CH-15-027

Analysis and Monitoring of Energy Consumption and Indoor Climate in a School Before and After Deep Energy Renovation

Jørgen Rose, PhD **Kirsten Engelund Thomsen**

Niels C. Bergsøe, PhD **Ove Christen Mørck, PhD**

ABSTRACT

Denmark is participating in the International Energy Agency—Energy in Buildings and Communities (IEA-EBC) Annex 61, titled Development and Demonstration of Concepts for Deep Energy Retrofit in Government/Public Buildings*. The purpose of IEA-EBC Annex 61 is to improve the decision-making process to achieve deep energy retrofits of government/public buildings, starting with the determination of working bundles of technologies and corresponding business models using combined public and private funding.*

Denmark will contribute to the project with seven buildings in total—two schools and five kindergartens/institutions— that will undergo deep energy renovation over the next few years. The seven buildings are being energy-renovated and monitored with support from the European Union-CONCERTO initiative as part of the project titled Cost-Effective Low-Energy Advanced Sustainable Solutions—Class1 *(2014). The buildings are very different and therefore the energy renovations vary from building to building. The gross list of energy-saving measures that have been implemented includes improved insulation of roof and external walls, new low-energy windows and shading systems, new or renewed ventilation systems with heat recovery, low-energy lighting, water-saving measures, improved insulation of piping, and improved control using building energy management systems. This paper presents preliminary results of the analysis and monitoring of energy consumption and indoor climate in one public school before and after deep energy renovation.*

INTRODUCTION

Improving the energy efficiency of buildings represents a key target area in European countries, because 40% of the total energy consumption in the European Union is related to the building sector (European Commission 2010). This requires, among other things, increasing the energy standard of existing buildings in order to reduce heat loss through building envelopes, and implementing a greater share of renewable energy in buildings.

The scope of the International Energy Agency—Energy in Buildings and Communities (IEA-EBC) Annex 61 project is to improve the decision-making process associated with achieving deep energy renovation of government/public buildings (office/administrative buildings, dormitories/ barracks, educational buildings, etc.), starting with the determination of working bundles of technologies and corresponding business models using combined public and private funding. This decision-making process must improve to overcome existing barriers in the execution of complex projects co-funded by government, public entities, energy service companies, and other market partners. Barriers include the exclusion of individual energy conservation measures (ECMs) with long payback times and the challenges of combining energy-related measures with non-energy-related measures (e.g., building sustainment, repurposing, and improvement in quality of life). The objectives of IEA-EBC Annex 61 are the following:

- To provide a framework and selected tools and guidelines to significantly reduce energy use (by more than 50%) and to improve indoor environment quality in government and public buildings and building communities undergoing renovation
- To gather and, in some cases, research, develop, and demonstrate innovative and highly effective bundled packages of ECMs for selected building types and climatic conditions

Jørgen Rose, **Kirsten Engelund Thomsen**, and **Niels C. Bergsøe** are senior researchers in the Department of Energy and Environment, Danish Building Research Institute, Aalborg University, Copenhagen, Denmark. **Ove Christen Mørck** is partner at Cenergia Energy Consultants, Herlev, Denmark.

- To develop and demonstrate innovative, highly resource-efficient business models for retrofitting/refurbishing buildings and community systems using appropriate combinations of public and private funding such as energy savings performance contracts and other concepts to be developed together with the building owners
- To support decision makers in evaluating the efficiency, risks, financial attractiveness, and contractual and tendering options conforming to existing national legal frameworks
- To engage end users, mainly building owners and other market partners, in the proceedings and work of the IEA-EBC Annex 61 subtasks

The IEA-EBC Annex 61 working phase was started in July 2013 and ends in September 2016.

