School of the Future




SOLUTION SETS FOR ZERO EMISSION / ZERO ENERGY SCHOOL BUILDINGS

Guidelines for energy retrofitting - Towards zero emission schools with high performance indoor environment

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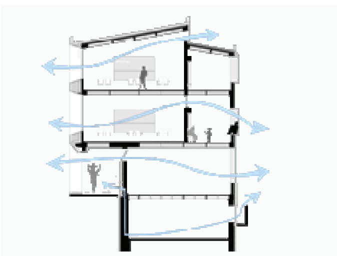

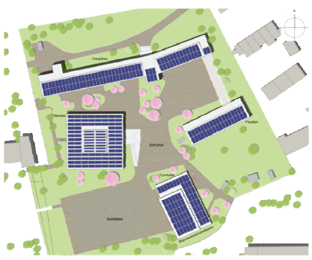


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Solitude Gymnasium, Stuttgart, Germany. Photo: Ingenieurbüro Fisch.

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Bottom from left:

Night ventilation concept of the plus energy school Uhland Schule in Stuttgart, Germany. Graphic: hotz + architekten

Façade and PV modules at the plus energy school Hohen Neuendorf, Germany. Photo: I. Lüttkemeyer

PV plan on the buildings of the plus energy school in Stuttgart. Graphic: hotz + architekten

Façade of the plus energy school in Montpellier. Photo: H. Erhorn-Kluttig.

INTRODUCTION

One of the purposes of the School of the Future project is to provide designers and planners with retrofit guidelines for concepts and technologies regarding energy efficiency and good indoor environment quality in school buildings - from simple, but significant energy reduction and indoor environment improvements up to the final target: Zero Emission Schools.

The objective of these guidelines is to develop an overview on the available building and system retrofit technology systems for energy efficient school buildings including their impact on the energy performance and indoor environment quality and their economic feasibility.

The guideline on Solution Sets for Zero Emission and Zero Energy School Buildings introduces the terms and definitions for zero energy, zero emission, plus energy and passive house and 3-liter house schools as major steps towards these most advanced energy performance levels. Strategies and technologies for the building design, building envelope and building services systems, the electrical school equipment and renewable energy systems that can be applied in school are listed and described, and the option of integrating energy concepts into the lectures is emphasized. There’s a chapter full of examples of zero emission, zero energy and plus energy schools from different countries which includes a tabular comparison of the different concepts. Finally, the most commonly used solution sets and reasonable alternatives are presented.

Besides the guideline on Solution Sets for Zero Emission/Zero Energy School Buildings three guidelines on Improved Indoor Environmental Quality, Building Construction Elements and Building Services Systems have been written.

The intended audience for the guidelines are designers and planners of school buildings. The idea is that municipalities all over Europe can use the guidelines and find useful technologies for their specific school buildings. In addition, the work constitutes background knowledge for further work in the “School of the Future” project.

“SCHOOL OF THE FUTURE” PROJECT

“School of the Future” is a collaborative project within the 7th Framework Programme of the European Union in the energy sector. It started in February 2011 and was terminated in January 2016. The aim of the “School of the Future” project is to design, demonstrate, evaluate and communicate shining examples of how to reach the future high performance building level. School buildings and their primary users: pupils – the next generations – are in the focus of the project. Both, the energy and indoor environment performance of 4 demonstration buildings in 4 European countries and climates will be greatly improved due to holistic retrofit of the building envelope, the service systems, the integration of renewables and building management systems. The results and the accompanying research and dissemination efforts to support other actors dealing with building retrofits can lead to a multiplied impact on other schools and on the residential sector, since the pupils can act as communicators to their families. Tailored training sessions are aimed to improve the user behaviour and the awareness of energy efficiency and indoor environment.

Zero emission buildings are a main goal in various country roadmaps for 2020. The demonstration buildings within the project may not completely reach this level as the aim of the call is cost efficiency and multiplication potential. The retrofit concepts will, however, result in buildings with far lower energy consumption than in regular retrofits with high indoor environment quality - thus leading the way towards zero emission. They can be considered as schools of the future. Results from national examples of zero emission schools will complete the information used for developing the deliverables such as guidelines, information tools, publications and a community at the EU BUILD UP portal.

The project is based on close connection between demonstration, research and industry represented by the "design advice and evaluation group". The proposal idea was introduced at the E2B association brokerage event with high interest, which resulted in a consortium including well-known partners from the building industry.

