OR-16-025

# EU Project "School of the Future"—Refurbishment of School Buildings Toward Zero Emission with High-Performance Indoor Environment

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## ABSTRACT

*The aim of the School of the Future project (Fraunhofer-IBP 2015), which receives funding within the European Union's 7th Framework Program, is to design, demonstrate, evaluate, and communicate shining examples of how to reach the future high-performance building level. School buildings, their owners, and their primary users, namely students, i.e., the next generation, are the focus of the project. The energy and indoor environment performance of four demonstration buildings in four European countries and climates have been significantly improved due to holistic retrofits of the building envelope, their service systems, and the integration of renewables and building management systems. It is anticipated that the results of the project and the associated research and dissemination efforts will support others dealing with building retrofits and will thereby have a multiplied impact on other schools and on the residential sector since the students will act as communicators to their families. Training sessions specifically tailored to their needs have improved user behavior and awareness of energy efficiency and indoor environment. The success is measured by how well the retrofits meet the following goals:*

- *Reduction of the total energy use by more than a factor of 3, verified through monitoring*
- *Reduction of the heating energy use by more than 75%, verified through monitoring*

*The improvement of the indoor environment quality (air, daylight, acoustic, thermal comfort) and the associated impact on the students' performance will be analyzed by short-term measurements and questionnaires.*

*The work of the local integrated planning teams responsible for retrofitting the demonstration buildings at each city (Stuttgart, Germany; Cesena, Italy; Ballerup, Denmark; and Drammen, Norway) was mirrored by the Design Advice and Evaluation Group, which is composed of all industry and research partners of the project. Highlights of the retrofit technologies applied in the four schools include greatly improved thermal quality of the opaque building envelope components, triple-glazed windows (also in a listed historic, heritage protected building), an automatically controlled natural ventilation system based on $CO_2$ sensors, a cogeneration unit, a ground-coupled heat pump, subdivision of heating circuits, adaptation of the heating and ventilation system operation to actual room use, rooftop-mounted photovoltaic systems, LED lighting, and removal of an external brick façade plus addition of insulation and new lightweight façade envelope.*

*This paper provides an introduction to the EU project. It includes all results and a comparison of the four demonstration buildings as well as a more detailed description of the German demonstration project.*

## CONCEPT OF THE PROJECT

The concept of the School of the Future project consists of the following three main parts:

1. Design, demonstration, and evaluation of highly energy-efficient retrofitting measures for schools in four different European countries with differing climates
2. Development of guidelines and tools, building upon existing knowledge and tools, that are applicable throughout the EU countries

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3. Dissemination of results, guidelines, and tools, including training activities

The part “design, demonstration and evaluation” of the school retrofits simultaneously addresses two major challenges: energy savings and indoor environment quality.

The development of guidelines and tools builds on existing knowledge and advances already-available instruments to combine energy efficiency and indoor environmental quality. The guidelines and tools are applicable throughout the EU countries. The guidelines address four different subjects: building construction components, building services systems, improved indoor environment quality, and solution sets for zero-emission schools.

Two types of simple-to-use tools are being further developed: one that focuses on the presentation of information, such as case studies and retrofit technologies (which will also contain the guidelines and a benchmark system for average and best-practice energy performance data), and one that allows assessing the energy performance of school buildings with and without retrofit measures. The main target groups of the information tool are public authorities and planners. The calculation tool enables different user groups, including students, to perform a simple assessment of the energy quality of school buildings.

The project results and the deliverables are available on the project website and on the EU platform for energy efficiency in buildings “BUILD UP” (2015). Here, the project submits results and deliverables as news, publications, tools, and case studies. A community “School of the Future” was started that provides a platform for discussions and gathers targeted information on energy-efficient school buildings with high levels of indoor comfort.

The training activities support the energy saving retrofits by providing the building users (students, teachers/office workers, and caretakers) with information on how to correctly use the building and the integrated technologies to enable further reductions in energy use.

