ENERGY USE CONSEQUENCES OF VENTILATIVE COOLING IN A ZEB RESIDENTIAL BUILDING

Maria Justo Alonso*[1], Cathrine Kirkøen[2] and Hans Martin Mathisen[2]

1 SINTEF Building and Infrastructure
Alfred Getz v 3
7465 Trondheim, Norway
**Corresponding author: maria.justo.alonso@sintef.no*

2 Norwegian University of Science and Technology,
Kolbjørn Hejes vei 1b,
7491 Trondheim - Norway

Note: the contact addresses may be re-arranged

ABSTRACT

New buildings have to satisfy ever-tightening standards regarding energy efficiency and consumption. This results in higher insulation levels and lower air leakages that reduce heating demands. However, even at moderate outdoor temperatures these buildings are easily warmed up to such a degree that in order to ensure acceptable indoor environment quality, removal of excess heat becomes unavoidable. Use of electric energy related to mechanical cooling is considered incompatible with achieving zero energy buildings (ZEB). The use of ventilative cooling (VC) in combination with mechanical cooling means energy consumption reduction due to lower use of mechanical ventilation and cooling system.

This paper examines the application of ventilative cooling solutions in cold climates through simulations of an existing detached single family house in Norway, the ZEB Living Lab at NTNU/SINTEF. The house has computer controlled motorized windows. This will enable natural ventilation in some part of the year and could then reduce the energy use of fan power. The openable window are placed at the north and south facades and this enables considerably cross ventilation and also stack ventilation as some windows are placed four meters high.

IDA ICE program will be used to calculate the energy consumption of the baseline simulation: demand controlled ventilation with variable air volume and mechanical cooling. By means of using controlled window opening angles in IDA ICE it is possible to calculate the energy consumption while using hybrid mode ventilation.

Results show significant energy savings when using ventilative cooling. Due to the low outdoor temperatures in Norway the use of ventilative cooling remove mechanical cooling demands almost completely. The reference for comparison has been the European standard EN15251 (class II).

Ventilative cooling is proven to be relevant in combination with mechanical ventilation and will be crucial to achieving energy targets for new zero energy buildings while the indoor climate is maintained.

KEYWORDS

Ventilative cooling, energy saving, simulations IDA ICE, motorized window opening

1 INTRODUCTION

Standards for construction and refurbishment of buildings are increasingly demanding regarding energy efficiency and reduced energy consumption. Demands on the insulation level and reduced air leakages have reduced heating demands. However, this high level of insulation becomes an intrinsic heat and solar gain trap even when heating is not needed. Overheating is more often experienced and in such cases to sustain an acceptable indoor climate, removal of excess heat becomes a need. Ventilation has an important role in a building's indoor air quality (IAQ) and comfort (Sundell, 2004). People's trend of spending most of their time indoors (Lück, 2012) makes IAQ requirements become more important. Heating, ventilation and air-conditioning systems (HVAC) are responsible for 39% and 31% of primary energy end-use in residential and commercial sector respectively (Solutions, 2011). Nielsen studied cooling demands in a Danish low energy house and concluded on peaks of up to $60W/m^2$, that can be reduced when having appropriate solar shading to $25W/m^2$ (Nielsen, 2011). When the building does not have any cooling means, 30% of the time temperatures would be over 26 degrees (Nielsen, 2011). Melcnik (Mlecnik et al., 2012) did some post occupancy questionnaires and concluded that 34% of his respondents experienced eventual high indoor temperatures in the living room and 49% complained about bedroom over temperatures during summer. (Samuelsson, 2009) research revealed dissatisfaction in users of passive houses in Sweden due to over temperatures. In particular, more than 50% of the residents reported that it was too hot in the summer. The same conclusions are obtained by Kleiven for Norway (Kleiven, 2007).

The removal of surplus heat is often done through mechanical cooling (MC). However, energy consumption related to MC is considered incompatible with realizing zero balance. As a response, the use of Ventilative cooling solutions (VC) is settling (Venticool, 2013). VC refers to the use of ventilation air in order to reduce or eliminate the need for mechanical cooling. VC can be applied through both mechanical and natural ventilation strategies, or as a combination of the two strategies. To achieve efficient VC while ensuring an acceptable thermal climate, one should include measures that provide minimization of heat gains. (Oropeza-Perez & Østergaard (2014) studied through validated simulations of a passive house. Using natural ventilation as VC could reduce the number of hours when mechanical ventilation was needed with 90.4%. This resulted in a 37.5% reduction in energy use.

