DTU Library

Low-energy mechanical ventilation
a case study of two new office buildings

Andersen, Claus Wessel; Hviid, Christian Anker

Link back to DTU Orbit

Full paper no: 89

Low-energy mechanical ventilation: a case study of two new office buildings

Claus Wessel Andersen, M.Sc. [1]
Christian Anker Hviid, Assistant Professor [1][2]

[1] ALECTIA A/S, Denmark
[2] Department of Civil Engineering, Technical University of Denmark, Denmark

SUMMARY:
In 2010 an internationally renowned company initiated an architectural competition for two new office buildings to be constructed in Denmark. The design objectives were to construct a sustainable office building according to Danish low energy class 2015, with a good indoor climate and with as little energy consumption as 41.1 $kWh/m^2/year$ including heating and all building services with no use of renewable energy such as PV-cells or solar heating. One of the key means of reaching the objectives was to implement mechanical ventilation with low pressure loss and therefore low energy consumption. The project consists of two buildings, building one is 6 stories high, and building two is 4 stories high. The buildings have a gross area of 50,500 m^2 including underground parking. The ventilation and indoor climate concept was to use mechanical ventilation together with mechanical cooling and fan-assisted natural ventilation for free night cooling, hence minimizing the energy consumption for cooling. The paper describes the initial ventilation requirements and the implemented ventilation system. The specific fan power, SFP, with maximum air flow rate was measured to be 0.9 kJ/m^3 to 1.2 kJ/m^3, with an average of 1.1 kJ/m^3. The yearly mean SFP based on estimated runtime is approx. 0.8 kJ/m^3. The case shows the un-locked potential that lies within mechanical ventilation for near-zero energy consuming buildings.

1. Introduction

Mechanical ventilation has been the most widely used principle of ventilation over the past 50 years, but building services, including ventilation, represents a growing share of the total energy consumption. In the EU, HVAC systems accounts for 48% of the building sector energy consumption (Perez-Lombard et al. 2008) and, of this, fans accounts for 15-50 % depending on the type and design of the system (Wouters et al. 2001, Perez-Lombard et al. 2011).

To bridge the widening gap between the demand for fossil fuel reductions and the demand for improved indoor climate, other principles of natural and hybrid ventilation systems have emerged (Delsante 2002), intended to reduce the energy consumption for ventilation, specifically the power consumption of fans in mechanical systems. However, these alternative systems have many other flaws, e.g. ventilation heat losses, uncontrollable ventilation air supply and high risk of draught (Hviid 2010).

Meanwhile, little has been done to improve the performance of mechanical ventilation systems. The specific fan power (SFP), which expresses the ratio of power consumption to air flow rate of the ventilation system, is far from optimal. Terkildsen (2013) quotes four guidelines from the past 15 years that recommend 1.0 kJ/m^3, yet data from Hvenegaard (2007), Jagemar (2003), and Nilsson (1995) shows SFP-values of 2.5-3.5 kJ/m^3 with newer systems around 2.0-2.5 kJ/m^3. Only a few custom-designed systems comply with the guidelines. Berry (2000) reported a custom-made air handling plant with the specific fan power of 0.5 kJ/m^3. Hviid & Svendsen (2012) came as low as 0.6 kJ/m^3 with a prototype low pressure ventilation system, using custom build liquid-coupled indirect heat exchangers, diffuse ceiling inlets and low pressure dampers. In simulations, Terkildsen &

Svendsen (2013) came as low as 0.33 kJ/m^3 with an conventional mechanical ventilation system using different pressure reducing technologies like bypass of heat recovery unit, diffuse ceiling inlets, active electrostatic filtration and optimized pressure/flow control.

The discrepancy between guidelines and practice is mainly due to the industry focus on minimising space for building services, but it is also due to the low innovation focus in the ventilation industry to develop low-pressure solutions. This paper describes the ventilation system and the design process and the energy measurements on the completed system, thereby documenting the feasibility of conventional mechanical ventilation systems for realised low-energy buildings.

2. Design process

The core design team consisting of architects and engineers started from scratch with an integrated design approach where all stakeholders were included before the first lines were drawn. This approach, depicted on FIG 1, formalises the process by setting up initial design goals that are specific and measurable which enables concrete and continuous evaluations throughout the entire construction period. The expectations among the different stakeholders were aligned to match design goals that were sound, economically viable and socially responsible. These design goals formed the sustainability profile which the finalised building had to comply with. The profile was highly transparent and boosted the awareness of the different focus areas which the design team had to contribute to and comply with when the solutions were implemented.

