CONVERTION FROM CAV TO VAV – A KEY TO UPGRADE VENTILATION AND REACH ENERGY TARGETS IN THE EXISTING BUILDING STOCK

Mads Mysen[1,2], Peter Schild[2], Finn Drangsholt[1], Bjørn Tore Larsen[3]
[1]Oslo University College, Oslo, Norway.
[2]SINTEF, Oslo, Norway.
[3]Vekst Foundation, Oslo, Norway.

Abstract

Demand controlled ventilation (DCV) can considerably reduce the ventilation airflow rate and energy use for fans, heating and cooling compared to constant air volume (CAV) ventilation. Based on the new EPBD Recast directive from the EU Parliament, there is a potentially enormous upcoming marked for converting from CAV to efficient DCV in existing commercial buildings.

However, several DCV-solutions are not very suitable for upgrading applications because they require redesign of airflow paths or introduction of several new components that are difficult to integrate into existing CAV-systems. A normal consequence is that ventilation upgrading is postponed, or the existing ventilation system is completely discarded and replaced. Such complete replacement of existing systems is probably not environmentally friendly, and has considerable additional costs like loss of estate rental income during the rebuilding period.

This paper presents DCV-systems that seem particularly promising for upgrading ventilation in existing commercial buildings. At the moment, DCV with variable supply air diffusers seems generally most suitable for upgrading from CAV to VAV, but project-specific requirements and circumstances must be emphasized before the final choice in each project is taken.

Keywords: CAV, demand controlled ventilation, existing building stock, energy, retrofit

1 Introduction

IPCC (The Intergovernmental Panel on Climate Change) recommends a 50% reduction of manmade CO_2 emissions before 2050 to avoid severe problems of global warming. The IEA report “Energy Technology Perspective 2008” has presented the Blue Map scenario on how to achieve this emission reduction (IEA report, 2008).

A consequence for the building sector is that a widespread conversion of buildings to very low energy consumption and even zero energy buildings is necessary. The EU Parliament approved in 2010 a directive (EPBD Recast) that requires member states to implement ambitious plans to upgrade much of the existing building stock to near zero energy buildings (NZEB) by 2020, with intermediate goals to be set for 2015.

Ventilation constitutes a major share of the total energy use buildings of existing non-commercial buildings in the Nordic countries, typically 35-50% for office buildings (Wigenstad and Grini, 2010). Existing office buildings in Norway have an average energy use of 245 kWh/m^2 according to Enova (2010). Most non-residential buildings have Constant Air Volume (CAV) ventilation leading to over-ventilation in periods with low or no occupancy. Comparison of perceived indoor climate in schools with CAV-systems and DCV-systems does not indicate that CAV-systems add extra quality to the indoor climate (Mysen Doctoral Theses 2005). The purpose of extra ventilation with CAV-systems is therefore questionable as it leads to additional energy use.

Demand controlled ventilation (DCV) considerably reduces the ventilation airflow rates and energy use compared to CAV systems. This conclusion is based on an inspection of 157 classrooms in primary schools (Mysen et al. 2005). Installation of variable air volume systems (VAV) in an existing office building reduced the need for air heating by more than 90% and electrical energy for air distribution by 60% (Maripuu et al. 2004).

DCV in existing commercial buildings is probably a prerequisite to achieve the ambitious energy-goal for existing commercial buildings. The recommendation from the EU parliament and recently started activities like IEA Task 47 will probably trigger the marked for converting from CAV to DCV in existing commercial buildings. However, there are three major challenges to overcome before a successful conversion.

i) Some DCV-solutions are probably not suitable for upgrading applications because they require redesign of airflow paths or introductions of several new components that is difficult to integrate in existing CAV-systems. A likely consequence is that ventilation upgrading is postponed, or that demolition of the existing ventilation system is chosen. Demolition of the existing system is probably not environmentally friendly and has considerable additional costs including loss of rental income during the rebuilding period.
ii) Ductwork air-tightness is a prerequiste for proper functionality for several DCV-solutions.
iii) DCV-based ventilation systems in general must become more reliable to close the gap between theoretical and real energy-performance. This implies among others that operating personnel must have knowledge and skills to match the system complexity (Cappellin, 1997). Interactive systems must communicate smoothly. Crucial components must have proper quality, and it must be possible to scan and check functionality of crucial components (Mysen et al. 2010).