## OBJECTIVES OF THE PROJECT

The objectives of the School of the Future project are as follows:

- To raise public awareness of energy conservation by presenting real-world examples of highly energy-efficient retrofit projects of school buildings that will lead the way to carbon-free approaches, while ensuring high-performance indoor environments. Success of the retrofits are measured by how well they meet the following goals:
    - Reducing the total energy use by more than a factor of 3, verified through monitoring
    - Reducing the heating energy use by more than 75%, verified through monitoring
    - Improving the indoor environment quality (air quality, daylighting, acoustics, thermal comfort), which will impact the students’ performance, to be analyzed by short-term measurements and questionnaires
- To demonstrate that substantial energy savings can be achieved at limited additional costs (< 100 €/m$^2$ [11 \$/ft$^2$]). This will motivate other actors in the sector to increasingly apply the concepts. Schools of the future can be realized already today
- To reduce the hesitation to use innovative, energy saving retrofit concepts in public building administrations by providing reliable information, including energy saving potentials and costs
- To develop national and European benchmarking systems, including those that will estimate the potentials of innovative, cost-efficient energy retrofit strategies

## MAIN RESULTS SO FAR

### Development of the Energy-Efficient Retrofit Concepts for the Four Demonstration School Buildings

The development of the retrofit concepts for the four demonstration school buildings in Stuttgart (Germany [D], ASHRAE International Climate Zone 5), Cesena (Italy [I], ASHRAE International Climate Zone 4), Ballerup (Denmark, [DK], ASHRAE International Climate Zone 5), and Drammen (Norway [N], ASHRAE International Climate Zone 6 [see Figure 1]) followed the defined energy efficiency goals of the project, namely the reduction of the total energy use by a factor of 3 and the reduction of the heating energy use by more than 75%, while ensuring improved indoor environmental quality. The work of the local integrated planning team in each city was mirrored by the Design Advice and Evaluation Group (Figure 2), which includes all industry and research partners involved in the project. Two meetings were held at each school building, in which the energy concept was reviewed and proposals for further improvement and for innovative technologies were made. The local planning group then evaluated this advice in terms of applicability and a final retrofit concept was designed.

Highlights in the four energy efficient retrofit projects are:

- The thermal quality of the building envelope of the Solitude Gymnasium in Stuttgart, Germany was greatly improved by insulation improvements and window replacement (triple glazing). There is an automatically controlled natural ventilation system based on $CO_2$ sensors. The heating for all building units is provided by a cogeneration unit. Together with the photovoltaic system on the roof, electricity is generated by the school building, which is connected to the city’s long-term monitoring and control system after the renovation.

***Figure 1*** *Photos of the four school buildings in the School of the Future project (top row: before retrofitting, bottom row: after retrofitting). From left to right: Solitude Gymnasium in Stuttgart, Tito Maccio Plauto Middle School in Cesena, Hedegårdsskolen in Ballerup, and Brandengen skole in Drammen.*


***Figure 2*** *Workflow of the Design Advice and Evaluation Group supporting the demonstration partners and the local planning team during the design, realization, and evaluation phases of the retrofit projects.*

- At the Tito Maccio Plauto Middle School in Cesena, Italy, the renovation measures include the insulation of the exterior walls, the cellar ceiling, and the attic, which eliminates various previously existing thermal bridges. Modifying boilers by adding advanced control systems and by subdividing the heating circuit will ensure the energy-efficient operation of the heating system. Adapting the operation of the heating system and the mechanical ventilation system to the actual use of the rooms will further reduce the use of heating energy. A photovoltaic system on the roof will decrease the use of electricity from the grid.
- At Hedegårdsskolen in Ballerup, Denmark, it was decided to demolish the external brick wall layer and to add insulation and a light façade envelope instead. Rooftop photovoltaics and different lighting systems that will be tested in classrooms are also part of the renovation concept.
- The Brandengen skole in Drammen, Norway, a listed building, was allowed to replace the windows with triple-glazed windows after several meetings with the historic monuments protection authorities. The walls between the mansard windows and the floor of the attic were insulated. Heat is provided by a geothermal heat pump, and the existing ventilation ducts were insulated.

Table 1 lists the window and roof U-factors of the four school buildings before and after renovation. Please note that some of the schools consist of more than one building. During the renovation process, the envelope structures of some buildings were modified. A comparison of all four demonstration