Egedal Municipality is participating in the European Union Class1 project with energy renovation of seven municipal buildings. The Class1 project is part of the CONCERTO initiative (European Commission 2014). In a CONCERTO project, energy conservation within buildings and renewable energy supply go hand-in-hand in a chosen community. Egedal Municipality is participating with the town of Stenløse, where a number of new dwellings have been constructed and renovation of public/municipal buildings has been carried out. The renewable energy supply will be in the form of large-scale photovoltaic (PV) installations on the municipal buildings.

The municipal buildings that have undergone the energy renovation will be the Danish contribution to IEA-EBC Annex 61—Development and Demonstration of Financial and Technical Concepts for Deep Energy Retrofits of Government/Public Buildings and Building Clusters.

RENOVATION OF PUBLIC BUILDINGS IN EGEDAL

The Energy Renovation Projects—A Short Presentation

The energy renovations carried out by Egedal Municipality encompass seven public buildings: two schools—Bækkegårdsskolen and Stengårdsskolen—and five kindergartens/institutions. The total area renovated is 20,443 m^2 (220,046 ft^2). The two schools are approximately 8500 and 9000 m^2 (91,493 and 96,875 ft^2), respectively, and the remaining buildings between 500 and 1000 m^2 (5382 and 10,764 ft^2). Stengårdsskolen consists of two buildings erected in the years 1970–1978. The external walls are concrete sandwich-type walls with an insulation thickness of 75 mm (29.5 in.) (Figure 1).

The main—most costly—energy renovation measure is external insulation with new cover plates of all the external walls, shown in Figure 2.

Installation of PV Systems on the Public Buildings

The municipality of Egedal has installed nine PV systems comprising a total of 916.3 kWp (868 Btu/s) with a total guaranteed annual electricity production of 885,113 kWh ($3.02 \cdot 10^9$ Btu). Figure 3 shows one of the facilities.

The Energy Renovation to Take Place

The energy renovation of the seven public buildings has been split into two major packages: Package 1 is the façade renovation of Stengårdsskolen, which was designed to give a complete new impression of the school from the outside. An architectural company has designed the new façade and is responsible for the implementation. Package 2 was all other energy renovation works on the seven buildings. This package is handled by a local engineering company who has contracted each part to different subcontractors depending on the nature of the renovation works. The energy renovation technologies in play are:

- Installation of building energy management systems for better control of heating and ventilation systems, including circulation of domestic hot water

Figure 1 *Stengårdsskolen before renovation.*

Figure 2 *Schematic rendering of Stengårdsskolen after renovation.*

Figure 3 *PV installation at Stengårdsskolen: 220 kWp (209 Btu/s)—annual production 173 MWh (590 × 10^6 Btu).*

- Installation of decentralized, mechanical, CO_2-based demand-controlled ventilation in classrooms
- Insulation of pipes, ducts, and heat exchangers
- Insulation of roofs
- Insulation of floors above basements
- Insulation of basement floor toward the ground
- Insulation of walls toward noninsulated rooms
- New, well-insulated light façade system
- Change of piping including layout, and dismantling of electrical heating of piping (electric tracing)
- Change from electrical to hydronic preheating of ventilation air
- Closing down old exhaust ventilation systems
- installation of new ventilation systems with heat recovery
- Replacing windows and doors
- New electrical lighting system
- Mounting of solar collectors
- Closing of old roof lights
- Installation of new, low-energy circulation pumps on the hydronic heating system

The engineering company has carried out optimization calculations for all buildings and identified which technologies are to be implemented in which buildings. In this paper we use Stengårdsskolen as an example, and the technologies implemented there are:

- New façades on external walls, including 250 mm (98.4 in.) of additional insulation
- New mechanical ventilation system with an 82% heat recovery rate
- New electrical lighting system with advanced control and increased efficiency
- Improved/increased insulation of technical installations, such as pipes and ducts
- Improved electrical lighting system in the basement, e.g., movement sensors
- New circulation pumps on the hydronic heating system: lower power, better controls
- PV system on the roof: 1495 m^2 (16,092 ft^2) panels with a peak power of 0.15 kW/m^2 (47.5 Btu/h·ft^2)

ENERGY CALCULATIONS AND MEASUREMENTS

Calculations

The overall CONCERTO requirement is that the energy renovation of the buildings shall result in a final energy consumption that does not exceed what is required for new buildings according to the building regulation (BR) in force. In this case, the Class1 project was initiated in autumn 2007 and the BR in force was BR08 (Danish Enterprise and Construction Authority 2008).