This paper describes and roughly evaluates the well known DVC systems “Pressure Controlled DCV” (PC-DCV) and “Static Pressure Reset DCV” (SPR-DCV), together with two less known systems in Norway “Digital Demand Controlled Ventilation” (DDCV) and “Variable Air Supply Diffusor” (VASD-DCV) in the context of upgrading CAV to VAV. Figures 1-4 show the supply ductwork of different DCV-systems. The exhaust system is similar in principle, or based on a master-slave concept related to the supply air flow.

2 Methods

2.1 Functionality and energy use

The DCV-systems are theoretically evaluated to see how suitable and robust they are for reaching air flow targets with sufficient accuracy, thus reduce need for over-ventilation, and minimum fan energy use. CO_2-based, temperature based and occupancy based DCV-concepts are evaluated in relation to the air flow targets set in each project. Normal DCV-control in Norway is to set a base ventilation flow rate to account for background pollution loads such as emissions from buildings materials. This base ventilation is the minimum air flow rate throughout the operating time of the air-handling-unit (AHU). The flow rate increases when rooms or zones are occupied. CO_2-based DCV increases the air flow when CO_2-level increases or reaches a maximum, depending of the control strategy. Occupancy based DCV normally has bimodal operation according to detected occupancy. The ventilation rate is reduced to a minimum when the room is unoccupied, and is increased to the design ventilation rate whenever the room is occupied.

Reduced ventilation airflow rates will approximately lead to a proportional reduction in energy use for central heating and cooling according to Mysen et al. (2003). Note that there might be a considerable additional reduction in local space heating because the supply of relatively cold ventilation air is reduced in periods with no or low occupancy.

The potential for optimal fan energy use is considered theoretically. The potential for fan energy reduction depends on the pressure/airflow control strategy, which is not given much attention in traditional DCV design. At design airflow rate, all the control strategies have approximately the same Specific Fan Power (SFP) of about 2 kW/(m^3/s)) inn accordance with the Norwegian building code, but at normal operating airflows between 30 and 80% of design value, there are considerable differences in energy use between good and poor control design (Schild and Mysen, 2009).

2.2 Investment cost and potential loss of rental income

Investment costs and potential loss of rental income is important to consider. We have received some comparable cost figures for CAV and the DVC systems “Pressure Controlled DCV” (PC-DCV) and “Variable Air Supply Diffusor” (VASD-DCV) from one of the main HVAC entrepreneurs in Norway, GK AS.

Rent expenditure for offices is typically from 100 to 300 Euro/m^{2}year in urban areas like Oslo (ref.: www.finn.no). A ventilation upgrade that incurs loss of rental income during the rebuilding period will have considerable additional costs beyond the cost of the ventilation system. Hence, the ability to upgrade to DCV without closing down the building during rebuilding period will have a major economical advantage.

2.3 Field measurements

DDCV was applied and monitored in the Cultural building of the Asker municipality outside Oslo and monitored in May and December. Mysen et al. (2011) has described the field measurements and results.

VSAD was applied as a retrofit measure at Rosenholm Campus southeast of Oslo. Airflow rates and acoustics were measured in two randomly picked offices. Airflow rates were measured according to Nordic methods for airflow measurements (Nordiska Ventilationsgruppen Byggforskningsrådet, 2007). The overall measurement uncertainty is ± 7%. Acoustics were measured according to Norwegian standard 8175 (2008) beneath the VSAD 1,6 meter above the floor. The measurement uncertainty is is ± 3 dBA. The results are compared to the maximum acceptable noise level from technical equipment in offices of 35 dBA

3 Alternative DCV-systems

Figure 1 shows a traditional DCV system based on static pressure control, PC-DCV. The purpose of static pressure control is to control the airflows according to a momentary demand indirectly by controlling the pressure in a strategic duct position. The solution can be improved by additional static pressure branch control.

Figure 2 shows an implementation of modern Static Pressure Reset DCV. Static Pressure Reset Control (SPR-DCV) is used to make pressure controlled systems more energy-efficient by emulating direct flow control functionality.

