COMBINING A BUILDING SIMULATION WITH ENERGY SYSTEMS ANALYSIS TO ASSESS THE BENEFITS OF NATURAL VENTILATION

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ABSTRACT

This article shows the combination of a thermal-airflow simulation program with an energy systems analysis model in order to assess the use of natural ventilation as a method for saving energy within residential buildings in large-scale scenarios. The aim is to show the benefits for utilizing natural airflow instead of active systems such as mechanical ventilation or air-conditioning in buildings where the indoor temperature is over the upper limit of the comfort range. The combination is done by introducing the energy saving output - calculated with a model of natural ventilation using a thermal-airflow simulation program - into the energy systems analysis model. Descriptions of the energy systems in two geographical locations, i.e. Mexico and Denmark, are set up as inputs. Then, the assessment is done by calculating the energy impacts as well as environmental benefits in the energy systems analysis. Results show that for an energy system such as the Mexican, with a relatively simple connection between supply and demand of electricity, natural ventilation mainly creates savings, whereas in the Danish system, the system operation is also affected by energy savings through natural ventilation.

INTRODUCTION

The potential cooling demand in both commercial and residential buildings is increasing over the time, both in developed and developing countries (Seo *et al.*, 2012; Sivak, 2009).

Regarding developed countries, in US for example, in 2011 there was a consumption of 440 TWh for cooling buildings; 273 TWh for the residential sector and 167 TWh for the commercial sector (U. S. Energy Information Administration, 2012).

On the other hand, 38 of the 50 largest metropolitan areas in the world are located in developing countries. Of them, 27 are in warm to hot climates (Sivak, 2009) thus their buildings need to be cooled somehow.

For supplying this demand, active cooling methods such as air-conditioning (AC) and fans often claim to be as the only mean to reach thermal comfort – especially during the warm season. However, these technologies could be very energy consuming. As previous assessments point, in developing countries, residential AC alone could consume more electricity than the total remaining consumption of the dwelling (Ekwall, 1991).

Furthermore, electricity production from fossil fuels in many countries is commonly used (Maruyama *et al.*, 2009) making that these fuels could disappear in the coming decades leaving coal as the only fossil source. Before the exhaustion of these resources, increasing costs, due mainly to the scarcity of them, it will make very difficult their purchase at reasonable prices. It will therefore become too expensive to operate active cooling methods (Bastide *et al.*, 2006).

In addition, the use of this kind of technology enhances the emission of greenhouse gases to the atmosphere (Caldeira *et al.* 2003; Dincer *et al.*, 1998).

Hence, a manner to cool down buildings without using great amounts of energy must be found out; otherwise, comfort and/or health issues among the occupants could arise.

For the right environmental conditions, buildings with controlled natural ventilation can be one of the ways to obtain thermal comfort while maintaining low levels of energy consumption (Allard, 2002; Etheridge, 2012).

In order to assess the benefits for using such a passive cooling method on a given large-scenario it is necessary to estimate the potential energy saving. Then, an analysis of its influence within the corresponding energy system can be carried out.

With that, a further analysis could be made thus it will be more elements to drive the best strategy of controlled natural ventilation in different scenarios.

The relevance of this is to measure the actual scope of the potential within energy systems which have different cooling demands, sources of electricity generation and lines of distribution, among others. If there is an energy saving potential by using natural ventilation, it affects in different manners the energy systems which have particular generation methods, distributions and electricity demands.

SIMULATION

In this paper Energy Plus (U. S. Department of Energy, 2012) is used as the building simulation program to estimate the energy saving potential and EnergyPLAN (Aalborg University, 2012) as the energy systems analysis program.

The methodology is divided into three parts: the building simulation, the energy systems analysis and the combination of both.

Building simulation

The building simulation for the thermal analysis of natural ventilation is run with a model which takes account of a set of inputs (Oropeza-Perez *et al.*, 2012). This set is divided in three main groups: behavior of the occupants, building design, and outdoor conditions. Each one of them has the following data.