The buildings are of different ages, and therefore their energy consumption varies in the range from 145–284 kWh m^2/yr (45,979–90,056 Btu/ft^2/yr) (calculated according to the Danish energy-frame calculation procedure, where electricity consumption is multiplied by a factor of 2.5). The goal, according to BR08, is an energy frame of 95 kWh m^2/yr (30,124 Btu/ft^2/yr), corresponding to reductions of 34%–67% in energy use.

The school has a prerenovation primary energy consumption of about 145 kWh/m^2/yr (45,979 Btu/ft^2/yr). Calculated results for Stengårdsskolen are presented in Figure 4 and Table 1.

It appears that the primary energy consumption at Stengårdsskolen is reduced by 34% by implementing the energy renovation measures. Taking into consideration the energy production by the PV system on the school, the primary energy is reduced an additional 49 kWh/m^2/yr (15,538 Btu ft^2 yr) down to 39 kWh/m^2/yr (12,367 Btu/ft^2/yr), which corresponds to what is today referred to as *low-energy class 2015* requirements in the present Danish building regulations. Low-energy class 2015 is expected to become the requirement for new buildings from 2015 and onwards (Danish Enterprise and Construction Authority 2010).

The total CO_2 reduction is 394 tons/yr (868,621 lb/yr) for the energy saving measures and 87 tons/yr (191,802 lb/yr for the PV system, i.e., a total amount of CO_2 reduction of 481 tons/yr (1,060,423 lb/yr).

Measurements

Systems for continuous energy monitoring have been installed on all seven Class1 public buildings. The system is Internet-based and all data are available online. In a similar way, online monitoring of the electricity production of all PV systems has been installed.

This analysis is based on the data from August 2013 to March 2014—almost a full winter season. These eight months have, in total, 80% of the average heating degree-days in Denmark. Therefore, to estimate the heating energy consumption for a full year, the degree-day-corrected monitored heating energy data for these eight months was multiplied by a factor of 1.25. The electricity consumption for the full year is established in a similar way by multiplying by a factor of 1.5 (12/8).

In Table 2, the average annual heating energy consumption over the six years is compared to the heating energy consumption after the energy renovation—both the totals and normalized consumption per m^2 is shown.

Furthermore, in Table 2, the average yearly total electricity consumption before the renovation is compared to the total electricity consumption after the energy renovation. It is obvious that the reductions are relatively smaller than for heating consumption. The main reason for this is that within the total electricity consumption there is a large fraction of electricity consumption that is directly related to the use within the buildings: computers, photocopiers, refrigerators, and other electrical equipment.

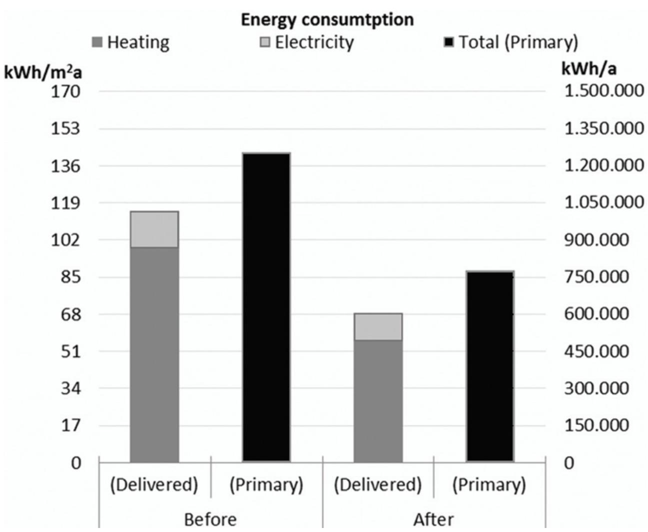

Figure 4 *Calculated, delivered, and primary energy consumption before and after the energy renovation. 1 m^2 = 10.7639104 ft^2.*