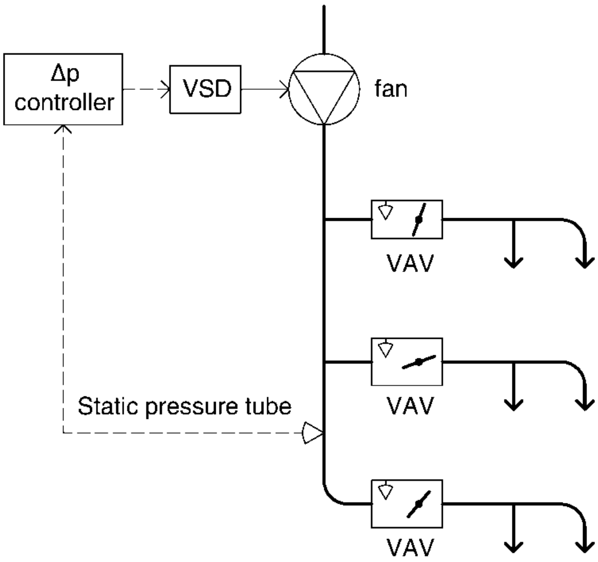

Figure 1. Principle of constant static pressure control. The critical path VAV damper is in max position only at times of maximum flow rate demand.

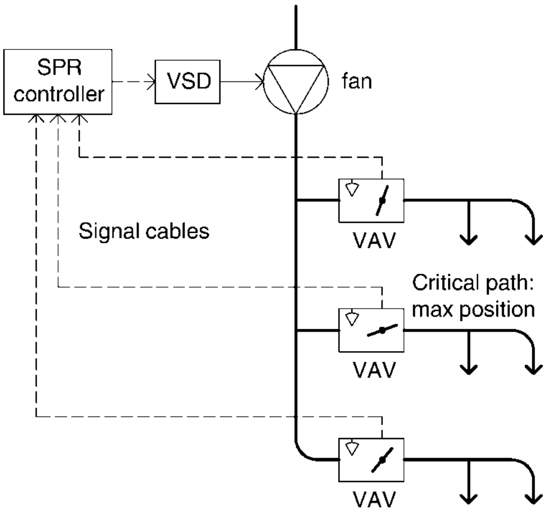

Figure 2. Illustration of SPR control. At least one VAV balancing damper is in max position (the critical path).

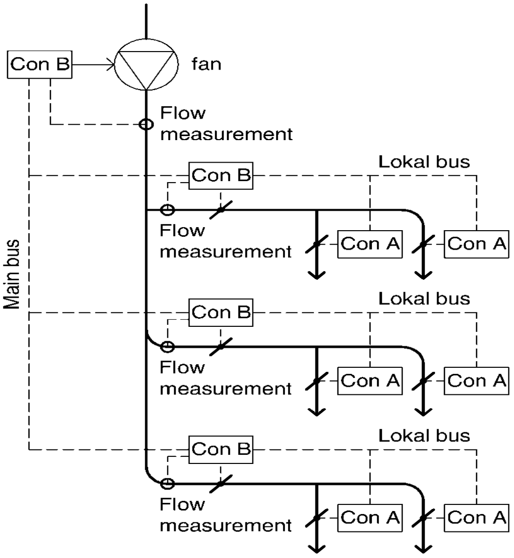

Figure 3. Principle of Digital Demand Controlled Ventilation.

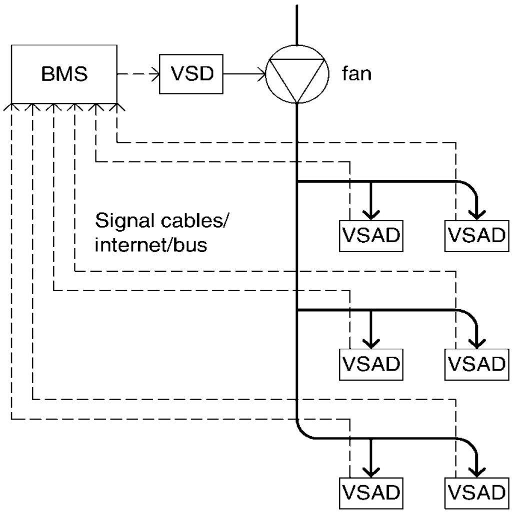

Figure 4. Principle of VSAD-DCV.

SPR constantly tries to satisfy all air flow requirements with a minimum of the fan speed drive by ensuring that the VAV damper(s) along the present critical path (Figure 2) are in a maximum open position, thus the SPR controller is frequently called an “optimizer”. The duct path with the greatest flow resistance from the AHU to any terminal is called the ‘*critical path*’. Dampers cannot be 100% opened due to need for control authority, i.e. to prevent excessive servo motor wear due to ‘hunting’.