PARTNERS WITHIN THE "SCHOOL OF THE FUTURE" PROJECT

Country	Partner
Germany	Fraunhofer Institute for Building Physics (Fraunhofer IBP, Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung), Coordinator
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Italy	ENEA (Agenzia Nazionale Per Le Nuove Tecnologie, L'Energia E Lo Sviluppo Economico Sostenibile)
	Comune di Cesena
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Denmark	Cenergia Energy Consultants ApS
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	Ballerup Kommune
	Saint-Gobain Isover a/s
	Schneider Electric Building Denmark AS
Norway	Stiftelsen SINTEF
	Drammen Eiendom KF
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BACKGROUND: EUROPEAN SCHOOLS IN NEED OF RENOVATION

Throughout Europe, most school buildings were built between the 1950s and the 1970s and are by now in need of renovation, including an energy upgrade. Many renovation projects focus on damages and changes required by modern teaching styles. Others include the retrofit of building components and upgrades of building services systems components. Specific guidelines for energy efficient building envelope renovation and building services systems updates are available within the series of the School of the Future retrofit guidelines together with a guideline on improved indoor environment in schools.

Some schools have "more ambitious targets" and go for a holistic energy retrofit that can reduce the energy consumption significantly - like in the School of the Future project, where all four demonstration buildings aimed to reduce the delivered total energy to a third of the energy use before the renovation. The resulting energy use after the renovation is in the range of nearly-zero energy buildings (NZEB), the target for new buildings in the European Member States by 2019/2021 according to the Energy Performance of Buildings Directive recast [1]. It has to be noted though that the national application of the NZEB definition differs from country to country and is not yet fixed for all EU Member States.

Already a step ahead are the zero emission, zero energy or even plus energy buildings. Pilot projects in some European Member States also include school buildings, a few of them also as renovation of existing buildings. This guideline presents renovation measures that can be combined to so-called solution sets to realise this highest level of energy performance of school buildings, and it refers to already available pilot projects.

ZERO EMISSION, ZERO ENERGY OR PLUS ENERGY?

First of all: All three levels are really ambitious, and school buildings that fulfil any of them should be regarded as buildings with the highest energy performance. Their definitions differ as described below and for all of them the following boundary conditions have to be analysed in detail before even trying to compare the projects' ambitions:

- *Included energy uses:* Are all energy uses of the school building included such as heating, hot water, ventilation, lighting, cooling where necessary, auxiliary energy for pumps and control as well as electricity use for school equipment like computers, printers, copy machines, vending machines, cafeteria equipment and even canteens? As the electricity use for school equipment such as white boards or computers can be a significant part of the overall electricity use, the balancing of all energy uses is more difficult than the balancing of the energy uses that are covered by the energy performance calculations following most national building codes for non-residential buildings (heating/hot water/ventilation/lighting/cooling/auxiliary energy).
- *Included buildings and building usages:* Is the school used mostly in the morning (primary school) or during the whole day (secondary school)? Is it used in the evening by other groups or for special events? Is a sports hall included in the energy use or even a swimming hall?
- *Balancing method:* Is the zero energy or emission level achieved through an annual balance of the total energy use and the total energy generated at the school? This approach is often called "net zero energy building". Is the balance done monthly, hourly or is the school even energy self-sufficient ("energy autarky") and needs no energy from the grid or similar?
- *Energy level:* Most balances of energy are based on final (delivered) energy. From that other energy levels can be derived such as:
    - (Non-renewable) primary energy by a multiplication with the (non-renewable) primary energy factor for each energy source,
    - CO_2 emissions by multiplication with the CO_2 emission factor for each energy source
    - CO_2 equivalent emissions that take into account also other greenhouse gases by multiplication with the CO_2 equivalent emission factor for each energy source

  Some balances are based on final energy and do not use any conversion factor. Depending on the energy source the conversion factors can make a balancing of the energy used with the energy generated at the school easier. A zero energy school based on final energy is the most ambitious target if compared to primary energy or CO_2 emissions or CO_2 equivalent emissions.
- *Operational energy vs. life cycle energy*: The balancing of energy used with energy generated mostly includes the operational energy use only. More advanced approaches however can also take into account the energy that is used during the whole life-time of a building, including the creation of the building components and services systems components, the transport to the building site, the energy used for erecting the building, the energy use for operating the building and the energy used for demolishing the building. In buildings with a conventional energy efficient level the

operational energy use is about 90 % of the life cycle energy. In zero energy buildings the operational energy use ratio is somewhat lower and can be about 75 %, depending on the building material and the energy used and energy generated.