Table 1. Calculated Energy Consumption Before and After the Energy Renovation of Stengårdsskolen

Annual Energy Consumption	Heating, kWh/m^2 (Btu/ft^2)	Electricity, kWh/m^2/yr (Btu/ft^2/yr)	Total (Primary), kWh/m^2/yr (Btu/ft^2/yr)	Total (Primary), kWh/yr (Btu/yr)
Before energy renovation	97.7 (30,981)	17.7 (5613)	142.0 (45,028)	1,254,412 (4.28·109)
After energy renovation	55.5 (17,599)	13.0 (4122)	88.0 (27,905)	777,656 (2.65·109)
Energy saving	42.2 (13,382)	4.7 (1490)	54.0 (17,123)	476,756 (1.63·109)

Statistical information about the building-related electricity consumption for ventilation and lighting (and cooling) is available for a large number of Danish schools and institutions. Based on this, an average percentage of 55% has been used to calculate that part of the total electricity consumption for the average consumption over the six years before the energy renovation. After the energy renovation and the installation of the new monitoring equipment, electricity meters are monitoring the electricity for ventilation—the separate electricity consumption for lighting could not be measured in a cost-efficient way and has therefore been estimated based on statistical information. For the energy-frame calculation, the electricity consumption for ventilation and lighting is added and multiplied by a factor of 2.5, and the total is then added to the heating consumption. Finally, the total is divided by the heated area of the individual buildings.

INDOOR CLIMATE MEASUREMENTS

Investigations were performed in two classrooms at Stengårdsskolen located in Egedal Municipality. The investigations were performed in two periods—before the ventilation systems were renovated (February 2013) and after the ventilation systems were renovated (January 2014).

During both periods, the investigations comprised continuous registration of indoor air temperature, relative humidity, and CO_2 concentration. Registrations were made using programmable data loggers with registration every five minutes. Furthermore, the ventilation in the classrooms was measured using passive tracer gas technique, called the *PFT technique*. Measurements with the PFT technique are performed over a period, and the result of a measurement is the average ventilation condition during the measurement period. Finally, surveys among the students were conducted.

Table 2. Measured Heating and Electricity Consumption Before and after Energy Renovation

Stengårdsskolen	2007–2012		After Renovation	
	kWh (Btu)	kWh/m^2/yr (Btu/ft^2/yr)	kWh (Btu)	kWh/m^2/yr (Btu/ft^2/yr)
Heating consumption, degree-day adjusted	1,065,809 ($3.64 \cdot 10^9$)	120.6 (38,242)	707,001 ($2.41 \cdot 10^9$)	80.0 (25,368)
Total electricity	244,929 ($0.84 \cdot 10^9$)	27.7 (8784)	191,028 ($0.65 \cdot 10^9$)	21.6 (6849)

The investigations performed before the ventilation systems were renovated were conducted from February 1 to February 20, 2013. The period included a normal working week, from February 4 to February 8, which is reported in this document. The investigations performed after the ventilation systems were renovated were conducted during a normal working week from January 20 to January 24, 2014. Concerning both periods, the passive tracer gas measurements included the preceding weekend.

Renovated Ventilation System

In most classrooms in the school, including rooms 58 and 40, which were the focus in this experiment, new mechanical ventilation units have been installed, as shown in Figure 5 and Figure 6. In each room the ventilation rate is controlled according to both temperature and CO_2 concentration. In addition, the units are timer controlled, turning on one hour before teaching begins and off one hour after the last lesson.