Digital Demand Controlled Ventilation (DDCV) is based on communication between sensors and actuators using bus technology, thus the notation digital. The principle of DDCV is illustrated in Figure 3. Each room has a motorized supply air “Room damper” connected to a special type of controller, “Con.A”. A room sensor is connected to each Con.A. The room sensors might be a combination of a presence detector (PIR) and a temperature sensor, or a CO_2-sensor.

The airflow in the branch that supplies air to the rooms is controlled by a motorized branch damper connected to a controller of type “Con.B”. Con.B also supplies set point values to the airflow controller of the Air Handling Unit (AHU).

The controllers Con.A and Con.B have the following purpose and properties:

- **Con.A** is a simple controller that communicates only on the Local bus, and can only control room dampers of the “two position type” (max/min).
- **Con.B** is an advanced controller with a programmable micro processor. Con.B communicates on both the L**ocal** bus and the Main bus of the Building Management System (BMS). It can also supply 0-10 V set point values and to the air flow controller of the Air Handling Unit (AHU).

Figure 4 shows the principle with Variable Supply Air Diffuser (VSAD-DCV). The air terminal units have a built-in VAV-unit and an occupancy and temperature sensor, hence there is no need for additional active control dampers in the duct system. Each VSAD covers the area beneath the air-terminal-device. Required air flow rate, actual air flow rates, temperature and corresponding opening percentage of the VAV-unit is communicated to the BMS regulating the fan speed drives in the AHU so that all the terminal devices are satisfactorily close to requirements and at least on air terminal devices have maximum opening.

4 Results and Discussion

4.1 Pressure controlled DCV

Conversion from CAV to pressure controlled DCV requires installation of active VAV-units controlling supply and exhaust air flows to each VAV-room/zone and static pressure tubes in the main duct. Ventilation systems covering vast areas or several floors will probably need additional VAV-units and static pressure tubes controlling the main branches. CAV terminals must be connected to specific CAV branches, or they must branch off close to the pressure sensor. If this is not possible, such rooms must have “expensive VAV-units” with active control dampers to ensure constant air flow with variable duct pressure.

Controlling fan speed to maintain a constant static fan pressure rise, will result in unnecessary throttling along the critical path during most of the AHUs operating time, and therefore unnecessary fan energy use. The worst case is only a proportional fan energy and flow rate reduction (Schild and Mysen, 2009), while the ideal case is energy reduction according to the cube fan law (ASHRAE, 1996). The latter case assumes no laminar flow elements in the AHU, and zero minimum pressure drop at control points.

One unfortunate experience of pressure controlled DCV system is that minor changes in room demand just redistribute airflow in the duct system with the airflow in the AHU being more or less constant, and no energy saving is actually achieved. This is probably enhanced by factors like low sensor accuracy, poor ductwork air tightness and unfavourable location of the pressure sensor.

However, it is possible to convert from CAV to pressure controlled DCV, but it is questionable whether fresh air is supplied with sufficient accuracy and minimum possible energy use. This challenge with pressure controlled DCV accounts for new HVAC-installations as well. Another challenge with pressure controlled DCV is where to put the pressure sensor for optimal functionality. In an upgrading case, it is at least possible to control if the pressure is stable before mounting the sensor.

The typical investment cost in Norway for pressure controlled DCV is about 18 EURO/(m^3/h) while the corresponding investment cost for CAV is about 8-9 EURO/(m^3/h) according to Bergstrøm (2011).

4.2 Static Pressure Reset DCV

Conversion from CAV to SPR-DCV requires additional controls (relative to Pressure controlled DCV) for continuously optimising the VAV-damper-position (either stand alone controllers or BMS programming). A traditional SPR system will also have duct pressure sensors controlling the branch dampers, whereas modern systems need no pressure sensors.

Well functioning SPR represents the ideal case in terms of energy use, and air flow rate accuracy. The catch is that SPR systems require more control components and hence are potentially more complicated and less robust. SPR-DCV has probably higher investment cost than pressure controlled DCV due to extra controls for continuously optimising the VAV-damper-positions.

4.3 Digital DCV

Conversion from CAV to DDCV requires installation of motorized room dampers connected to Con.A (Figure 3). These dampers are simpler and potentially cheaper than VAV-units. Each branch must have a flow meter connected to Con.B. controlling a motorized branch damper. In addition there must be a total airflow measuring device connected to another Con.B. controlling the fan speed. Some modern air-handling-units are delivered with integrated flow measurement.