By doing this, the design team was able to adjust the design pro-actively in order to combine the demands of the client with low energy consumption and a highly sustainable profile. The design outcome was a state of art building with indoor climate class I and II according to EN 15251.

The means of achieving low-energy consumption encompassed a few elements: optimised building form, a façade optimised for daylight and sufficiently high insulation level, low energy electrical lighting and low pressure VAV ventilation system. Especially the ventilation was under close review because badly designed ventilation would make it impossible to apply the highest indoor climate class with low overall energy consumption.

It was of particular interest to the client that there was no use of renewable energy sources such as PV-cells or solar heating, and that all solutions were proven and commercially available on the market.
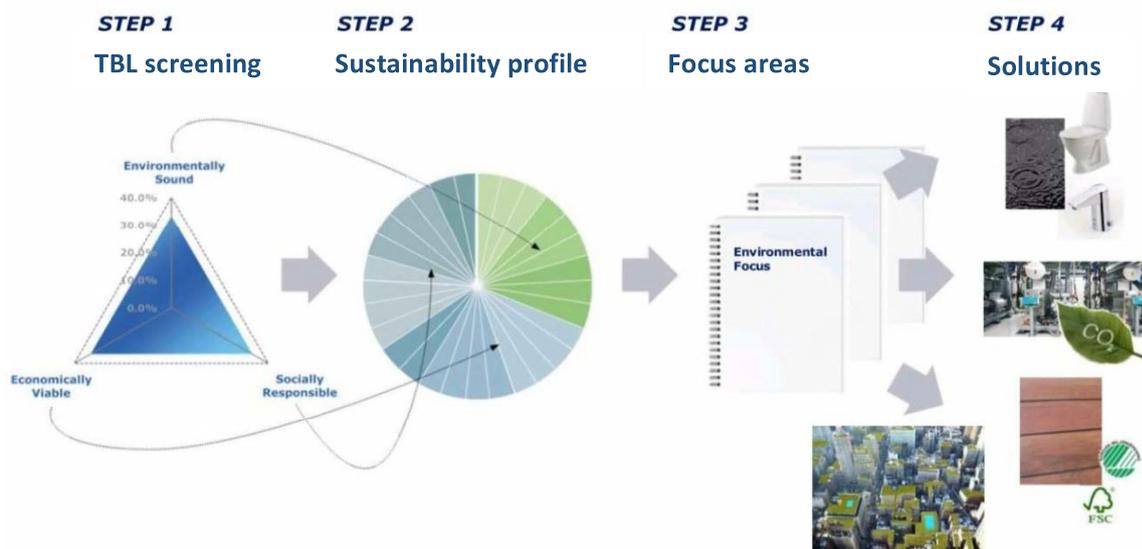

FIG 1. Integrated design process

3. Building

The project consists of two buildings, building one is 6 stories high, and building two is 4 stories high. The buildings have a gross area of 50,500 m^2 including underground parking. The ventilation and indoor climate concept was to use i) mechanical mixing ventilation together with mechanical cooling and ii) fan-assisted natural ventilation for free night cooling. In this manner, the energy consumption for cooling was minimised.

The core of each building is an atrium. At the ground floor and first floor the common facilities are located. The rest of the building floors are office spaces mainly along the outer façade. Rooms with none or less daylight requirements, e.g. service rooms, shafts, cafés and meeting rooms, are located between the perimeter spaces and the atrium,