Behavior of the occupants

- Number & schedule of occupants
- Use of electric devices
- Windows opening & solar shading operation
- Temperature set point

Building design

- Materials of construction
- Building shape & orientation
- Openings size, shape & orientation
- Surroundings
    - Adjacent constructions & trees
- HVAC systems
    - Air-conditioning
    - Fans
    - Heating systems
    - Etc.

Outdoor conditions

- Outdoor temperature
- Relative humidity
- Wind speed & direction

With the simulations run by Energy Plus – choosing its simplified natural ventilation model because the purpose is to analyze the saving into a large-scale scenario - the calculation method proposed in this article is then the estimated electrical energy saving given by the difference between the cooling energy demand without natural ventilation – which is validated with data from literature – to the cooling energy demand with natural ventilation.
However, one must take into account that, due to the complexity of natural ventilation, the model could have some limitations, especially into a small-scale scenario.

Assessment of the energy saving potential under warm conditions

The proposed method has two main approaches: under warm conditions and under cold conditions. For the first one an air-conditioning system with varying demand is considered.
The thermal energy balance in the zone air is given by Eq. (1) assuming that the indoor temperature is well mixed (Etheridge, 2012):

$$\rho c_p V \frac{dT}{dt} = E_{Conv} + E_{Int} + E_{AC} + E_{Vent} \quad (1)$$

To estimate the energy saving potential, the active cooling method demand without natural ventilation must be calculated. Thus, E_{Vent} in Eq. (1) is left out, as well as the variation of the indoor temperature, since this temperature is considered constant through the time due to the use of the active cooling method

$$E_{AC} = -\sum_{i=1}^{n} h_{Conv} A_i \left(T_i - T_{Set-Point}\right) - E_{Int} \quad (2)$$

E_{AC} is calculated with Eq. (2) by using the given internal loads, variant by a schedule set-point, and the respective convective heat transfer calculated in every time-step of the simulations by Energy Plus setting a constant indoor temperature set-point and given as an output by the program.
When natural ventilation is applied, in Energy Plus the schedule of the openings is set in such a way that in every time-step it is possible to reach the temperature of comfort, i.e. the temperature set-point. In that case E_{AC} is considered with a value of zero. When it is not possible, it is assumed that the air-conditioning system is switched on therefore the energy rate of the air-conditioning using natural ventilation is given by Eq. (3).

$$E_{AC-Vent} = \rho c_p V \frac{dT}{dt} - E_{Conv} - E_{Int} - E_{Vent} \quad (3)$$

$E_{AC-Vent}$ is estimated in each case study with Eq. (3) by using its respective internal loads. The energy stored and convective heat transfer from the zone surfaces are given by Energy Plus as outputs. As the program is a coupling of the thermal balance with the airflow balance within the dwelling, E_{Vent} is calculated in every time-step.
A saving energy of air-conditioning is presented when $E_{AC-Vent}$ is minor than $E_{AC.}$ Therefore, the estimated hourly energy rate savings are given by the difference between the active cooling method demand without natural ventilation and the demand using ventilation.

$$E_{Sav} = E_{AC} - E_{AC-Vent} \quad (4)$$

For calculating the electricity demand, an average simplified coefficient of performance (COP) of the active cooling method system is given (Etheridge, 2012)

$$COP = \frac{|E_{AC}|}{|D_{AC}|} \quad (5)$$

Therefore, the energy saving could be calculated during a certain number of hours as

$$EnSav = \sum_{i=1}^{n} \frac{|E_{Sav}|}{COP} \cdot h \quad (6)$$

For this article two kinds of simulations were run. The first one is without natural ventilation setting a given temperature set-point and calculating the E_{AC} necessary to keep thermal comfort with Eq. (2). The second one is using natural ventilation and thus calculating the necessary air-conditioning cooling rate.