**Table 1. U-factors of the School Buildings' Envelopes Before and After the Renovation**

| Location | | U-Factors: $W/m^2K$ ($Btu/hr \cdot ft^2 °F$) | | | |
|---|---|---|---|---|---|
| | | Solitude Gymnasium, Stuttgart (D) | Tito Maccio Plauto School, Cesena (I) | Hedegårdsskolen, Ballerup (DK) | Brandengen skole, Drammen (N) |
| Wall | Before | 0.44–3.65 (0.077–0.643) | 1.8–2.8 (0.317–0.493) | 0.57 (0.100) | 0.85 (0.150) |
| | After | 0.18–0.23 (0.032–0.041) | 0.28–0.31 (0.049–0.055) | 0.10 (0.018) | 0.81 (0.143)* |
| Window | Before | 3.1–5.80 (0.546–1.02) | 6.0 (1.06) | 3.1 (0.546) | 2.6 (0.458) |
| | After | 0.9–1.30 (0.158–0.229) | 1.2 (0.211) | 0.7 (0.123) | 0.8 (0.141) |
| Roof | Before | 0.67 - 0.96 (0.118 - 0.169) | 2.3 (0.405) | 0.45 (0.079) | 1.15 (0.203) |
| | After | 0.15–0.20 (0.026–0.035) | 0.18–0.20 (0.032–0.035) | 0.06 (0.011) | 0.12 (0.021) |
| Ground floor | Before | 1.50 (0.264) | 1.3 (0.229) | 0.40 (0.070) | 0.19 (0.033) |
| | After | 1.50 (0.264) | 0.28–1.3 (0.049–0.229) | 0.40 (0.070) | 0.15 (0.026)** |

* slight improvement due to resealing of cement fillets in the brick facade
** slight improvement due to reduction of cold bridge between the cellar wall and the ceiling

buildings shows that the U-factors before the retrofit differed widely, especially those pertaining to buildings of the Italian school that had single-glazed windows. After retrofitting, however, they reach nearly the same level: about 1.0 $W/m^2K$ (0.176 $Btu/h \cdot ft^2 °F$) for the windows and 0.11 to 0.20 $W/m^2K$ (0.019 to 0.035 $Btu/h \cdot ft^2 °F$) for the roof construction. A report documenting the design phase of all four demonstration school buildings is available on the project website (Zinzi et al. 2013).

Table 2 lists the calculated final energy performance of all four school buildings before and after the retrofit and the saving percentages.

The renovation of the four buildings is now completed, and the 1-year monitoring phase has started. A building diary with information on the building process (including photos and other material from construction site visits and planning meetings) is available on the project website (www.school-of-the-future.eu). The results of the commissioning and monitoring activities will be documented in the final demonstration building report of the School of the Future project to be published in February 2016.

## Database of Publications and Projects about Energy Efficiency and Indoor Environment Quality

The database on the project website (Buvik et al. 2013) includes a bibliography of publications about greenhouse gas emissions related to energy consumption, effects of indoor climate on health and performance, and relations between energy efficiency and indoor environments. Furthermore, the database includes information about international projects relevant to school building retrofitting, and suitable research programs and centers that were established in the participating countries.

## Guideline Relating to the Assessment of the Indoor Environment, Including an Occupant Questionnaire for Complaint Discovery and Measurement Instructions

To provide a basis for the indoor comfort survey in the four school buildings before and after the renovation, the Design Advice and Evaluation Group has developed a user questionnaire covering various indoor comfort areas (indoor air quality, lighting, noise, temperature, etc.). The report (Steiger et al. 2012), which is applicable to other projects as well, also includes background information for measuring indoor comfort.

## Screening of Possible Retrofit Technologies for School Buildings

The screening process resulted in an overview of the available building and system retrofit technologies for energy efficient school buildings, including their impact on the energy performance and indoor environment quality and their economic feasibility as a knowledge base for all designers and planners of school buildings (Mørck et al. 2014). The idea is that municipalities all over Europe can use the screening results

**Table 2. Calculated Final Energy of the Four School Buildings**

| Type of Energy | | Final Energy: kWh/m$^2$yr (kBtu/ft$^2$yr) | | | |
|---|---|---|---|---|---|
| | | Solitude Gymnasium, Stuttgart (D) | Tito Maccio Plauto School, Cesena (I) | Hedegårdsskolen, Ballerup (DK) | Brandengen skole, Drammen (N) |
| Heating energy (space heating + hot water) | Before | 213.1 (67.6) | 124.0 (39.3) | 187.0 (59.3) | 181.0 (57.4) |
| | After | 53.1 (16.8) | 23.7 (7.5) | 44.7 (14.2) | 42.0 (13.3) |
| Electricity (lighting + ventilation + auxiliary) | Before | 12.1 (3.8) | 13.0 (4.1) | 22.1 (7.0) | 27.0 (8.6) |
| | After | 4.6 (1.5) | 0.0 (0.0) | 8.2 (2.6) | 26.0 (8.3) |
| Total energy | Before | 225.2 (71.4) | 137.0 (43.5) | 209.1 (66.3) | 208.0 (66.0) |
| | After | 57.7 (18.3) | 23.7 (7.5) | 52.9 (16.8) | 68.0 (21.6) |
| Savings | Heating energy | 75% | 81% | 76% | 77% |
| | Total | 74% | 83% | 75% | 67% |