Direct flow control systems like DDCV are potentially more responsive and accurate than pressure based flow control, because the airflow is not indirectly controlled by a pressure sensor with corresponding time-lag problems and measuring uncertainty. It is also possible to combine CAV and VAV rooms without using “expensive VAV-control” to each room. DDCV is tested and commissioned by occupancy sensor controlling the airflow to maximum and minimum. Theoretically, DDCV can be applied in systems with a modulating damper, for instance controlled by a CO_2-sensor, but such solutions need to be further evaluated before it can be recommended.

Good ductwork air tightness is probably important for the proper functioning digital DCV, though it might be possible to somehow compensate for air leakage in the summation of air flows.

We have not been able to quantify comparable cost figures for Digital DCV, but this DCV solution was recently chosen as a retrofit measure in Storgata 33 in Oslo/Norway, which shows that it is cost competitive and relevant to consider when upgrading from CAV to VAV. Digital DCV was applied in Storgata 33 without closing down the building during rebuilding period. This upgrading will be further evaluated.

4.3.1 Results from field studies

DDCV was applied and monitored in an office area in the Cultural building of the Asker municipality. When all offices are in use, the AHU design airflow is 7500 m^3/h. When all the offices are unoccupied the AHU design airflow is 4350 m^3/h (Mysen et al. 2011).

When an office is unoccupied, the ventilation air flow is reduced to minimum 30 minutes after people have left the office. Minimum airflow was in this case set to 50% of maximum, but the airflows and the delay period can be set according to specific needs in each project.

The monitoring shows that the ventilation rates follows the demand for ventilation quite accurately. The energy saving compared to having a constant AHU airflow of 7500 m^3/h is (7500 - 5500)/7500 = 0,27 or 27 % presupposed a proportional reduction of ventilation airflow and energy use for heating.

4.4 Variable Supply Air diffuser DCV

Conversion from CAV to Variable Supply Air diffuser requires replacements of all supply air terminal devices to Variable Supply Air diffuser and VAV units for controlling the exhaust which in many cases, can be limited to a few units connected to the corresponding VSAD based on master-slave control. Beyond this, VSAD-DCV requires no additional components in the duct system.

This means that existing CAV-based duct system can be used in a VAV-system with a minimum of changes. Most control units will be easily accessible from the rooms and easy to control, monitor and replace if necessary. VSAD-DCV have potentially the lowest need for rebuilding work to upgrade from CAV to VAV. Ductwork air tightness is not crucial for functionality.

The solution is evaluated in an upgrading from CAV to VAV-perspective by Maripuu (2009), but it is not developed and tested with CO_2 controlled airflow rates.

This solution requires variable supply air diffusers with good airflow control properties and with a low noise generation even at a high pressure drop over the device. Noise properties are especially important since potentially noise generating throttling appears so close to the occupied zone.

The typical investment cost in Norway for VSAD-DCV is about 15 EURO/(m^3/h). This is less than corresponding cost for pressure controlled DCV due to lower installation costs because of prefabrication of VAV-units and control components integrated in the supply air diffuser (Bergstrom, 2011). The investment cost for converting from CAV to VSAD-DCV is about 9-10 EURO/(m^3/h) according to Bergstrom (2011) exclusive planning costs, making this a profitable alternative to complete replacement.

4.4.1 Results from field studies

In office 01.4.30 at Campus Rosenholm, the measured airflow was 6,1 l/s ± 7% while the required airflow was 6,0 l/s. The corresponding measured sound level was 27 dBA (± 3 dBA). In office 01.3.17 the measured airflow was 42,2 l/s ± 7% while the required airflow was 44,0 l/s. The corresponding measured sound level was 30 dBA (± 3 dBA). This results show that the specific solution at Campus Rosenholm delivers quite accurate air volumes even at very low air flow rates, and does not indicate that the solution will contribute to acoustic problems even though the VAV-unit is located close to the occupied zone.

4.5 Overall discussion

In general, pressure controlled DCV is considered to use more energy than the other alternatives because of unnecessary throttling (increased fan energy) and lower accuracy leading to over ventilation to reach same minimum air flow requirements.

Table 1 shows a rough qualitative evaluation of the different systems when applied in upgrading from CAV to VAV. When it comes to installation in new buildings, the situation may be quite different.