Assessment of the energy saving potential under cold conditions

For the second approach, i.e. under cold conditions, it is considered a fan with constant airflow as the active cooling method.
In this case it is found that is possible to reach the temperature of comfort by using natural ventilation. Therefore, $E_{AC\text{-}Vent}$ in Eq. (3) & (4) is considered with a value of zero.

$$E_{Sav} = E_{AC} \quad (7)$$

Thus, the energy saving could be calculated with a constant COP in the hours when the fan is turned off as

$$EnSav = \sum_{i=1}^{n} \frac{E_{Sav}}{COP} \cdot h = D_{AC} \cdot \sum_{i=1}^{n} h \quad (8)$$

As the approach under warm conditions, two types of simulations, i.e. with and without natural ventilation, were run. Furthermore, the simulations without natural ventilation were validated with measured data of a case study (Larsen *et al.*, 2012).
For both warm and cold conditions, the maximum indoor air temperature set-point is given by the European guideline EN 15251:2007 for residential buildings during the cooling season, i.e., 27°C (European Committee for Standardization, 2007). This standard was chosen because it gives a realistic comfort criterion for indoor conditions and is applicable to both warm and cold conditions.
Thereby, *EnSav* is calculated with Eq. (6) for warm conditions and Eq. (8) for cold conditions. Thereupon, the subsequent hour is calculated. The entire iteration could be carried out for a determined period of time. For this article, hourly calculations are done during one year. Furthermore, the inputs, e.g., outdoor temperature, COP etc., and boundary conditions, e.g., wind speed, are taken from the case studies.

Energy systems analysis

The energy systems analysis program, i.e. EnergyPLAN, relies on the characteristics of the energy system as the following:

Installed capacity

- Hydro power
- Nuclear
- Geothermal
- Waste-to-energy plant & CHP
- Landfill gas & other biogas
- Renewable energy
  - Wind power
  - Photovoltaic
  - Solar thermal
  - Ocean power
  - Biomass
  - Etc.
- Fossil fuel
  - Natural gas
  - Coal
  - Petroleum

Energy demand

- Cooling & heating demand
- Electricity demand

The energy systems analysis program models based on one hour steps throughout the modeled year. The program is developed with a focus on high renewable energy systems and thus includes parameters describing fluctuating energy sources and the variation in several demands including electricity, heat and transport. The model has been applied in a series of case studies (Alberg Østergaard *et al.*, 2010; Lund *et al.*, 2009; Østergaard *et al.*, 2011). However, it has never been focused on natural ventilation.

Cooling demand

EnergyPLAN makes the analysis based on the hourly distributions of the total annual cooling demand for each energy system.
These hourly data points are usually between 0 and 1 representing 0-100% of the demand. Furthermore, they must be 8784, i.e. 366 days.
Thus, for calculating this cooling demand, which is relative to the maximum yearly indoor temperature, Eq. (9) is developed.

$$CD = \frac{T - T_{set-point}}{T_{max} - T_{set-point}} \quad (9)$$

When the cooling demand (CD) is positive, it will vary from 0 to 1. And if it is negative, i.e. when indoor temperature is below the temperature set-point, CD is considered as a value of 0. Furthermore, when the maximum temperature is below to the temperature set-point, even though CD is positive, the cooling demand is considered as 0.

Combination

The assessment of natural ventilation could be carried out as is shown in Fig. 1.

The method links both programs by setting the annual cooling demand without and with natural ventilation into EnergyPLAN. The demand without ventilation is calculated with Eq. (2), which is validated by the literature, while the demand with ventilation is the difference between the calculated cooling demand and the energy saved with Eq. (6) & (8), as the case may be.

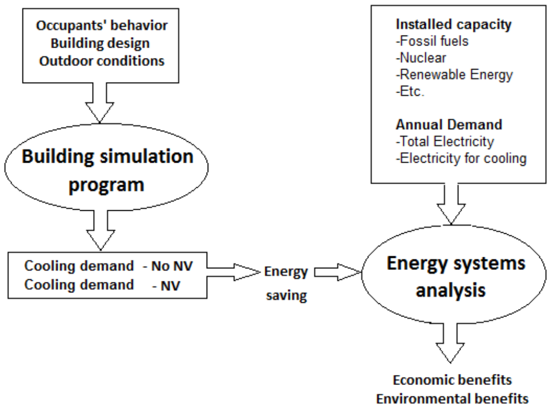

Figure 1 Method to assess natural ventilation

Also, the total annual electricity generation of each energy system and its proportions of installed capacity of the different electricity production means – nuclear, hydro, wind, coal etc. – are set as inputs.
As outputs of the entire method, there is among others the saved electricity demand distributed monthly as well as the CO_2 mitigation within the corresponding system.