It is possible for each of the classrooms at Stengårdsskolen to identify periods where there is a uniform, continuous decay in the CO_2 concentration. Assuming the classroom is unoccupied during periods with a uniform, continuous decay in the CO_2 concentration, the air change rate during these periods can be determined on the basis of decay curves.

The calculation is based on rewriting the equilibrium equation as follows:

$$\eta = 2.3 \cdot \frac{\log\left(\frac{c_1 - c_i}{c_2 - c_i}\right)}{\tau_2 - \tau_1}$$

Figure 5 *New ventilation units installed in room 58.*

Figure 6 *New ventilation units installed in room 40.*

Table 3. Results of Ventilation Measurements Using PFT Technique

Schoolroom	Measurement Period		Air Changes per Hour, h^{-1}
Room 58, before renovation	Feb. 1 to Feb. 8, 2013	Normal week + weekend	0.29 ± 15 %
Room 58, after renovation	Jan. 17 to Jan. 24, 2014	Normal week + weekend	0.40 ± 11 %
Room 40, before renovation	Feb. 1 to Feb. 8, 2013	Normal week + weekend	0.86 ± 15 %
Room 40, after renovation	Jan. 17 to Jan. 24, 2014	Normal week + weekend	0.45 ± 11 %

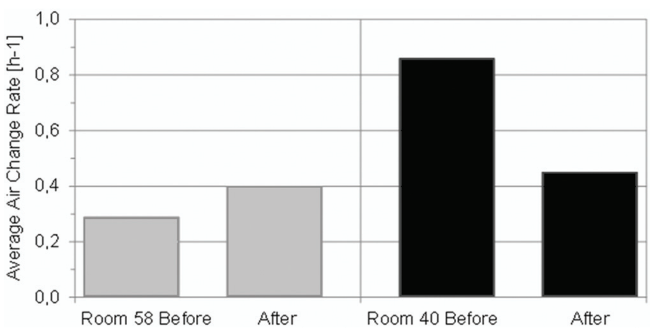

Figure 7 *Room 58 and room 40 average air change rates before and after renovation.*

Where η is the air change rate (h^{-1}), c_1 and c_2 are concentrations at time τ_1 (h) and τ_2 (h), respectively, and c_i is the background concentration.

The calculation takes into account the background concentration of CO_2. Through comparing this result with the result of the ventilation measurement using the PFT technique, which determines the average air change rate during the entire period, the air change rate during periods of use—i.e., teaching time—can be estimated.

Results of Measurements

Table 3 and Figure 7 show the results of the measurements of the average air change rate in the two classrooms before and after renovation.

Figures 8 and 9 serve as an example of the presentation of results of measurements of room air temperature, relative humidity, and CO_2 concentration in a classroom. The overall picture from the results of the measurements is that the ventilation conditions in the classrooms have improved significantly, first and foremost in terms of reduced CO_2 concentrations and room air temperatures, but also in terms of more steady ventilation rates.

Ventilation

The results of the ventilation measurements using the PFT technique show that in February 2013, i.e., before the renovation, the ventilation rates in the rooms were very different. In room 58 the ventilation rate was about 0.3 h^{-1} and in room 40 it was more than 0.8 h^{-1}. After the renovation the average ventilation rate is roughly the same in both classrooms, about 0.4 h^{-1}.

CO_2 Concentration

In February 2013, i.e., before the renovation, the CO_2 concentration in room 58 one day peaked at more than 3000 ppm. Other days the CO_2 concentration reached about 2000 ppm. In room 40, the CO_2 concentration generally reached between 1000 and 1500 ppm during the day.

In January 2014, i.e., after the renovation, measurement results show that in both classrooms the CO_2 concentration was kept well below 1000 ppm, except for one day when the CO_2 concentration in room 58 peaked at just below 1000 ppm.

