor temperature variation in highly insulated building structure B.

The performance of the two buildings structure with applied different type of simulated systems was again evaluated according the indoor temperatures variation.

In Figure 7 are shown air and operative temperatures variation of one of the warmest week of the year (end of July and beginning of August). Among the two building´s structure it can be observed higher day-night temperatures´ variation, in the range of 3.5 ˚C - 4.5 ˚C, in building A (see Figure 7 left side), while the results of the higher insulation used in the building envelope B (Figure 7 right side) turned in a more constant air temperature, with an amplitude variation of 0.5 ˚C -1.5 ˚C, and an increased operative temperature due to the entrapped heat from solar radiation through the wider windows surface. The capacity of building B to achieve less temperature variation, with operative temperature below 26 ˚C, was achieved when the solar shading strategy was applied (M_HC_S), which it did not comply with the best results in term of energy saving observed in M_HC_Na simulation.

Finally, by combining the results obtained when observing the indoor operative temperature and the lower energy demand, the desired building model resulted to be the one with integrated both passive strategies (M_HC_SNa_HRV). However, when lowering the temperature during the night it not causing any thermal discomfort, the night-time cooling of indoor air and indoor building structures (precooled building thermal mass for the benefit of cooling on the following day) it can be freely performed by the natural night ventilation (model M_HC_Na) which can also contribute to a better indoor air quality.



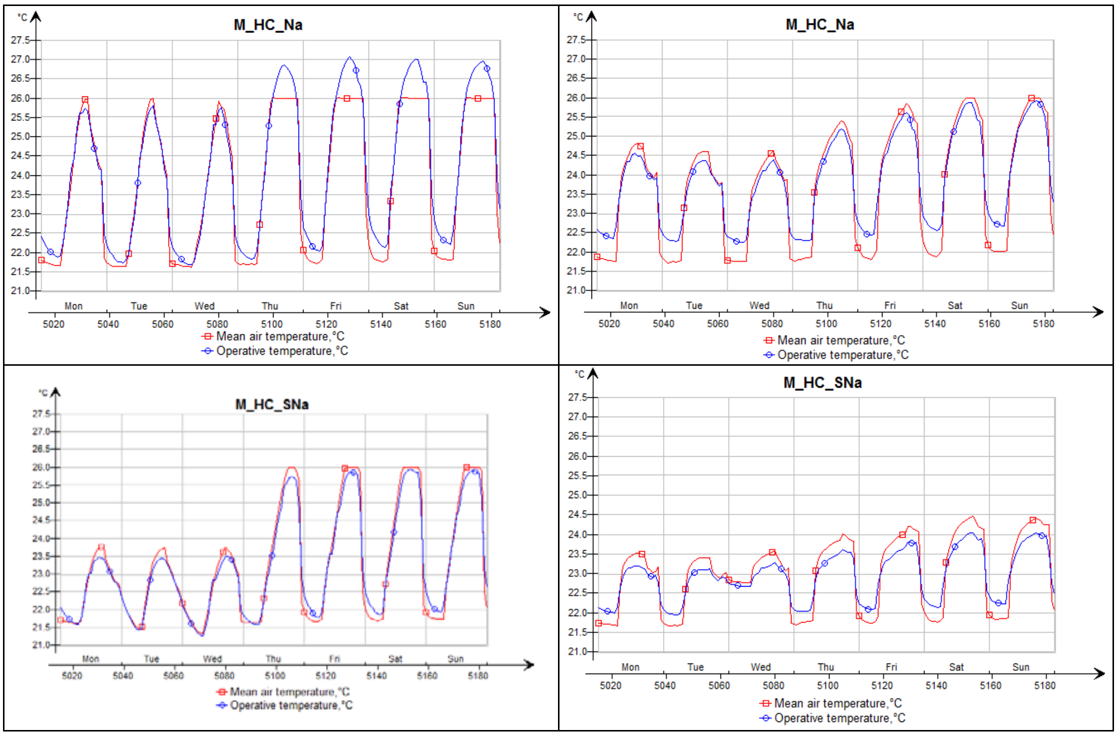


Figure 7. Air and operative temperature variation of all study cases of building A (on the left) and building B (on the right)

When the solar shading strategy is applied, alone or combined with the use of nighttime natural ventilation, the percentage of the windows coverage resulted from the simulations is reported in table 5. The use of the shading resulted more dominant for the more insulated building B, in particular when it was considered as the only cooling strategy. Those values should be considered important for countries like Denmark with low sunshine hours, where it can make the habitants reluctant on the use of the solar shading strategy looking for alternative cooling systems.

Table 5. Percentage of windows coverage when solar shading strategies are applied

Case studies	Solar shading coverage [%]					
	Structure A			Structure B		
	<50%	>50%	100%	<50%	>50%	100%
M_HC_S	84	16	6	68	32	16
M_HC_SNa	87	13	4	82	18	1

If the natural night ventilation was considered as cooling strategy, alone or combined with the use of solar shading, the period of its working time was estimated and, as reported in table 6. It is evident that, to avoid overheating, the nighttime ventilation should also be applied during the mid-seasons, starting already from April. Besides, to cool the higher insulated building, higher air change rate (ACH) needed to be guarantee which could result in higher indoor air velocities.