DISCUSSION AND RESULT ANALYSIS

Two case studies in two different geographical locations, i.e. Denmark – cold conditions – and Mexico – warm conditions – are presented in this article. Both scenarios were analyzed within one year and both take the energy saving assessed for a national level.
In the case of Mexico, the assessment was carried out by performing thermal-airflow simulations of 27 common cases of households in the country – including features of occupants' behavior - by multiplying their proportional number arranged by location – outdoor conditions - and material of construction & size – building design - of the 4.5 million dwellings with AC in 2008 (Instituto Nacional de Estadística y Geografía, 2010), with a given general COP of 3.5 (Secretaría de Energía, 2009) finding a saving of 4.2 TWh in the residential sector for 2008. The cooling demand is found in 7.7 TWh, the same order of magnitude than the presented in literature in the same sector and year, i.e. 8 TWh for Mexico in 2008 (Rosas-Flores *et al.*, 2011).
In the Danish case, simulations were run within a given passive house thus the energy saving is an extrapolation of the potential for the rest of the Danish residential sector, i.e. 2.5 million of dwellings in 2009. This is by considering the passive house of the case study as an extreme case where the highest indoor temperature could be reached in any house located in Denmark. Therefore, during summer time, if the use of natural ventilation helps to cool down the dwelling, it is considered that natural ventilation is also sufficient to cool down the other households. In this case, the cooling demand was found in 285.4 GWh, whereas the actual cooling demand in 2009 in Denmark for fans was 250.7 GWh (Danmarks Statistik, 2010) The energy saving is calculated in 102.7 GWh for 2009.
Free-running indoor temperatures, i.e. when AC or fan is turn off, of the case study for Denmark and one chosen case study for Mexico can be seen in Fig. 2 & 3, respectively. It is shown that natural ventilation does help to achieve thermal comfort for both cases.
Also, with Eq. (9) the relative cooling demand for both cases is shown in Fig. 4 & 5, respectively. It can be seen than in Denmark there is cooling demand only during spring and summer, i.e. April, May, June, July, August and September, whereas in Mexico the demand is all year long (cf. Fig. 4 & 5).

Characteristics of the Danish energy system

In 2009, Denmark had an electricity generation of 36.4 TWh (Danish Energy Agency, 2010). The cooling demand due to fans represents 0.7% of the total electricity production. The means of generation are shown in Table 1.

Table 1
Means of electricity generation in Denmark (ibidem)

Share of total	Production source
61.1%	Large-scale power units
19.6%	Wind power
13.1%	Small-scale power units
6.2%	Auto producers

Large-scale power units use mostly coal (*ibidem*), while both small-scale units and auto producers are to a great extent combined heat and power plants (CHP) (*ibidem*). Random generation sources such as wind power make the energy saving of using ventilation to not have a directly influence to the electricity generation and the demand. In this case, it might be necessary to make a further analysis taking account of the means of production, the cooling demand and the expected energy saved.

Characteristics of the Mexican energy system

In 2008, the electricity generation in Mexico was 261.8 TWh (Secretaría de Energía, 2009). Almost three quarters of this generation, i.e. 73%, was based on fossil fuels, whereas the main source of renewable energy was hydropower (see Table 1).

Table 2
Means of electricity generation in Mexico (ibidem)

Share of total	Production source
73.6%	Large-scale power units
14.8%	*Petroleum*
46.3%	*Natural gas*
12.1%	*Coal*
0.4%	*Diesel*
21.9%	Hydropower
2.6%	Nuclear
1.7%	Geothermal
0.2%	Wind

In this case, due to all the generation sources have a direct relationship between their production and the demand, the energy saving has a simpler influence within the energy system.

Cooling demand due to air-conditioning in Mexico for 2008 represented 3% of the total electricity production in the same year. In this case, due to the lack of data (Secretaría de Energía, 2009) only the air-conditioning demand, i.e. mainly compression heat pumps, is taken account of. However, one must realize the existence of other means of cooling such as fans and evaporative coolers.