Informative note: Requirements in the current Danish building regulations are that the outdoor air supply to a classroom must be no less than 5 L/s (1.32 gal/s) per person plus 0.35 L/s per m^2 (1.00 gal/s per ft^2) floor area. In addition, the CO_2 concentration in the room air must not exceed 0.1% for an extended period of time.

Room Air Temperature

Before the renovation the average room air temperature was 22°C–24°C (71.6°F–75.2°F) in both classrooms with peaks of more than 25°C (75.0°F). After the renovation, the room air temperature is, to a large extent, more stable and typically around 20°C–21°C (68.0°F–69.8°F).

Results of Questionnaires

Questionnaires were distributed among the students before and after renovation of the ventilation systems in the two classrooms. The questionnaires were on the students' assessments of room air temperature, indoor air quality, daylight and artificial light conditions, and acoustics and noise conditions. The questions concerning room air temperature and indoor air quality were divided into focusing on summer conditions and winter conditions, respectively.

Figures 10 and 11 serve merely as examples of the presentation of the results of the students' assessments. It should be noted that the students in the classrooms before the renovation are different from the ones in the classrooms after the renovation.

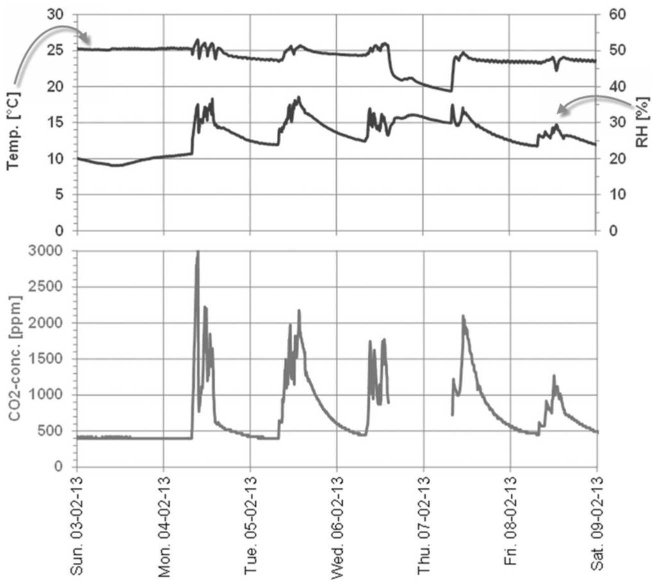

Figure 8 *Room air temperature, relative humidity, and CO_2 concentration of room 58 before the renovation.*

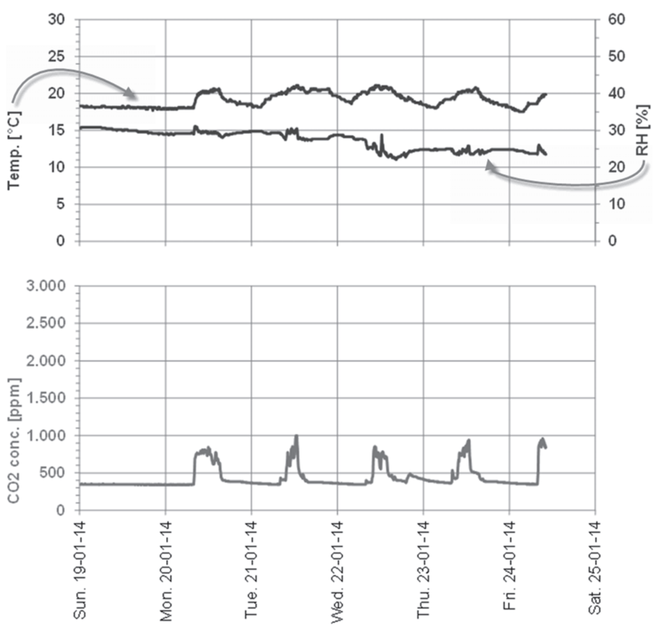

Figure 9 *Room air temperature, relative humidity, and CO_2 concentration of room 58 after the renovation.*

Room Air Temperature and Acceptability

Regarding room 58, the students' assessments of the room air temperature and the acceptability during summer conditions (two separate questions) show no difference between before the renovation and after the renovation. About 70% of the students find the room air temperature to be "to the warm side" and 85% find it acceptable.