to find useful technologies for their specific school buildings. The covered retrofit strategies for improved energy performance and indoor environment quality are as follows: reduction of heat losses from the building envelope, optimal handling of solar and internal gains, heating/cooling/ventilation and lighting systems, and energy supply/generation systems. The forthcoming technology screening reports include brief explanations of the measures. The effects of the different measures on the selected reference buildings were analyzed using calculation and simulation tools to determine energy use, indoor environment quality, and investment and operational costs. The calculations were carried out for one representative climate in Norway, Germany, and Denmark and for three representative climates in Italy. For each energy retrofit measure, the results of the energy calculation screening are presented in four diagrams, showing simple payback time and physical lifetime, net present value and investment, $CO_2$ reduction, and saved energy (heating, electricity, and total primary). The results of the indoor environment calculations are presented as plots, showing the inner surface temperatures on the north-facing external wall (or window) in winter, the cold air drop next to north-facing windows in winter, the mean radiant temperatures in winter, the dry resultant temperatures in summer (south-facing rooms), and the $CO_2$ level in winter. As a representative example, Figure 3 shows the results of the energy-related calculations for extra wall insulation at a central corridor school in the German representative climate. All retrofit measures are presented in this way in the technology screening reports. Additionally, two packages of measures were evaluated (Mørck et al. 2014).

### Retrofit Guidelines towards Zero-Emission Schools with High-Performance Indoor Environment

Based on the experience gained in the project and the knowledge of both the included research partners and the industry partners, four different retrofit guidelines have been developed in the following areas:

- Improved indoor environmental quality
- Building construction components
- Building services systems
- Solution sets for zero-energy/emission schools

The retrofit guideline on improved indoor environmental quality, which is already available on the project website, addresses thermal indoor climate, indoor air quality, lighting conditions, acoustics, and noise protection. It explains the requirements regarding the indoor environment and presents strategies to improve the indoor comfort, supplemented by photos of specific solutions realized in the four School of the Future demonstration buildings and other school buildings.

### Community "School of the Future" on BUILD UP

The project has launched an information and discussion platform (Erhorn et al. 2015) on the European Union's portal for energy efficiency in buildings, BUILD UP (2015). Project results and news are presented there, as is information on other national and international projects dealing with energy-efficient school buildings.

## THE GERMAN DEMONSTRATION BUILDING—SOLITUDE GYMNASIUM

The Solitude Gymnasium is a secondary school located in the northwestern outskirts of Stuttgart. The entire school had to be renovated because of structural damage to the buildings. Because the energy consumption of the building was very high in comparison to other Stuttgart schools, an energy retrofit was planned. Financial support of the European Commission via the School of the Future project allowed the whole school to be substantially improved to reduce energy consumption.