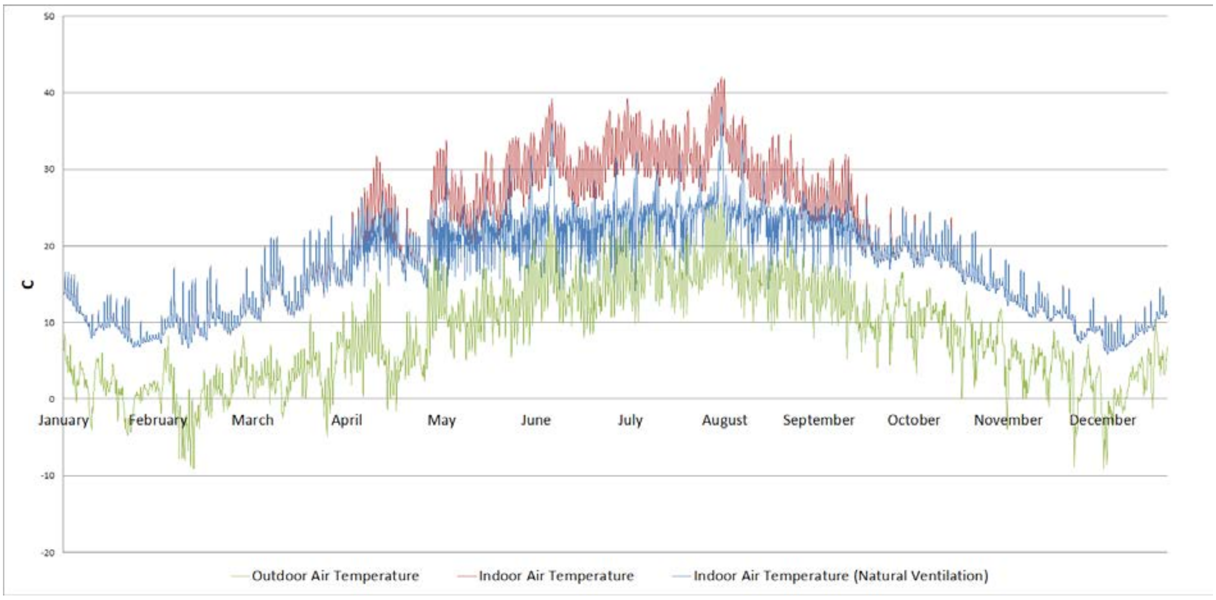

Figure 2 Outdoor (green line), indoor without natural ventilation (red line) and indoor with natural ventilation (blue line) temperatures for a case study in Denmark