Natural ventilation is considered one of the most effective techniques for cooling whenever outdoor temperatures are lower than indoor temperatures. Also when adaptive comfort criteria can be applied to switch between mechanical and natural ventilation to reduce energy consumption while preserving satisfactory indoor climate(da Graca, Chen, Glicksman, & Norford, 1999).

VC should therefore be perceived as an integrated part of an overall system including solar shadings, minimization of internal heat gains and intelligent use of thermal mass (Venticool, 2013) should be combined with night set back.

This work examines the application of ventilative cooling in cold climates through simulations of an existing residential building (Living lab) in Norway. This building has the ability to be ventilated through mechanical ventilation and hybrid mix mode ventilation with motor controlled windows.

The overall scope of this paper is to evaluate the performance of the Living Lab ventilation solution concerning thermal comfort and energy consumption. Further, it is to compare the results against conventional all-mechanical (no cooling) ventilation systems to evaluate the most energy-efficient solution without compromising the IAQ and comfort.

2 LIVING LAB

The Living Lab is representative of the Norwegian residential building stock regarding typology (detached, single family house) and surface, while integrating state-of-the-art technologies for energy conservation and solar energy exploitation.

The test facility is a single family house with a gross volume of approximately 500 m^3 and a heated surface (floor area) of approximately 100 m^2. The data acquisition system is primarily designed to be able to measure energy demand for heating, ventilation, lighting and appliances, as well as renewable energy harvesting by means of a roof-integrated PV system and of façade-integrated solar thermal panels. Accumulation tanks and indoor environment are also fully monitored.

Table 1 - Thermo-physical properties of building envelope components

Thermo physical properties	
U-value wall	0.11 W/m^{2}K
U-value floor	0.10 W/m^{2}K
U-value roof	0.10 W/m^{2}K
U-value windows (south façade)	0.65 / 0.69 (when ventilated) W/m^{2}K
U-value windows (north façade)	0.97 W/m^{2}K
U-value windows (east-west façade)	0.80 W/m^{2}K
U-value skylight	1.0 W/m2K
g-value for windows	0.5-
Air tightness, n_{50}	0.5 ach

The ventilation is designed as a mixed-mode hybrid system with mechanical balanced ventilation. Supply air terminals are located in the living room and in the bedrooms; extract in the bathroom and kitchen. A heat wheel unit with efficiency of 85% at nominal value and a hydronic heating coil capable of warming up the inlet air up to 40^{o}C are installed (Finocchiaro, Goia, Grynning, & Gustavsen, 2014). The dwelling has operable windows on every facade in order to profit from both stack and cross flow ventilation through mechanical opening of windows.

On the North side an elongated window is implemented. It is constructed with hinges at the top, and opens towards the interior to a maximum angle of 39˚. On the West and East side there are glass sliding doors. Two sets of rooftop skylight tripled glazed windows facing north have been implemented. They open horizontally to a maximum angle of 30˚. The South windows open a maximum of 37˚.See **Error! Reference source not found.**.

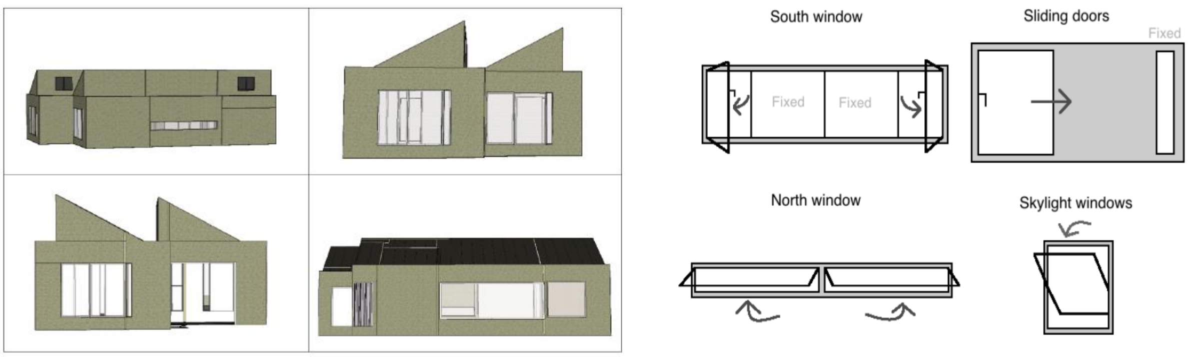

Figure 1:(a)Placing of windows in the Living Lab (b) Window opening in the Living Lab

3 SIMULATIONS

3.1 Window control

For calculations, the simulation program IDA ICE was used. The calculation period was the warmest week in Trondheim (Norway) in IDA ICE's climate TMY year. Preliminary simulations to determine the warmest and coldest room have been done so that these rooms are used for comparison. Six different strategies for control of thermal comfort were compared; afterwards the energy consumption was analyzed. The opening of windows combines with mechanical ventilation. In case of too low outdoors temperatures mechanical ventilation ensures hygienic ventilation rates. To analyze thermal comfort, the number of hours with overheating and over cooling have been studied For determination of these temperatures, optimization was based on natural ventilation.