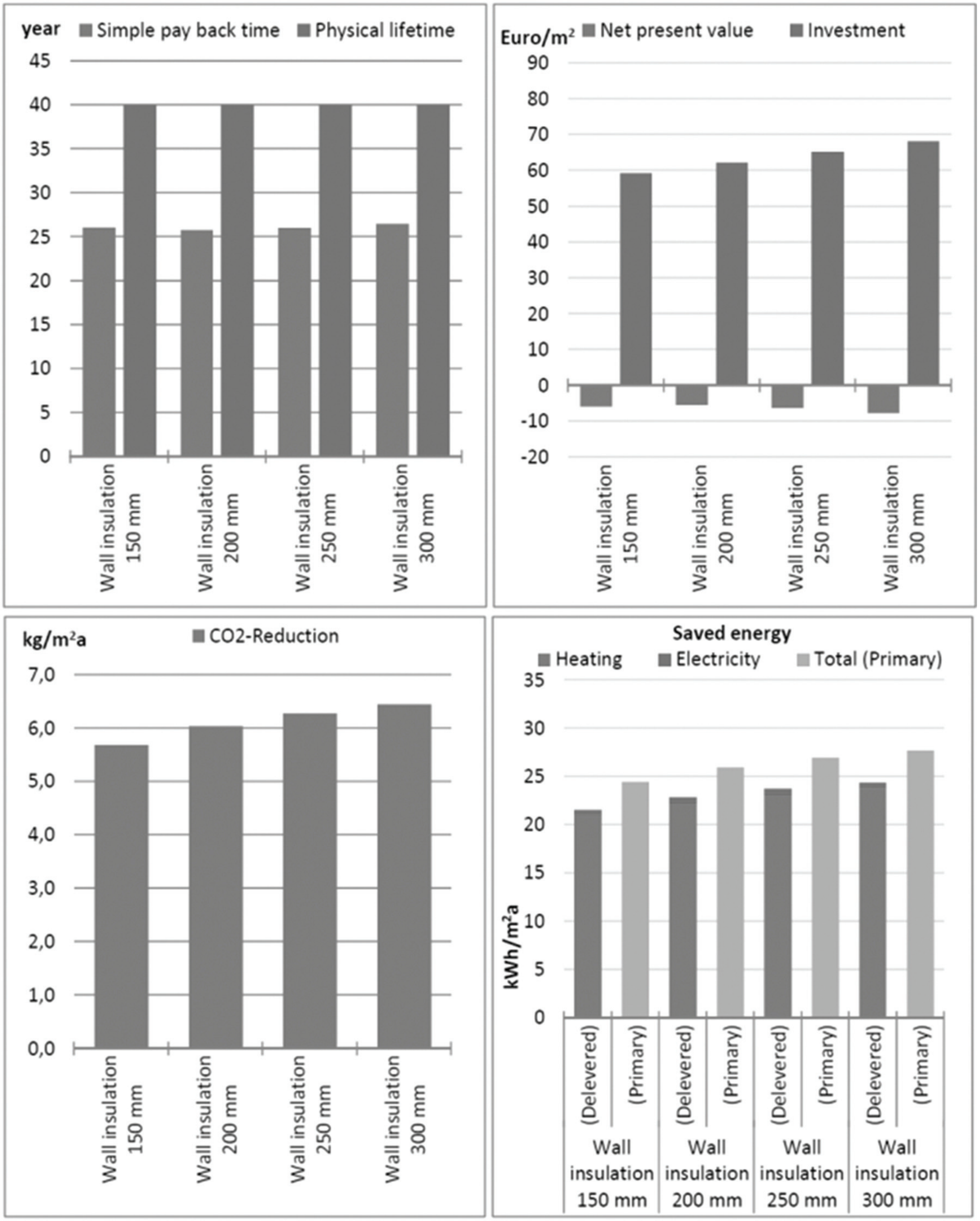


***Figure 3*** *Result diagrams of the calculations made for extra wall insulation at the central corridor school (based on the German representative climate) as part of the technology screening.*

For the City of Stuttgart, which is the demonstration partner, the objective of the project is to reduce the total energy consumption of the Solitude Gymnasium by a factor of 3, and the heat consumption by 75%. In addition, the indoor environmental quality of the class rooms will be improved.

### The School Before the Renovation

The exterior walls were made of exposed concrete. Some wall areas had primary walling made of brick, other areas had a concrete weather shell (interspace filled with 8 cm [3 in.] of insulation). Most of the windows were uPVC (unplasticized polyvinylchloride)-framed double-glazed windows. In some parts of the buildings (corridors and stairways), some windows were still single-glazed. All buildings had flat roofs made of concrete, partly covered with gravel. The roofs of the main building and of the gym also had some dome lights. Some parts of the roofs of the buildings were not sufficiently insulated. Also, the ground floor and basement ceilings were not properly insulated. To get accurate information about the actual U-factors of the building envelope, small sections of the different components were opened. This and data from national standards led to the values in Table 3.

The school's heating system, which is located in the main building, consisted of a boiler room with two gas boilers and gas burners that were installed in 2004. The boiler room supplied space heating to the main building, the science building, the big pavilion, and the gym. Appropriate pipes were installed in the main distributing system of the boiler room. The control of the space heating differentiated between the different buildings and heating circuits (zones) within the buildings depending on the orientation. Hot-water pipes were (and still are) buried in the ground of the schoolyard from the main building to the gym.

The small pavilion was not connected to the main heating system. Its demand for space heating was covered by a small gas boiler built in 1989. There were two secondary distributing stations in the school, one in the science building and the other in the gym. From these stations, space heating was allocated to the relevant building. Thermal transfer in the gym was ensured by the ventilation system for the hall and by several radiators located in the toilet and locker rooms. The domestic hot water for the sanitary facilities (e.g., showers) in the gym was heated indirectly by a heat exchanger via the distributing station. There was an electrical hot-water storage tank in the distributing station of the gym that supplied the caretaker's flat with hot water. The domestic hot water in the main building was supplied by small under-sink electrical heat boilers.

The boilers of the main building are in good condition and have been kept. The separate boiler in the small pavilion is rather old and must be replaced; however, because it is not yet clear whether the small pavilion will be used, its retrofit has been postponed.

The heat distribution system and the domestic hot water system are intended to be renewed; this would entail exchanging the heat pumps and establishing new heating groups corresponding to occupancy and orientation.