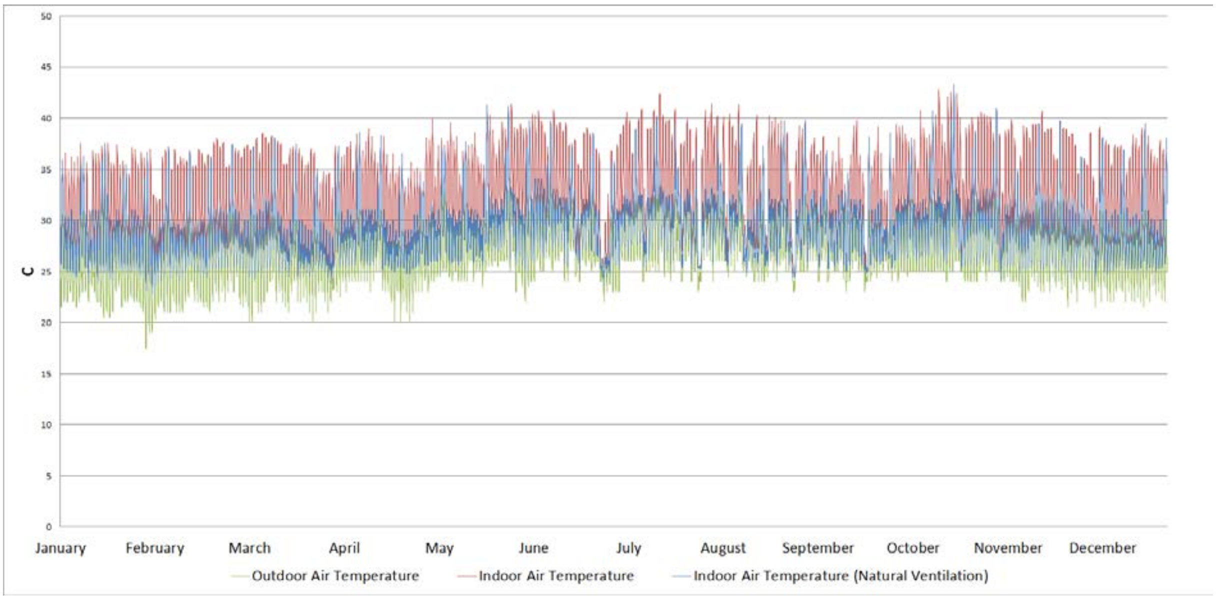

Figure 3 Outdoor (green line), indoor without natural ventilation (red line) and indoor with natural ventilation (blue line) temperatures for a case study in Mexico