Table 2 shows an overview of the performed simulations to define how to control windows and ventilation system to maximize the effect of ventilative cooling.

Table 2: Overview of simulations performed to determine how to apply ventilative cooling

Study	Tested solutions	Outcome
How to apply window control: Set point temperatures for opening	Various set-point temperatures for the window control systems	Set-points On/off control, Daytime exclusively Set-points On/off control, Night-time exclusively Set-points On/off control, All hours Set-points PI-Control, Daytime exclusively Set-points PI-Control, Night-time exclusively Set-points PI-Control, All hours
How to apply window control: Active window period	On/off control, Daytime only On/off control, All hours PI control Daytime only PI control, All hours	Best of the On/off control solutions Best of the PI control solutions Most influencing factors for window opening
How to apply ventilative cooling	Natural ventilation On/off control Concurrent On/off control Change-over On/off control Natural ventilation PI-control Concurrent PI-control Change-over PI-control	Best ventilative cooling solution

The first challenge to solve is the determination of the set point temperatures to control the window opening. These are chosen based on the type of control. For a more reactive control, three temperatures are defined for the PI control. For on-off control only two temperatures are selected. For both types of control, the goal is to minimize the number of hours with overheating and with overcooling. Table 3 and **Error! Reference source not found.** show the allowed hours of opening and the windows working for providing ventilative cooling.

Table 3: On Off control

Type	Hours applied	Windows utilized	Control signal design
VC Day	07.00-23.00	South + Skylight	Tzone < T1 -> closed Tzone > T1 -> open until T2 is reached
VC Night	23.00-07.00	South + Skylight Kitchen only	Tzone < T3 -> closed Tzone > T3 -> open until T4 is reached
VC All hours	All day long	South + Skylight (-23-07 Loft)	Tzone < T5 -> closed Tzone > T5 -> open until T6 is reached

The windows were frequently opened on sunny days regardless of the occupancy, outdoor temperature and presence of wind. For cloudy days, windows were frequently used for all set-point solutions when outdoor temperatures were high and the building was occupied. For cloudy days and low outdoor temperatures, windows were rarely open regardless of the occupancy schedule and wind.

Table 4: PI control

Type	Hours applied	Windows utilized	Control signal design
VC Day	Weekday:07.00-23.00 Weekend:09.00-24.00	South + Skylight + North (-08-17 weekdays)	Tout < 15 °C -> Hold T7 15 °C < Tout < 20 °C -> Hold T8 20 °C < Tout -> Hold T9
VC night	Weekday:23.00-07.00 Weekend:24.00-09.00	South + Skylight Kitchen only	Tout < 15 °C -> Hold T10 15 °C < Tout < 20 °C -> Hold T11 20 °C < Tout -> Hold T12
VC All hours	All day long	South + Skylight(-23-07 weekday - 24-09 weekend Loft) + North(-08-17 weekdays)	Tout < 15 °C -> Hold T13 15 °C < Tout < 20 °C -> Hold T14 20 °C < Tout -> Hold T15

The analysis of the optimal window control temperatures was based on results regarding overheating and overcooling. For overheating the number of hours over 24, 26 and 28 °C in the living room were used, and the maximum temperatures in the attic. For overcooling, the number of hours with temperatures below 20 °C in living room and kitchen and their air velocities were considered as these show overcooling and draft. Based on these, Table 5 shows the control temperatures and the general performance of the control.

Table 1: Overview of the thermal comfort achieved for each tested window control solution

Control	Temperatures and corresponding thermal comfort		
On/off daytime exclusively	(25-20)°C, (24-20)°C or (23-20)°C Poor	25-22°C Good	24-22 °C Best
On/off night-time exclusively	(22-20)°C or (20-19)°C Poor		
On/off all hours	(25-20)°C, (24-20)°C or (23-20)°C Poor	25-22 °C Good	24-22 °C Best
PI exclusively daytime	(22-24-26)°C, (21-23-26) °C or (20-22-26)°C Poor	23-23-26°C Good	23-24-26°C Best
PI exclusively night time	(20-20-21°C) or (19-19-20°C) Poor		
PI all hours	(22-24-26) °C,(21-23-26) °C or (20-22-26) °C Poor	23-23-26°C Good	23-24-26°C Best

According to the analysis of the results, the most influencing factors on the need for ventilative cooling at the Living Lab were: solar radiation, outdoor temperature and occupancy. The wind does not appear to have influence on the need for cooling but influences the efficiency of ventilative cooling.