Some ventilation systems were provided especially for indoor rooms inside the main building, some for spaces in the science building, and some for the gym (about 32,000 $m^3$/h (1,130,080 $ft^3$/h) incoming air volume). All ventilation

**Table 3. U-Factors of the Building Envelope Before the Renovation**

| Component | U-Factor, $W/m^2K$ ($Btu/h \cdot ft^2 {}^\circ F$) | Building |
|---|---|---|
| Concrete pillars and beams | 3.65 (0.643) | All |
| Face brick walls | 3.15 (0.555) | Big pavilion, science building |
| Walls with concrete weather shell | 0.44 (0.041) | Big pavilion, main building, gym |
| Roof | 0.67–0.96 (0.118–0.169) | All |
| Ground floor | 1.50 (0.264) | All |
| Single-glazed windows | 5.80 (1.021) | Science building, main building |
| Double-glazed windows | 3.10 (0.546) | All |

***Figure 4*** *The Solitude Gymnasium with its five buildings before the renovation.*

systems are conditioned by water-based heating coils and are not equipped with any heat recovery units. The mechanical ventilation in the gym is controlled centrally by a switch located at the housekeeper's office.

In most areas, T8 compact fluorescent lamps (CFLs) are installed. More recent T5 CFLs were installed only in the gym. The installed power is reduced to the minimum required in the national standards by simply taking out unnecessary lamps. No controls are installed, except for the outdoor lights in the entrance area, which are switched on at dusk and switched off at 11 p.m.

The following consumption data is climate-corrected according to the VDI 3807 (VDI 2013). In 2011, the school required about 895,123 kWh (3,056,397 kBtu) for space heating and hot water heating with overall costs of 66,040€ ($69,890). The specific heat consumption is about 126.6 kWh/m$^2$yr (40.1 kBtu/ft$^2$yr), which is 22% more than the average amount required by the schools in Stuttgart. The electricity consumption in 2011 was 234,091 kWh/yr (799,304 kBtu/yr) or 26 kWh/m$^2$yr (8.2 kBtu/ft$^2$yr) with overall costs of 42,230€ ($48,142).

## The Renovation Design and Realization

An analysis showed that the use of a cogeneration plant (CHP) is economical. The combination of the CHP and the two existing boilers saves about 10,000€ (10,580$)of energy costs per year, compared to the existing heating system. The plant (capacity: 15 kW$_{el}$/30 kW$_{th}$ or 51.1 kBtu/h$_{el}$/ 102.4 kBtu/h$_{th}$) will cover the heat demand for space heating and hot water for the school area, except for the small pavilion. The small pavilion is supplied separately. The plant also supplies heat to the caretakers' flats and is designed for approximately 4000 hours per year. The existing gas boilers are in good condition and will be kept to cover the peak load and for redundancy.

The CHP will operate by demand. The new heating system combines the CHP, the gas boilers, and heat storage. The produced electricity will mainly be used on site; excess electricity will be sold and fed into the grid. The hydraulic system is optimized, i.e., at the substations of the heating system, the heating pumps without speed control are exchanged and sliders are generally exchanged for valves. The electric boiler at the caretaker's flat in the gym will be removed. Domestic hot water will be provided by the gym's storage tank. The operating hours of the heat exchanger will be analyzed and reduced to an optimal minimum.

In general, the City of Stuttgart tries to avoid any kind of mechanical ventilation systems in their school buildings. However, when accurate indoor environment conditions cannot be guaranteed with natural ventilation, the most energy efficient ventilation systems are chosen. In the main building, no air cross-flow is possible. Natural ventilation was found to be insufficient. In the auditorium, a central unit was installed (6700 m$^3$/h [236,610 ft$^3$/h], heat recovery >90%, temperature- and $CO_2$-controlled, 5.6 kW [19.1 kBtu/h]). The indoor bathrooms are supplied by a central unit (3600 m$^3$/h [127,134 ft$^3$/h,] heat recovery >70%, time-controlled, 3.3 kW [11.3 kBtu/h]), the bathrooms by simple duct fans, (700 m$^3$/h [24,721 ft$^3$/h], exhaust air only, time-controlled, 0.15 kW [0.51 kBtu/h]). Ventilation in classrooms and indoor rooms was realized using decentralized ventilation units (680 m$^3$/h [24,014 ft$^3$/h], heat recovery >80%, CO2-controlled, 0.13 kW [0.44 kBtu/h]). In the science building, a heat recovery unit (>90%) was added to the existing ventilation system. This unit had to be placed on the roof. Additional ventilation ducts were necessary to connect the heat recovery unit with supply and exhaust air. Due to the critical static load capacity of the roof, all roof installation had to be placed over load-bearing walls. The hybrid ventilation system is time- and $CO_2$-controlled. In the big pavilion, a hybrid ventilation system was implemented. The natural ventilation system works by the aid of actuators, which open the upper parts of the windows automatically during breaks (controlled by timers). Additionally, the actuators can be controlled manually by the teacher. Because there is sufficient air