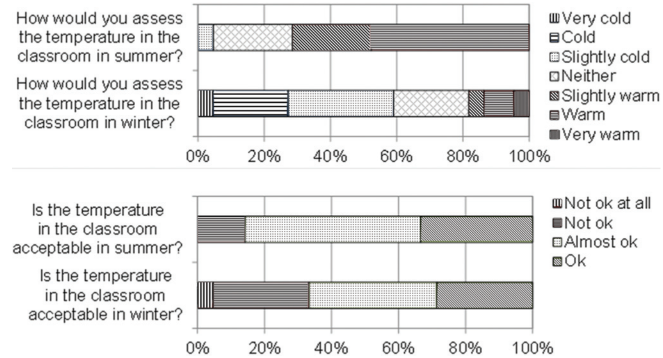

Figure 10 *Students' assessment of the temperature summer and winter, respectively, in room 58 before the renovation.*

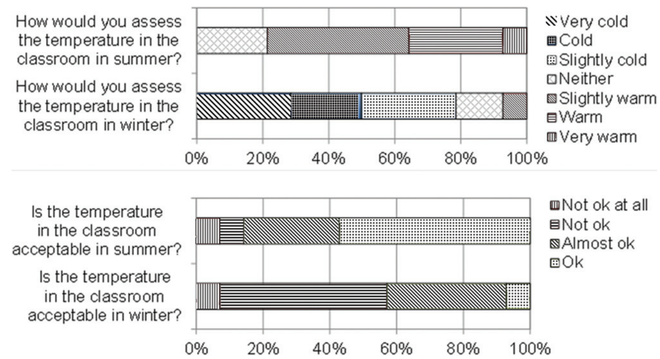

Figure 11 *Students' assessment of the temperature summer and winter, respectively, in room 58 after the renovation.*

Regarding room 40, there is a slight shift in the students' assessments from before the renovation to after the renovation. An increasing number of students find the room air temperature to be "to the warm side" (80% → 90%) and an increasing number of students find it acceptable (90% → 100%).

Concerning winter conditions, in room 58, a shift in the students' assessments is noted as more students find the room air temperature after the renovation to be 'to the cold side' (60% → 80%) and more students find it acceptable (35% → 60%). In room 40, no particular shift is noted: about 65% of the students find the room air temperature to be "to the cold side" and about 25% find it acceptable.

Indoor Air Quality and Acceptability

Regarding the students' assessments of the indoor air quality during summer conditions only small changes are noted from before the renovation to after the renovation. This is true for both room 58 and room 40. Concerning winter conditions, in room 58 the students' assessments are shifted towards "fresh"; however, at the same time, an increasing number of students find the air quality less acceptable. In room

40, no significant changes are noted from before to after the renovation.

Light—Daylight and Artificial Light

The renovation of the ventilation systems is not expected to cause changes in the lighting conditions in the classrooms. Nevertheless, in both classrooms a shift is noted in the students' assessments towards more "bright" and less "dark" conditions. This applies to both daylight and artificial light.

Regarding issues such as operation of the artificial light, glare from the artificial light, and ability to see out of the windows, the students are indicating a high degree of satisfaction on all three parameters. Changes from before the renovation to after the renovation are not observed.

Acoustics and Noise

The renovation of the ventilation systems is not expected to cause changes in the acoustic conditions in the classrooms. However, after the renovation an increasing number of students in room 58 find the acoustics neither "hard" nor "resonant." Of the students not ticking "neither" in the questionnaire (i.e., ticking either "hard" or "resonant"), 1/3 find the acoustics to be "hard" and 2/3 find the acoustics "resonant." This is valid for both before the renovation and after the renovation.