The façade is optimised for optimal daylight access to the office space with large windows, but with insulated parapet below table height, preventing excessive solar heat gains and increasing the overall thermal insulation. The façades are equipped with external solar screens, and internal glare protection screens. The artificial lighting systems is low-energy and with dimmable daylight control.
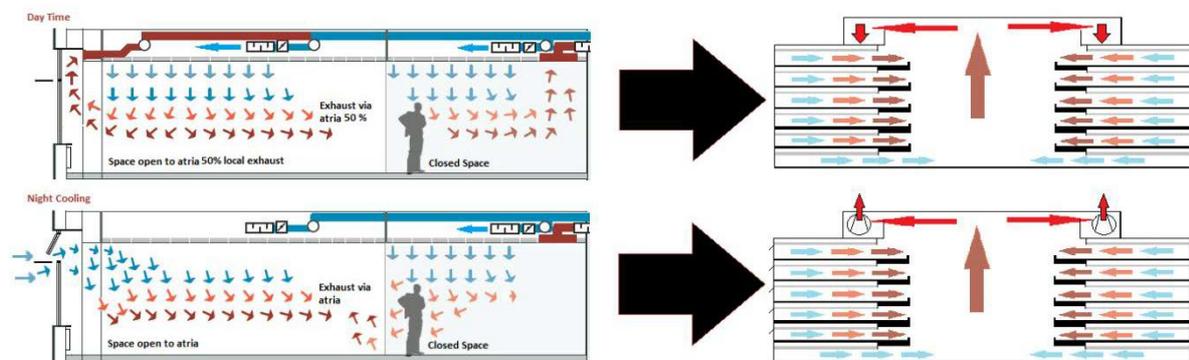
3.1 Ventilation system

FIG 2. Principle of main building ventilation system; balanced mechanical day time ventilation and night cooling by operable façade windows and exhaust ventilation

The energy consumption of the ventilation system is related to the ventilation rate, resistance to the airflow, efficiency of the fan and motor, and operation time.

In mechanical systems, the fan power is approx. proportional to the ventilation rate cubed. Consequently, the first step was to minimise the ventilation rate demands, i.e. use low-emission building materials and exploit the fact that passive cooling means were implemented from the very first design phase.

The second step was to minimise flow resistance. This was achieved by planning the optimal duct routing, thus reducing the duct lengths. The central atrium was planned to function as non-ducted extract route. Plant rooms were located centrally. FIG 3 and FIG 4 depict parts of the ventilation routing while FIG 5 is more schematic.

The initial design pressure drop of the duct system was chosen to be maximum 150 Pa as a compromise between keeping the size of the air handling units down while still having an SFP value of 1.1 kJ/m^3 at maximum flow.

The design duct pressure loss was achieved with the following design criteria: Design pressure gradient of <0.4 Pa/m in general with, as additional constraint, maximum airspeed of 5 m/s in the main ducts.

For comparison the rule of thumb recommended by Nilsson (1995) and ASHRAE (2007) is 1.0 Pa/m; it is 0.8 Pa/m by Schild et al. (2009) while Hvenegaard (2007) accepts 1.5-2.0 Pa/m for systems with moderate operation time (offices).

The latter condition of 5 m/s was imposed because losses in bends and fittings are proportional to the air velocity squared. The break-even point of pressure gradient versus air speed was in this case Ø630 mm.

The air terminals were replaced by diffuse ceiling ventilation (Fan et al. 2013). Air is supplied in the plenum above the acoustic ceiling and distributed through cracks to the room below. The inlet velocity is very low and with no fixed jet direction, hence the term diffuse. The diffuse ceiling, which measured 5 Pa at 100 % airflow and 1-2 Pa at 30 % airflow, is employed in the office spaces to reduce the pressure losses of conventional mixing terminals (approx. 30 Pa) and to increase draught-free comfort.
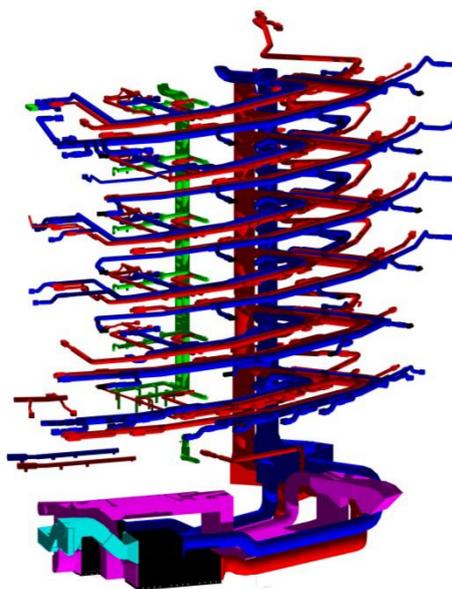