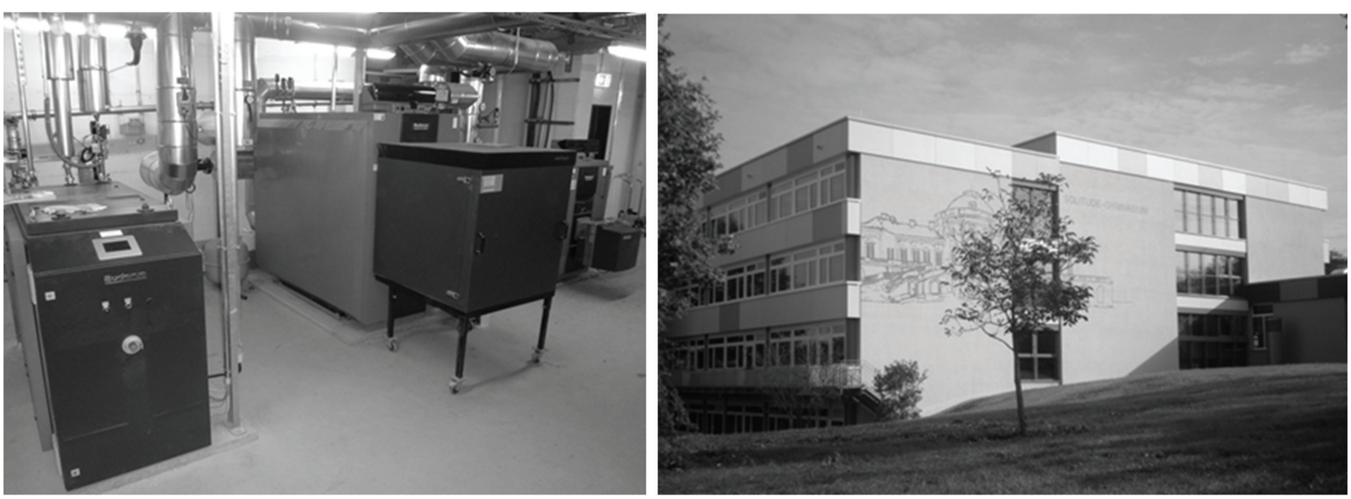

***Figure 5*** *CHP unit and two boilers (left) and the renovated main building (right).*

cross-flow, no mechanical ventilation system is needed. The lower parts of the windows can be opened manually.

In the gym, the retrofit of the ventilation system, which is also used for heating, was not possible. There is a lack of space between the roof and the intermediate ceiling of the hall. There are four inspection chambers to control the ventilation system. The access to the ventilation system in the hall is at a height of around 3 to 4 m (10 to 13 ft) and can be reached by the aid of a hydraulic lift. Also, the critical static load capacity of the gym roof is maxed out; it can support no more weight. For these reasons, there is no possibility to add any heat recovery equipment to the ventilation system. The ventilation system operates with recirculating air, and the volume of outdoor air is planned to be $CO_2$-controlled.

In the course of the refurbishment of the facades (for U-factors, see Table 4), the indoor surfaces of the walls were painted. To maintain good visual condition, some minimum reflection factors are required: 0.8 for ceiling, 0.5 for walls, and 0.3 for floors. For the main building, a comprehensive electrical renovation was planned, including the installation of daylight detection controls (staircases) and presence detectors. Old T8 CFLs were replaced by T5 CFLs. Conventional ballasts were replaced by electronic ballasts.

Several calculations were done to check if the selected energy measures are sufficient to ensure that the project targets will be accomplished. The national assessment method (DIN V 18599 2009) was used to reproduce the actual buildings, and a model picturing the school after the retrofit was created (see Table 5). The project targets will very likely be achieved. The bonus of the CHP is included in the calculated electrical energy use after renovation. The building status before renovation and the planned renovation measures are summarized in the work by Zinzi et al. (2013).

## Monitoring

The objectives of the project have to be verified through monitoring, which must span a full year. Before the retrofit, main meters were installed for the whole school (not per building) to measure gas, electricity, and water consumption on a daily basis. The school is monitored via Stuttgart's Energy Control System (SEKS), which sends the consumption data to the Department for Energy Management daily.