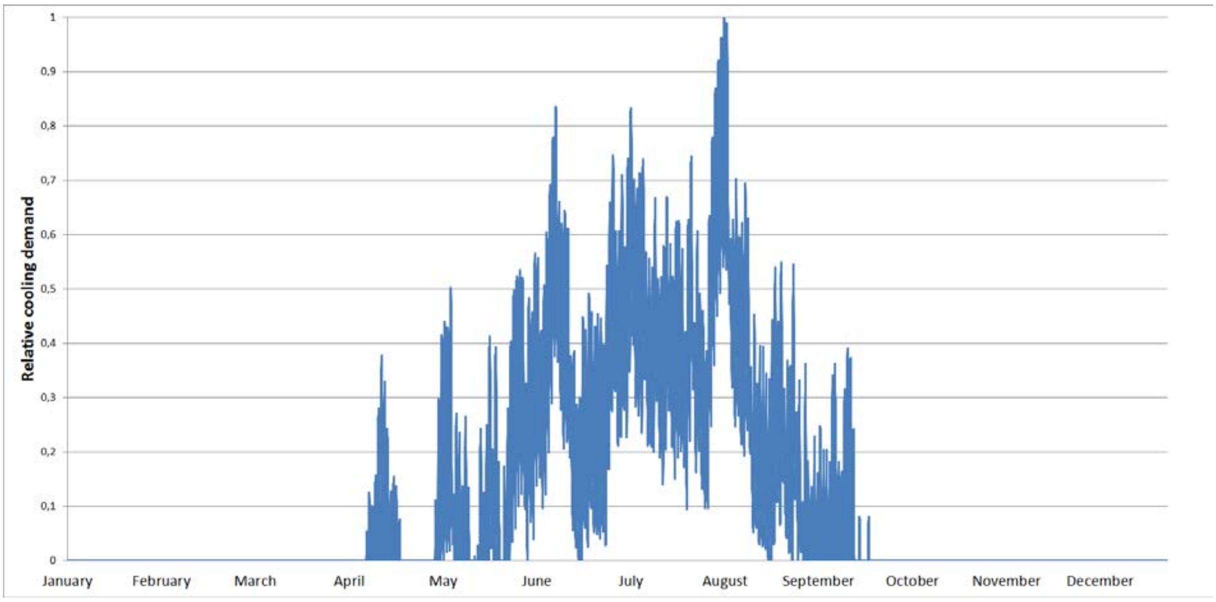

Figure 4 Relative cooling demand for a case study in Denmark

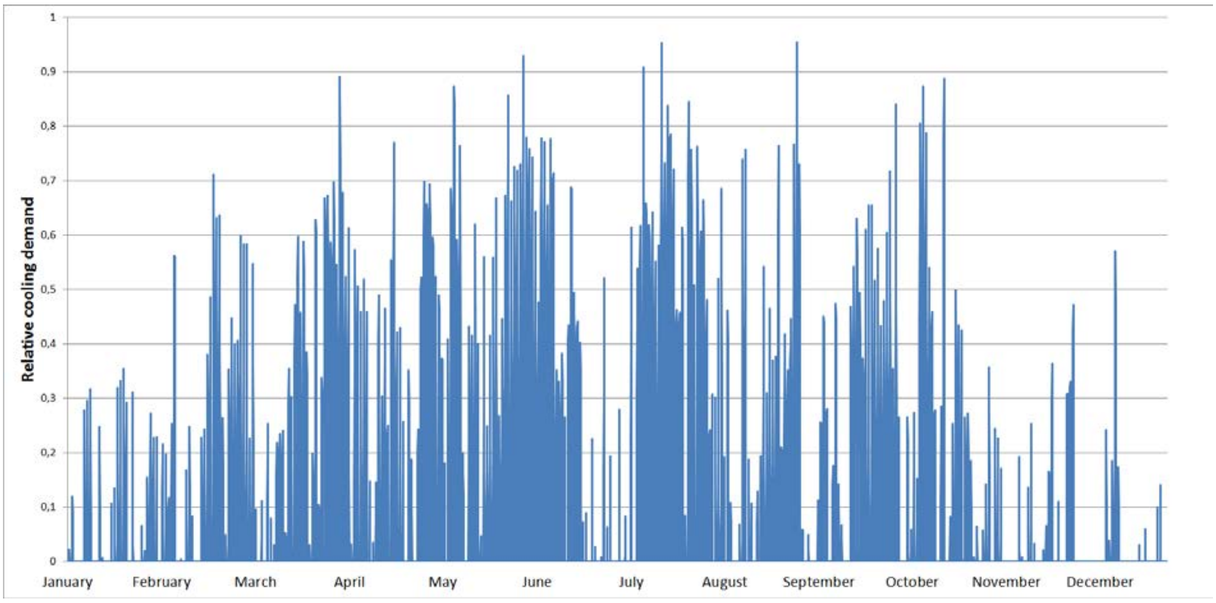

Figure 5 Relative cooling demand for a case study in Mexico

Assessment in Denmark

With the annual electricity generation in 2009, i.e. 36.4 TWh – 36,400 GWh, as input; and considering the calculated saving of 102.7 GWh for 2009, the cooling demand without natural ventilation, i.e. 285.4 GWh, and with ventilation, i.e. 182.7 GWh, the analysis is carried out by EnergyPLAN.

The hourly distribution of the relative cooling demand for 2009 given by Eq. (9) is also taken into account.

Thereby, monthly electricity demands could be distributed for Denmark. The results can be seen in Table 3.

Table 3
Electricity and cooling demands with and without natural ventilation for Denmark

Month	**Elec. demand [TWh]**	**Cooling demand (No NV) [GWh]**	**Cooling demand (NV) [GWh]**	**Saving [GWh]**
Jan	3.4	0.0	0.0	0.0
Feb	3.3	0.0	0.0	0.0
Mar	3.2	0.0	0.0	0.0
Apr	2.8	5.0	2.9	2.2
May	2.8	26.6	17.3	9.4
Jun	2.7	69.8	44.6	25.2

Jul	2.4	89.3	56.9	32.4
Aug	2.8	77.8	49.7	28.1
Sep	2.9	10.8	6.5	4.3
Oct	3.0	0.0	0.0	0.0
Nov	3.2	0.0	0.0	0.0
Dec	3.2	0.0	0.0	0.0
Average	3.0	23.0	15.1	7.9
Total	35.8	279.4	177.8	101.5

Table 3 shows that, in average, there is a monthly cooling saving of 7.9 GWh for 2009. However, one must take into account that the cooling demand is only present during six months. With this statement, the monthly saving is calculated in 16.9 GWh during cooling season.

In addition, one can notice that the total electricity demand, cooling demands without & with natural ventilation as well as the saving have the same order of magnitude than the calculated with Energy Plus.

As environmental benefit, EnergyPlan calculated a mitigation of 60.7 thousand tons of CO_2 equivalent due to the extensive use of natural ventilation in the Danish residential sector in 2009.

Assessment in Mexico

As Denmark, an analysis with EnergyPLAN is carried out for the Mexican case. The electricity generation in 2008, i.e. 261.8 TWh, the cooling demand without ventilation, i.e. 7.7 TWh, and the cooling demand with natural ventilation, i.e. 3.5 TWh, both for the same year, are analyzed. The results are shown in Table 4.