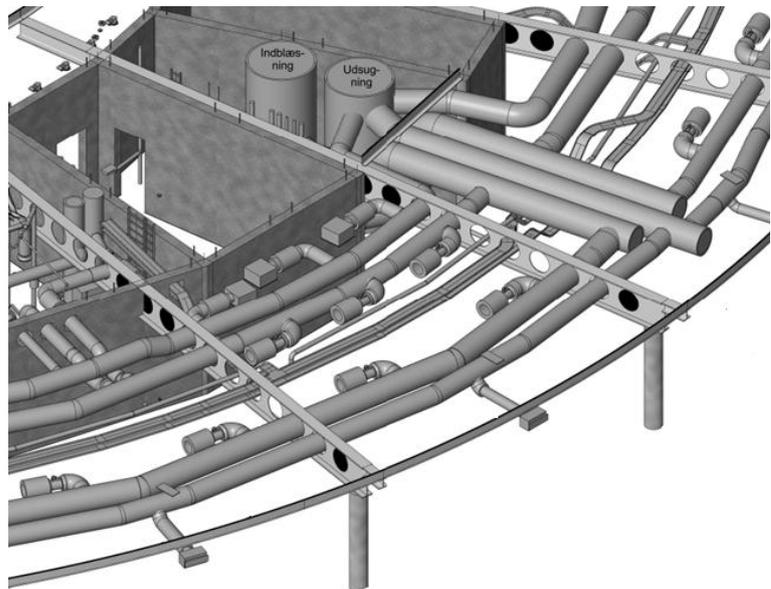FIG 3. 3D view of ventilation system in Navisworks

FIG 4. 3D view of floor section in Navisworks

With low-pressure ventilation systems, it is prudent to consider the motor, fan and drive efficiency because it can decrease significantly if the combination of airflow and pressure rise is not near the combinations giving peak efficiency. To avoid oversizing, smaller air handling units were installed in parallel two and two. At low load one unit shuts down, thus increasing flexible operation while maintaining fan efficiency. To recover heat, the air handling units were equipped with rotary heat exchangers with an efficiency of 80% or better.

3.2   Passive cooling strategy

The passive cooling strategy is four-legged with leg 1-3 depicted on FIG 2:

1.   Automatic façade openings

2.   Mechanical supply ventilation from the main air handling units to rooms with no façade and rooms on ground floor (safety reasons)

3.   Mechanical exhaust from the atria

4. Cooling of IT-racks by room air

The first three legs of the passive cooling strategy reduced the energy consumption for night cooling considerably, from the initial all mechanical ventilation solution with 1-2 ACH (SFP = 0.5 kJ/m^3) to the final hybrid strategy with SFP = 0.11-0.125 kJ/m^3.

The fourth leg cools the IT-racks on each floor by simple mechanical exhaust with air supply from adjacent rooms. FIG 5 depicts this as red markings.