## Indoor Environment

The occupant survey on the indoor comfort (Steiger et al. 2012) before the retrofit was conducted in Spring 2012. The answers are based on annual experiences with the building. The main results were that: the building is too warm in summer and too cold in winter; the air is experienced as clearly used. All in all, the building was perceived as "just acceptable." A comparison with the situation after the retrofit will be made in early 2016. Temperature, humidity, and $CO_2$ sensors will be installed in about two to three selected rooms of each building. Some visualization systems for indoor air quality are planned to be installed in several class rooms.

## Energy Performance

Meters to record the operating hours of electrical lighting, components of the heating system, and other systems were installed. The consumption of heat, electricity, and water per building is monitored. Extra meters were installed in the two caretaker's flats. The monitoring technology is based on electronic bus communication technology and will be used also after the EU project monitoring period for the long-term control system of the City of Stuttgart (SEKS).

## ACKNOWLEDGMENTS

The School of the Future project receives funding from the European Commission within the 7th Framework Programme under the contract no. ENER/FP7/260102.

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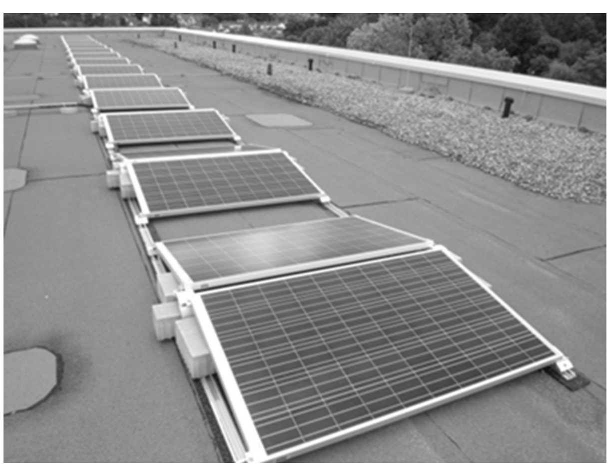

***Figure 6*** *Photovoltaic system on the roof of the main building (left) and the renovated big pavilion (right).*

**Table 4. Overview of the New U-Factors After Retrofit**

| Building | Component | U-Factor W/m²K | U-Factor Btu/h·ft²°F | Technology |
|---|---|---|---|---|
| Big pavilion | Walls | 0.23 | 0.041 | ETICS/curtain wall facade (14 cm (5.5 in.) of polystyrene/mineral wool [PS/MW]) |
| | Main roof | 0.19 | 0.033 | 16 cm (6.3 in) of expanded polystyrene (EPS) |
| | Middle roof | 0.20 | 0.035 | 14 cm (5.5 in.) of EPS |
| | Windows north | 0.90 | 0.158 | Triple-glazed |
| | Windows south | 1.30 | 0.229 | Double-glazed |
| | Glazed facade hallway | 1.20 | 0.032 | Double-glazed |
| Science building | Walls | 0.18 | 0.032 | ETICS/curtain wall facade (18 cm [7.1 in.] of PS) |
| | Roof | 0.15 | 0.026 | 22 cm (8.7 in.) of EPS |
| | Dome lights | 1.10 | 0.194 | — |
| | Windows | 0.90 | 0.158 | Triple-glazed |
| | Glazed facade | 0.70 glazing<br>1.20 frames<br>0.30 panels | 0.123 glazing<br>0.211 frames<br>0.053 panels | Triple-glazed |
| Main building | Walls | 0.18 | 0.032 | ETICS/curtain wall facade (18 cm (7.1 in.) of PS) |
| | Roof | 0.17 | 0.030 | 19 cm (7.4 in.) of EPS |
| | Windows | 0.90 | 0.158 | Triple-glazed |
| Gym | Walls | 0.18 | 0.032 | 18 cm (7.1 in.) of MW |
| | Roof | 0.20 | 0.035 | 17.5 cm (6.9 in.) EPS |
| | Windows | 0.90 | 0.158 | Triple-glazed |

**Table 5. Final Energy Figures of the Solitude Gymnasium**

| Use | Performance | Energy, kWh/m²a (kBtu/ft²yr) |
|---|---|---|
| Final heating energy use | Actual performance | 213.1 (67.6) |
| | After renovation performance | 53.1 (16.8) →75% savings |
| Final electrical energy use | Actual performance | 12.1 (3.8) |
| | After renovation performance | 4.6 (1.5) → 62% savings |
| Total final energy use | Actual performance | 225.2 (71.4) |
| | After renovation performance | 57.7 (18.3) → 74% savings |

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