3.2 Interaction between ventilative cooling and mechanical ventilation

The use of concurrent mechanical ventilation and window opening was compared to its use in change-over (meaning either windows opening or mechanical ventilation). For the concurrent

systems, the best on/off and PI window control systems were combined with mechanical ventilation so that constant hygienic mechanical ventilation flow rate was provided.
For the change-over systems, hygienic ventilation was provided either by the best performing on/off and PI window control systems or mechanical ventilation. Hence, both systems were decoupled when ventilative cooling was utilized. An additional control system was constructed to turn off mechanical ventilation when windows were open. The central AHU unit in IDA ICE is initially not able to retrieve signals indicating window opening position. Therefore, an on/off mechanical ventilation system had to be implemented for each zone. It was designed so that if one or more windows in the current zone were open, the mechanical ventilation in that particular zone would be turned off. A ventilation system with this design does no longer ensure a balanced mechanical ventilation system.

Ventilative cooling and on-off control

The results show that both solutions resulted in good thermal comfort, the results regarding overheating and overcooling were similar.

Table 5: Results from annual simulations using the on/off window control system.

Energy	Concurrent Mechanical and On/off window control	Change-over Mechanical and On/off window control
Recovery [kWh]	4798	4769
Zone heating [kWh]	5470	5489
AHU heating [kWh]	242	245
Fan energy [kWh]	1095	1052
Lighting [kWh]	1083	1083
Equipment [kWh]	1116	1116
Total energy demand [kWh]	9004	8984

The hours of overheating were the same for the two systems. The change-over system resulted, however, in slightly more hours of overcooling compared to the concurrent zoned system. The change-over system was designed to only turn off the mechanical ventilation units in the rooms that had open windows. This creates an unbalance in the mechanical ventilation and creates a more unpredictable and unstable system (also resulting in a small reduction on the efficiency of the heat wheel).
When comparing energy demand for both solutions, the differences in energy demand of both systems were not significant. The change-over system resulted in only slightly less energy demands than the concurrent system.
Mechanical ventilation was always in operation for the concurrent system. This should have resulted in a bigger increase in energy use for fans compared to the change-over system.
However, since the change-over system was designed as a zoned system, it only turned off the mechanical units in some of the rooms 10.8% of the time. The difference in energy use for fan operation was therefore not substantial. The pure natural ventilation (in change-over mode) was only utilized 13.2% of the time. For the remaining parts of the year there would be no air exchange except from infiltration though this is expected to be low in such a highly insulated building like Living Lab. The concurrent solution is expected to have the best indoor air quality because it operates mechanical ventilation constantly. It is also considered to be less complex than the change-over system. This is because the window control system and the mechanical ventilation system operate independently. Also, the concurrent system does not jeopardize the balancing of the mechanical ventilation system. Since all solutions provided good thermal comfort and the differences in energy demand for the mixed-mode systems were

not significant, the concurrent system solution was deemed the best ventilative cooling solution utilizing on/off window control.

Ventilative cooling using PI window control

The results from the whole year simulations of both ventilative cooling solutions utilizing PI window control are presented in Table 2.

The results regarding overheating were similar to those obtained when using on/off window control. There were very few hours of overheating. However, different results regarding overcooled hours were obtained. The results show that the risk of overcooling was significantly increased when utilizing the PI window control system. Since the window control system had a simpler design, applying mechanical ventilation system improved the situation. Use of mechanical ventilation reduced the need for natural ventilation, hence reducing the amount of overcooled hours.

Table 2: Results from whole year simulations using the PI window control system.

Energy	**Concurrent Mechanical and PI window control**	**Change-over Mechanical and PI window control**
Recovery [kWh]	4808.50	4137.4
Zone heating [kWh]	5470.4	6038.3
AHU heating [kWh]	243.0	177.9
Fan energy [kWh]	1094.9	943.7
Lighting [kWh]	1083.0	1083.0
Equipment [kWh]	1116.0	1116.0
Total energy demand [kWh]	9007.0	9358.9

The difference in energy demand for both systems was not significant in this case either. However, opposed to the on/off solutions, the change-over system obtained slightly higher energy demand than the concurrent system. In this case, the increase in energy use for the zone heating was bigger than the decrease in energy use for fans. The concurrent system was also deemed the best solution for ventilative cooling utilizing PI window control. Both solutions provided approximately equally thermal comfort and the differences in energy demand between the mixed-mode systems were not significant.