This makes it possible to turn off the main ventilation system outside office hours, while still cooling the racks with room temperature air supply. Depending on current building heat demand, the generated heat is either exhausted or distributed to the atrium depending on the current building heat demand which utilises the excess heat in a sensible manner and increases the overall building energy efficiency.
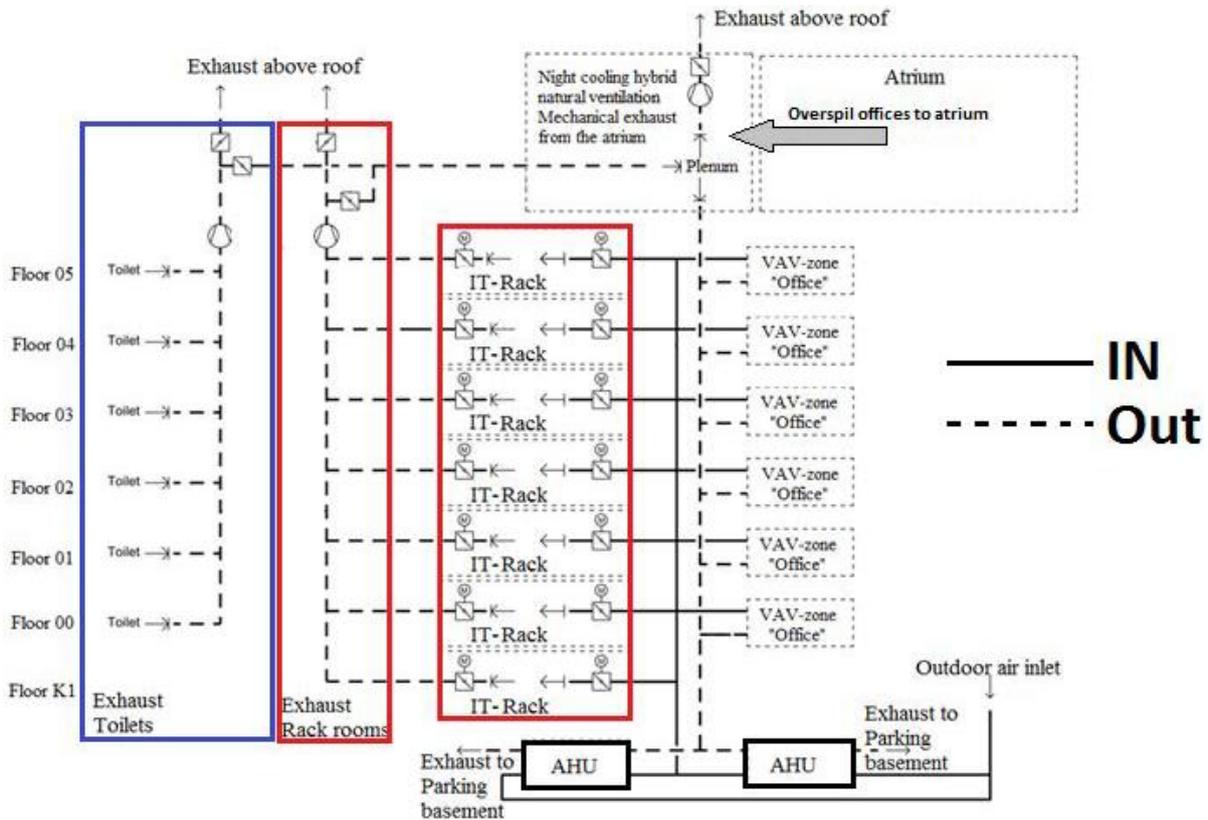

FIG 5. The ventilation system layout.

4. Results

The design pressure drops of the 19 air handling units with ductwork are 450 Pa to 550 Pa. This is the pressure drop from outdoor air intake to inlet to the office with full design air volume. In comparison, Hvenegaard (2007) reported the mean pressure drop from 100 mechanical ventilation systems in operation to be approx. 1400 Pa.

The energy efficiency, i.e. the specific fan power, is depicted on FIG 6. The figure shows measured values on the finalised installation at maximum flow rate. Systems for night cooling and exhaust systems have very low SFP values because of very short duct routing.
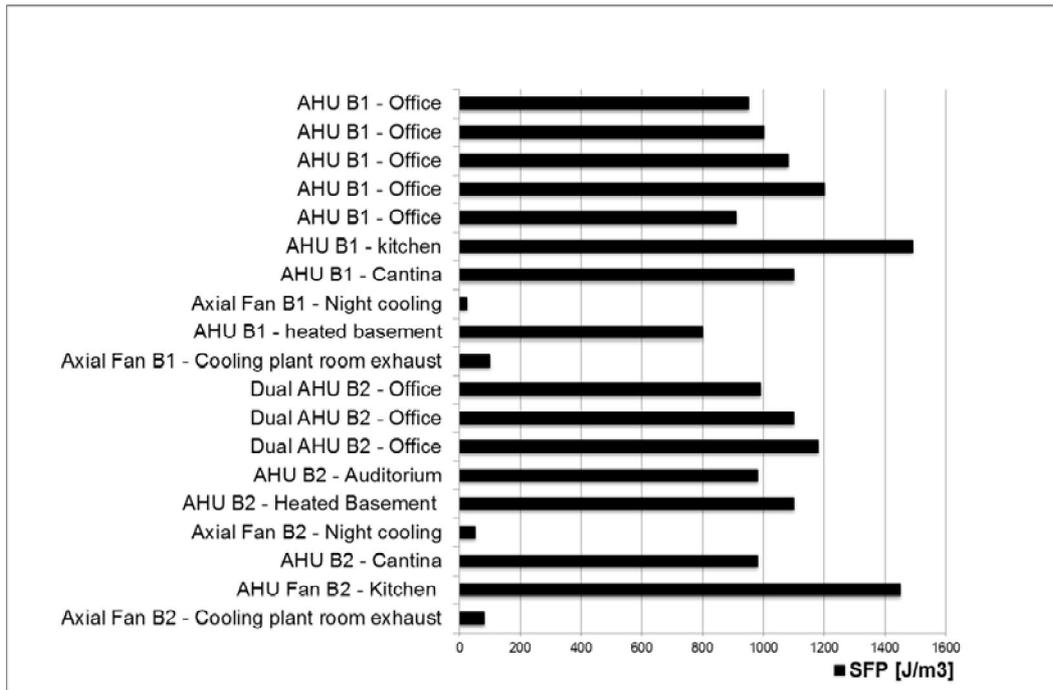
FIG 6. The specific fan power of the different air handling unit at maximum flow rate.