In room 40, the students' assessments of the acoustics in the room show a slight shift towards "resonant." The students' assessments of acoustics and noise in terms of ability to hear instructions from the teacher, noise from ventilation unit and the projector and other classroom equipment, noise from outside (windows open), noise from outside (windows closed), and noise from adjacent rooms generally indicate improved conditions and generally a high degree of satisfaction. One exception, though, is in room 58 where noise from adjacent rooms apparently has worsened significantly after the renovation. Before the renovation about 10% of the students found the conditions "not OK" whereas after the renovation 60% find the conditions "not OK."

It must be kept in mind when evaluating the students' assessments that the students participating in the two periods, before renovation and after renovation, were not the same students.

CONCLUSION

Denmark is participating in IEA-EBC Annex 61 and will contribute with seven public buildings that have undergone deep energy renovation. This paper presents measurements and calculations of indoor climate and energy consumption from one public school before and after renovation.

Indoor climate measurements show that the average air change rate in the classrooms before renovation is rather low—0.3–0.9 ach during a normal week. Consequently, CO_2 concentrations are somewhat high, in particular during class hours where the CO_2 concentration generally peaks at about 2000 ppm in room 58 and about 1500 ppm in the other classrooms investigated. The indoor temperature is high, about 25°C (77.0°F) during class hours, as well as during weekends and holidays. In room 40 at Stengårdsskolen, the average temperature is 3°C–4°C (5.4°F–7.2°F) lower. The overall picture from the results of the measurements after renovation of the ventilation system is that the ventilation conditions in the classrooms have improved significantly, first and foremost in terms of reduced CO_2 concentrations and room air temperatures but also in terms of more steady ventilation rates.

Calculations of energy consumption for Stengårdsskolen show an expected reduction in heating from 97.7 to 55.5 kWh m^2/yr (17,599 to 30,981 Btu/ft^2/yr). The measurements of the heating consumption show that the reduction is on the same level as expected, i.e., approximately 40 kWh/m^2/yr (12,684 Btu/ft^2/yr).

REFERENCES AND BIBLIOGRAPHY

Bergsøe, N.C. 2011. *BR's boligventilationskrav. Beherskes kravene og efterleves de i nye boliger?* SBi 2011:21. Statens Byggeforskningsinstitut (SBi). AAU. In Danish.

Class1 Project. 2014. The CONCERTO Initiative of the EU's 6th Framework Program. www.class1.dk.

Danish Enterprise and Construction Authority. 2008. *Building Regulation 2008.* Copenhagen: the Danish Ministry of Economic and Business Affairs.

Danish Enterprise and Construction Authority. 2010. *Building Regulation 2010*. Copenhagen: the Danish Ministry of Economic and Business Affairs.

European Commission. 2010. Directive 2010/31/EU of the European Parliament and of the council of 19 May, 2010 on the energy performance of buildings (recast). *Official Journal of the European Union*. http://eur-lex.europa.eu /LexUriServ/LexUriServ.do?uri=OJ:L :2010:153:0013:0 035:EN:PDF.

European Commission. 2014. *CONCERTO initiative—Energy solutions for smart cities and communities*. http://concerto.eu/concerto/

Madsen, J. and O. Mørck. 2013. *Class1 cost-effective low-energy advanced sustainable so1utions integrated project contract no.: 038572 interim activity report after 66 months.* Denmark: the Municipality of Egedal and Cenergia Energy Consultants.

Mørck, O., K.E. Thomsen, J. Rose, and M.D. Jørgensen. 2011. *Demonstration af omkostningseffektive lavenergibygninger. Stenløse, January 2011*. Statens Byggeforskningsinstitut (SBi). Cenergia Energy Consultants. In Danish.