As explained for the on/off solutions, the concurrent system is expected to provide better indoor air quality. It is also less complex than the change-over system.

4 CONCLUSIONS

The results from the simulations implied that there will be a severe risk of overheating in Living Lab if no active or passive cooling techniques are applied. The results showed nonetheless that ventilative cooling can prevent overheating without significantly increasing the energy demand. Due to the uncertainties related to increased air velocities, it was not possible to eliminate the risk of overcooling caused by ventilative cooling completely.

However, the study showed that the amount of hours with overcooling could be held at an acceptable level. The simulations revealed that nighttime ventilative cooling had no positive effect on the thermal environment in Living Lab. This building has low thermal mass and the control was built so that windows were not open during the day when most internal gains happen.

The study found that the best way to apply ventilative cooling in Living Lab would be to implement a concurrent mixed-mode system where the window control system is only active during the day. It should be designed to open the south and skylight windows to maximum opening when indoor air temperatures exceed 24°C and close them when indoor air temperatures drops below 22°C. The results revealed that this system would reduce the number of overheated hours recorded when not utilizing ventilative cooling with 99%. The number of overcooled hours would be kept at a moderate level, 48 hours/year. Utilizing this ventilative cooling system resulted in increased energy demand of 52 kWh/year compared to use of only hygienic mechanical ventilation.
In Trondheim (and by extension in cold climates) overheating in low-energy dwellings can be prevented with ventilative cooling. Ventilative cooling can have a significant positive effect on the thermal environment without having a significant negative effect on the use of energy. In some cases, energy consumption can even be reduced when applying ventilative cooling. Overcooling can be an issue when utilizing ventilative cooling in these cold climates. A careful design process is required for ventilative cooling to have the desired effect. The process should be individual for each building and climate. A more complex natural ventilation system requires a more accurate and careful design process. Also, the acceptable indoor temperatures for mechanically ventilated buildings often have to be adjusted for buildings intended to utilize ventilative cooling. An automatic window control system is often necessary for ventilative cooling to achieve the desired thermal environment.

5 ACKNOWLEDGEMENTS

This work has been supported by the Research Council of Norway and several partners through the SINTEF/NTNU “The research centre of Zero Emissions Buildings” (ZEB). Grant number 193830. And the industrial project Ventilative Cooling with ENOVA.

6 REFERENCES

da Graca, G. C., Chen, Q., Glicksman, L. R., & Norford, L. K. (1999). Simulation of wind driven ventilative cooling in an apartment building in Beijing and Shanghai. *Ishvac 99: 3rd International Symposium on HVAC, Vols 1 and 2*, 648-658.

Finocchiaro, L., Goia, F., Grynning, S., & Gustavsen, A. (2014). *The zeb living lab: a multi-purpose experimental facility*. Paper presented at the IEA EBC Annex 58 Expert Meeting, Ghent.

Kleiven, T. (2007). Brukerunderskelse i husby amfi. In S. Byggforsk. (Ed.).

Lück, K. (2012). Energy efficient building services for tempering performance-oriented interior spaces – A literature review. *Journal of Cleaner Production, 1-10*.

Mlecnik, E., T.Scutze, Jansen, S., de Vries, G., Visscher, H., & van Hal, A. (2012). End-user experiences in nearly zero-energy houses. *Energy and Buildings*.

Nielsen, L. S. (2011). Heating and cooling challenge in nZEB Experiences from built houses and detailed building simulations calls for a careful and integrated approach when designing heating and cooling systems for nearly zero energy buildings. *REHVA Journal*.

Oropeza-Perez, I., & Østergaard, P. A. (2014). Potential of natural ventilaton in temperate countries - a case study of Denmark. *Energy and Buildings*.

Pérez-Lombard, L., Ortiz, J., & Pout, C. (2008). A review on buildings energy consumption information. *Energy and Buildings, 40* 394-398.

Samuelsson, M. a. L., T. . (2009). *Passive houses from a users perspective.*

Solutions, C. f. c. a. E. (2011). Building Envelope.

Sundell, J. (2004). On the history of indoor air quality and health. *Indoor Air, 14, 51 – 58*.

Venticool. (2013). The international platform for ventilative cooling.