From FIG 6, the yearly mean specific fan power can be derived. SFP_{year} is a key performance indicator which is comparable across buildings and expresses the practical ventilation system efficiency. The results are shown in TABLE 1, however, the runtime can only be estimated at this current stage.

TABLE 1. Yearly mean specific fan power [SFP_{year}]*

	Building one	Building two
Daytime ventilation**	0.80 kJ/m^3	0.79 kJ/m^3
Night cooling hybrid systems	0.125 kJ/m^3	0.11 kJ/m^3

* Time and flow weighted average SFP_{year} calculation: $q_{v1} \times SFP_1 \times t_1 + q_{v2} \times SFP_2 \times t_2 \dots / q_{v1} \times t_1 + q_{v2} \times t_1 \dots$ where $q_v =$ air handling unit air flow, t= runtime and indices 1,2,…,n equals mode1,2,…,n; as an example mode 1 = 50 %, mode 2 = 75% etc.

** Ventilation during office hours, axial fans not included as they operate at night

In TABLE 2 the SFP is weighted by maximum flow rate. These results are not biased by the estimation of runtime, thus they are useful for evaluating the performance of the ventilation system before the final completion of the building.

TABLE 2. Flow weighted specific fan power of max flow rates [SFP_{max}]*

	Building one	Building two
Daytime ventilation**	1.08 kJ/m^3	1.03 kJ/m^3
Night cooling hybrid systems	0.15 kJ/m^3	0.14 kJ/m^3

* Flow weighted SFP_{max} calculation: $(q_{v1} \times SFP_1 + q_{v2} \times SFP_1 + \dots) / (q_{v2} + q_{v1} + \dots)$ where $q_v =$ air handling unit air flow and indices 1,2,..,n equals mode1,2…,n; as an example mode 1 = 50 %, mode 2 = 75% .

** Ventilation during office hours, axial fans not included as they operate at night

4.1 Energy consumption

The total calculated primary energy demand is 40.5 kWh/m^2/year for the two office buildings. Allowed primary energy demand is 41.1 kWh/m^2/year according to the Danish building code low-energy class 2015. The main thermal properties of the building envelope are listed in TABLE 3.

The distribution of the energy demand is depicted on FIG 7. It shows that the fans consume 23 % of the total energy consumption.

TABLE 3. Building insulation properties

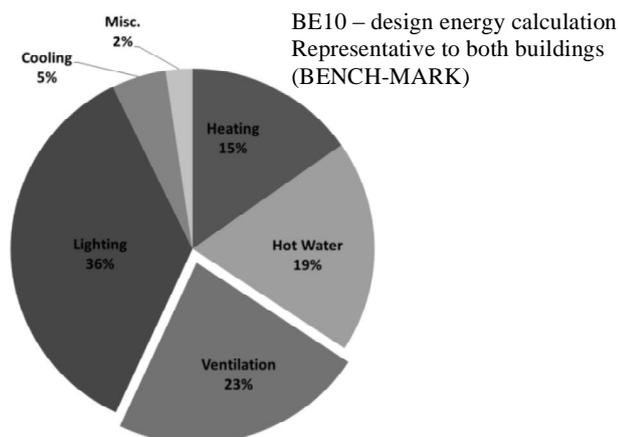| Component	U-value	g-value	Visual transmittance
Curtain wall facade -glazing to floor ratio 30 % -glazing to façade ratio 60 %	Total 0.65 W/m^{2}K Opaque = 0.15 W/m^{2}K Transparent = 0.8 W/m^{2}K	g = 0.51 and ext. solar shading	71 %
Atria skylight: triple layer glazing Roof Basement walls Basement floor slap	1.0 W/m^{2}K 0.10 W/m^{2}K 0.15 W/m^{2}K 0.10 W/m^{2}K	g = 0.27	60 %

FIG 7. Primary energy demand in % - Total energy demand 41 kWh/m^2/year with no renewables.