Table 4
Electricity and cooling demands with and without natural ventilation for Mexico

Month	Elec. demand [TWh]	Cooling demand (No NV) [GWh]	Cooling demand (NV) [GWh]	Saving [GWh]
Jan	24.3	175.7	86.4	95.8
Feb	24.0	531.4	262.1	289.4
Mar	23.1	728.6	359.3	398.2
Apr	20.4	805.7	397.4	439.9
May	19.9	1167.1	576.0	636.5
Jun	19.3	877.7	433.4	478.8
Jul	17.6	1121.8	553.7	612.0
Aug	20.2	671.0	331.2	366.5
Sep	20.8	676.8	334.1	369.4
Oct	21.6	576.7	285.1	314.6
Nov	23.3	166.3	82.1	90.7
Dec	23.3	68.4	33.8	36.7
Average	21.5	631.4	311.8	344.2
Total	257.6	7567.2	3734.6	4128.5

In this case, the monthly average saving is calculated in 344.2 GWh. The cooling demand is present all year long.

As Denmark, the total electricity demand, cooling demands without & with natural ventilation as well as the saving have the same order of magnitude than the estimated by Energy Plus.

Regarding an environmental benefit, a CO_2 equivalent mitigation in the Mexican residential sector for 2008 is estimated in 2 million tons.

Also, in the analysis by EnergyPLAN it was found that in a system based mainly on fossil fuels such as the Mexican, the energy saving should be reflected in the stopping of large-scale power units – with a sort of constant supply rate – while in systems with more presence of renewable energy such as the Danish the energy saving can be used to decrease the supply peaks caused by the random offer typical of the means of generation such as wind power and CHP.

CONCLUSION

The combination of two programs to assess natural ventilation as a mean to save energy in a large-scale scenario is shown in this article.

First, the energy saving of using such a passive method of cooling is found in two countries with different climates and building characteristics. This assessment is done by using the building simulation program Energy Plus.

Then, the savings are set as inputs into the energy analysis program EnergyPLAN. The two case studies have different electricity productions and demands.

Results show that in Denmark, with a production of 36.4 TWh in 2009, the saving is presented during the warm season, having a monthly average saving of 16.9 GWh with an annual mitigation of 60.7 thousand tons of CO_2 eq.

In the Mexican case, with a production of 261.8 TWh, there is saving all year long having a monthly average demand saving of 344.2 GWh, with an annual mitigation of 2 million tons of CO_2 eq.

Therefore, either in cold or warm conditions countries, natural ventilation represents an important mean to save energy by avoiding the use of mechanical ventilation and/or air-conditioning systems during total or partial periods of the cooling season.

Furthermore, both programs could be combined even though they were made for different scopes. With that, it is possible to open new possibilities to assess passive methods of acclimatization of residential buildings and their real energy impact within a large-scale scenario.

As a future work, there is the optimization of the corresponding energy system based on the monthly energy savings due to natural ventilation.

NOMENCLATURE

$\rho c_p V \frac{dT}{dt}$ =Energy stored in the zone air $[J/s]$

COP = Coefficient of performance of the air-conditioning [*dimensionless*]

CD = Relative cooling demand [0..1]

D_{AC} = Electrical demand of the air-conditioning $[W]$

h_{Conv} = Convective transfer coefficient $[W/m^2K]$
E_{Conv} = Convective heat rate from the surfaces $[J/s]$
E_{Vent} = Heat transfer due to natural ventilation $[J/s]$
E_{AC} = Active cooling method demand $[J/s]$
$E_{AC-Vent}$ = Cooling rate to be removed with air-conditioning after using natural ventilation $[J/s]$
E_{Int} = Internal heat loads $[J/s]$
E_{Sav} = Energy rate saved by natural ventilation $[J/s]$
$EnSav$ = Total energy saving potential due to natural ventilation $[Wh]$
h = Number of hours
T = Indoor air temperature at the time step n $[K]$
T_i = Temperature in surface i $[K]$
T_{Int} = Indoor air temperature $[K]$
$T_{set-point}$ = Temperature set-point $[K]$
T_{max} = Maximum Indoor Temperature within a given year $[K]$

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