Table 5. Natural night ventilation parameters

	Period		ACH [1/h]	
Case studies	Structure A	Structure B	Structure A	Structure B
M_HC_Na	Apr 12th -Sept 17th	Apr 14th - Sept 19th	1.3	3.4
M_HC_SNa	May 4th - Aug 29th	May 5th - Sept 16th	1.3	2

6. NIGHT VENTILATION: NATURAL vs MECHANICAL

The use of nigh-time ventilation for cooling was more analyzed and, at the same time, due to some drawbacks connected to the windows opening, it was directed on bringing the outside colder air inside through the mechanical ventilation system.

The possibility of using the nighttime cooling potential by an active strategy (mechanically assisted) instead of a passive one (windows opening) rise the need of evaluating the impact on the indoor environment and on the energy demand.

Referring to a period of 4 months (May-September), the simulated model with nighttime ventilation through windows opening (Na) was implemented by the only use of the mechanical ventilation with higher air change rate (MNa) and applied at building B higher insulated. As expected, results showed slightly higher energy demand for ventilation with 11.5 kWh/m^2 year in MNa-model instead of 9.4 kWh/m^2 year with Na-model, having both satisfying the cooling demand that was nullified.

The provided air change rates at nighttime through those simulated models are shown in Table 7, having a lower average 0.8 h^{-1} in MNa than 1.8 h^{-1} in Na model.

Table 7. Night-time air change rate when mechanical assisted (MNa) or only natural (Na) ventilations were simulated

Nighttime ventilation model	ACH [h^{-1}]		
	average	maximum	minimum
MNa	0.8	1.1	0.6
Na	1.8	18.5	0.6

The operative temperatures variations resulted most of the time higher when the active ventilative strategy (MNa) was applied than the passive one (Na). The temperature difference could reach 1.5-2 ˚C as shown in the temperature variation of August reported in Figure 8. The temperatures difference was attributed to the effect of higher air change rate with the windows opens which increased the utilization of building thermal mass.

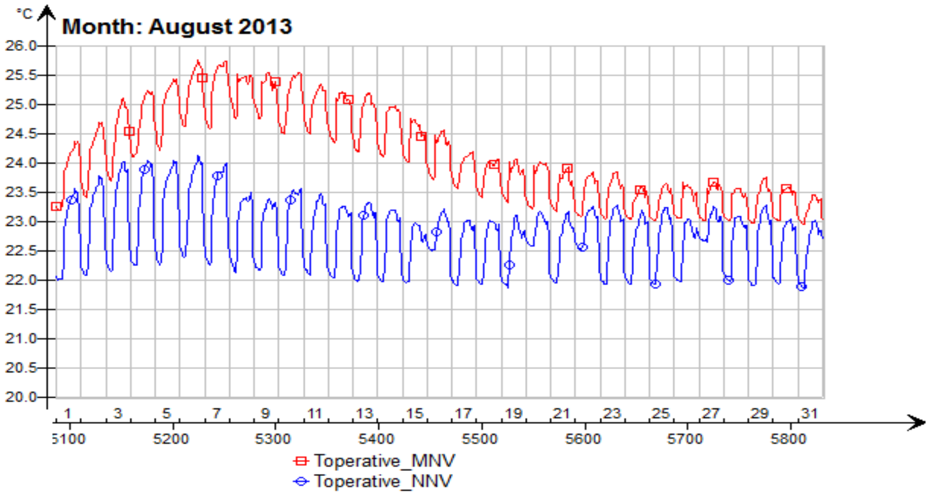


Figure 8. Operative temperature variation for MNa and Na simulated models in August

7. CONCLUSION

Moving towards zero energy buildings make the building construction more and more airtight and higher insulated. In this work a model of a residential low energy building has been considered and implemented. Simulations of two buildings type, located in the cold climate of Copenhagen, showed an additional 69% of energy saved on heating, while it increased the energy demand for cooling of 21.4 kWh/m^2 year. This result highlight the incoming overheating issue and indoor thermal discomfort, which, associated to the increasing outside temperature from climate change, may only increase and, if not controlled, end in higher building energy consumption.

The passive cooling strategies, as solar shading and nighttime ventilation, separately and coupled, and the heat recovery ventilation were implemented in the simulated buildings´ model. Results showed the lowest energy consumption (46.3 kWh/m^2 year) occurred when the only night-time natural ventilation, in the higher insulated building, was applied. However, the best solution in terms of energy demand and indoor environmental quality was the model (M_HC_SNa_HRV) with both passive strategies application in which the cooling demand was satisfied with environmental/energy friendly solutions.

The performed simulations confirmed the higher importance of solar shading application for the highly insulated buildings in summer time, which may not be the well accepted by the buildings´ occupants. As consequence, the use of night-time cooling ventilation was more focused. The use of the outside colder air was studied under two different conditions: when introduced inside by the windows opening or through the mechanical ventilation system supported only by a fan having higher air change rate (up to 1 h^{-1}). There was a small increase of energy demand due to the fan operation which it didn´t impact on the cooling need, in any case satisfied.

The increased air change during the night through the mechanical system can help to eliminate some drawbacks (e.g. security, rainy nights, noise, etc.) and, combined with the higher insulated building, resulted in a constant indoor temperature daily kept just below 26 ˚C. However, the natural night ventilation through the windows opening resulted in a constant and desired indoor temperature of 24 ˚C requested in previous studies.

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