5. Conclusion

The market for energy-efficient ventilation focuses on natural and hybrid solutions, leaving mechanical ventilation side-lined with a reputation of being energy-consuming and noisy. This paper shows a case where the design of conventional mechanical ventilation systems:

- was managed by a team of engineers, architects and contractors that understood their common goals, and agreed and adhered to a shared design process

- followed existing guidelines with some additional pressure-reducing technologies like diffuse ceilings and parallel air handling units

- was measured to be very energy efficient with an all units average SFP value of 1.0-1.1 kJ/m^3 (0.8 kJ/m^3 at yearly average airflow) compared to the Danish building code maximum allowed

SFP of 2.1 kJ/m^3. The energy use in this case is higher than custom best practice research systems with SFP as low as 0.6 and 0.33 kJ/m^3, but if these research systems were scaled to the same size as these buildings (one building has max. airflow approx. 180,000 m^3/h), they would take up significantly more building space

- the low pressure ventilation system is likely to be as low noise and it is low energy, resulting in less problems with noise

- low energy ventilation systems can help reduce energy demand in low energy buildings and subsequently reduce or remove the need for renewables. In other instances the reduced energy for ventilation can be "invested" in a less energy efficient layout or more freedom in the architectural expressions

6. Acknowledgements

References

ASHRAE. 2007. Handbook Applications. American Society of Heating, Refrigerating and Air-Conditioning Engineers

Berry J. 2000. Super-efficient mechanical ventilation. Indoor Built Environment 9. 87-96. 10p.

Fan J., Hviid C.A., Yang H. 2013. Performance analysis of a new design of office diffuse ceiling ventilation system. Energy and Buildings 59. 9 p.

Hviid, C.A. 2010. Building integrated passive ventilation systems. Ph.D. thesis, Dept. of Civil Engineering, Tech. Univ. of Denmark, Lyngby, Denmark.197 p.

Hviid, C.A., Svendsen, S. 2012. Wind and stack-assisted mechanical ventilation with heat recovery and night cooling, PSO project 339-24, Report R-282, Dept. of Civil Engineering, Tech. Univ. of Denmark, Lyngby, Denmark. 121 p.

Hvenegaard, C.M. (2007). Den lille blå om ventilation. 2nd edition. Dansk Energi. 120 p.

Jagemar, L. 2003. Målinger på ventilationsanlæg med lavt elforbrug i nyere kontorbygninger. By og Byg Dokumentation 039. Danish Building and Urban Research. Hørsholm. Denmark. 51 p

Nilsson L.J. 1995. Air-handling energy efficiency and design practices. Energy and Buildings 22. 1-13. 14 p.

Pérez-Lombard L., Ortiz J., Coronel J.F., Maestre I.R. 2011.A review of HVAC systems requirements in building energy regulations. Energy and Buildings 43. 255-268. 14 p.

Pérez-Lombard L., Ortiz J., Pout C. 2008. A review on buildings energy consumption information. Energy and Buildings 40. 394-398. 5 p.

Schild P.G., Mysen M. 2009. Recommendations on Specific Fan Power and Fan System Efficiency. Technical Note AIVC 65

Terkildsen S. 2013. Development of mechanical ventilation system with low energy consumption for renovation of buildings. Ph.D. thesis. Dept. of Civil Engineering. Tech. Univ. of Denmark. Lyngby, Denmark. 137 p.

Terkildsen S., Svendsen S. 2013. Performance potential of mechanical ventilation systems with minimized pressure loss. Internationl Journal of Ventilation 11. 13 p.

Wouters P., Delmotte C., Faÿsse J. C., Barles P., Bulsing P., Filleux C., Hardegger P., Blomsterberg A., Pennycook K., Jackman P., Maldonado E., Vitor L. and de Gids W. 2001. Towards improved performance of mechanical ventilation systems. EC JOULE- TIP-Vent project. 58 p.