***Table 1**: A rough qualitative evaluation of the different principles from – (potential weakness) to ++ (potential strength).*

Item	*IAQ-targets*	*Energy for heating and cooling*	*Fan energy*	*Robust-ness*	*Sensitivty to poor ductwork airtightness*	*Investment-cost*
Pressure Controlled DCV	-	-	-	+	+	-
SPR – DCV	++	++	++	+	+	--
DDCV	+	++	++	++	-	+
Variabel Supply Air Diffuser (VSAD)	++	++	++	++	++	++

DCV with variable supply air diffusers seems generally most suitable for upgrading from CAV to VAV, but project specific requirements and circumstances must be emphasized before the final choice in each project is taken.

5 Acknowledgements

This paper is funded by contributions from the industry partners **VKE** www.vke.no, **Undervisningbygg Oslo KF** www.undervisningsbygg.oslo.kommune.no, **Skanska** www.skanska.no, and **Optosense** as www.optosense.com and public funding from the Norwegian Research Council as part of the project “reDuCeVentilation”.

6 References

ASHRAE handbook (1996) *Systems and equipment, refrigerating and Air-Conditioning*, Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Bergstrøm, J. (2011) *Personell communications with Jan Bergstrøm GK AS in May 2011.*

Cappellin, T.E. (1997) *VAV Systems- What makes them succeed? What makes them fail?,* ASHRAE Transactions, no. 2, vol. 103, p. 814-822

Enova (2010) *Byggstatistikk 2008* (*Buildings statistics 2008* (in Norwegian)) Enova report 2010:2, Norway, ISBN 978-82-92502-43-3

Maripuu, M., Jagemar, L. (2004) *Energy savings by installing variable air volume systems (VAV) in existing office buildings. Experience from a new supply air terminal device concept*, in *Proceedings, 6th Int. Conf. Energy for Buildings*, October 2004, Vilnius. pp 301-311

Maripuu, M. (2009) *Demand Controlled Ventilation (DCV) Systems in Commercial Buildings Functional Requirements on Systems and Components*, Thesis For The Degree Of Doctor Of Philosophy, Building Services Engineering Department of Energy and Environment Chalmers University of Technology Göteborg, Sweden

Mysen, M., Schild, P.G., Drangsholt, F., Larsen, B.T. (2011) *Digital Demand Controlled Ventilation - An Alternative to Static Pressure Control,* Proceedings, 12th Indoor Air conference, USA, paper ID: 325.

Mysen, M., Schild, P.G. and Drangsholt, F. (2010) *Robustness and True Performance of Demand Controlled Ventilation in Educational Buildings – Review and Needs for Future Development,* Proceedings, 31st AIVC Conference, 'Low Energy and Sustainable Ventilation Technologies for Green Buildings', Seoul

Mysen, M. (2005) *Ventilation Systems and their Impact on Indoor Climate and Energy Use in Schools,* Doctoral Theses at NTNU. Trondheim, Norway, 2005:111

Mysen, M., Berntsen, S., Nafstad P. and P, Schild P.G (2005) *Occupancy density and benefits of demand-controlled ventilation in Norwegian primary schools*, Energy and Buildings, 37 (2005) 1234-1240

Mysen, M., Rydock, J.P. and Tjelflaat, P.O. (2003) *Demand controlled ventilation for office cubicles – can it be profitable?* Energy and Buildings, 35 657-662

Nordiska Ventilationsgruppen Byggforskningsrådet (2007) *Metoder för mätning av luftflöden i ventilationsinstallationer (Methods for airflow measurements in ventilation plants* (In Swedish)) Forskningsrådet FORMAS Sweden, ISBN 978-91-540-6001-6

Norwegian Standard NS8175 (2008) *Acoustic conditions in buildings - Classification of various types of buildings,* Standards Norway, http://www.standard.no/

OECD/IEA (2008) *Energy Technology Perspectives, Scenarios & Strategies to 2050*, International Energy Agency, Head of Communication and Information Office, Paris, France

Schild, P.G. and Mysen, M. (2009) *Recommendations on Specific Fan Power and System Efficiency*, Technical Note AIVC 65, International Energy Agency, Energy conservation in buildings and community systems programme.

Wigenstad, T. and Grini C. (2010) LECO *Fra normbygg til Faktor 10* (LECO From standard building to factor 10 ((in Norwegian)), Project Report 51, SINTEF Building and Infrastructure, Norway, ISBN 978-82-536-1133-4