In all cases the energy used by the building has to be as low as possible and balanced with energy generated at the building. This is realised mostly through PV generated electricity, but also other renewable energy sources can be used like wind, solar thermal, geothermal energy via heat pumps, biomass CHP, etc. Plus energy levels can only be achieved if the energy can be included in a public grid or (local district) heating net. The renewable energy generation can be divided into different levels as well:

- *Renewable energy generated directly at the building:* This can be solar thermal or solar electrical energy, wind energy from micro wind turbines, heat pumps, etc.
- *Renewable energy from outside the building property, used onsite the building property:* Biomass, biofuel and biogas is mostly produced outside of the building site and can be used in the building as boiler fuel or similar. District heating from renewable energy sources can also be considered as part of this group.
- *Renewable energy from outside the building property with no connection to the building besides the national grid:* Here the building owner buys renewable electricity. In reality there is not a direct connection from the electricity generation to the use. The building will use similar to all other buildings connected to the general electricity network the average electricity of the country and beyond. Therefore this renewable energy is only virtual.

Zero emission level

Buildings emit various gases during their operation and also during their life-time. Besides toxic emissions, the most interesting ones are the emissions that create the greenhouse effect of global warming. The biggest impact of the greenhouse gases has CO_2 due to the high occurrence in the emissions. Therefore this gas is often used as indicator for emissions. CO_2 equivalent emissions include also other emissions (e.g. methane, perfluorocarbons, nitrous oxide, etc.) with global warming impact by recalculating their influence to additional CO_2 emissions. Therefore the CO_2 equivalent emission factors are always (slightly) higher than the CO_2 emission factors. To be more specific (and more correct) zero emission schools would need to be called zero CO_2 emission schools or zero CO_2 equivalent emission schools. Otherwise any emission could be meant.

For reaching a zero (CO_2 or CO_2 equivalent) emission level the total final energy used by the building has to be either produced without emission or the emissions have to be compensated by emissions saved due to renewable energy generated on the building site and fed into a grid or net or used by another building instead of energy from fossil fuels.

CO_2 and CO_2 equivalent emission factors for energy sources are at least slightly different from country to country and can be found here:

- Germany: GEMIS - Globales Emissions-Modell integrierter Systeme (http://www.iinas.org/gemis-de.html)
- Italy:
    - CO_2 equivalent emission factors for electricity [fattori di emissione atmosferica di CO_2 e sviluppo delle fonti rinnovabili nel settore elettrico] (http://www.isprambiente.gov.it/it/pubblicazioni/rapporti/fattori-di-emissione-atmosferica-di-co2-e-sviluppo-delle-fonti-rinnovabili-nel-settore-elettrico)

  - CO_2 equivalent emission factors for different sources and uses [fattori di emissione per le sorgenti di combustione stazionarie in Italia] (http://www.sinanet.isprambiente.it/it/sia-ispra/serie-storiche-emissioni/fattori-di-emissione-per-le-sorgenti-di-combustione-stazionarie-in-italia/view)
- Denmark: Danish Energy Agency: Danish key figures including CO_2 emission factors (http://www.ens.dk/en/info/facts-figures/key-figures/danish-key-figures)
- Norway: Norway generates electricity mainly from hydro power (95%). The discussion of CO_2 emissions in Norway however takes a kind of Scandinavian and even European energy market into account. A proposal for CO_2 equivalent emissions including factors for different ways of electricity production is presented in a scientific article written by G. Laurent, M. Haase, A. H. Wiberg, T. Kristjansdottir, and B. Risholt from SINTEF and NTNU. The article can be downloaded from http://www.tandfonline.com/doi/abs/10.1080/09613218.2015.955755

Zero energy level

As described above zero energy can be on final energy or on primary energy level. The energy used by the building has to be balanced with energy generated from renewable energy sources (preferably generated on the building or on the building property). In a few cases [2], the balancing of energy used and energy generated is done completely without using the electrical grid or local heat net. That means that these buildings are energy self-sufficient ("energy autarky"), they can generate at any time all the energy they need. This is however a very expensive solution as it needs big storage systems for heating and electricity.

The most commonly applied solution is to use the electricity grid in order to balance the energy used and energy generated. Electricity is produced on the building or building property often by photovoltaic panels and if not used by the building itself, fed into the electricity grid. Thus all energy generated at any time can be accounted in the balance. Also the building can still use electricity from the grid in times where there is not enough electricity generated by the building. The generated electricity can also be used to balance other energy needs like the heating energy that does not necessarily have to be provided with electricity as source. The building services systems can be chosen freely as long as their total balance is zero. This allows for smaller energy generation systems and less (or no) storage systems. The electricity grid is considered as storage. If this kind of solution was applied to many or all buildings connected to the electricity net, the net would have to store all electricity during some phases and provide all electricity in other phases. This can't be managed so far as it would need large electrical storages (batteries) or huge power-to-gas facilities (or similar technologies). Local heating nets can be used in a similar way to provide energy to other buildings that can then be accounted for in the energy balance.

Within the framework of the Intelligent Energy Agency and their programmes "Solar Heating and Cooling" and "Energy in Buildings and Communities" a joint Task 40/Annex 52 has been working on "Net Zero Energy Solar Buildings" [3] and the collected case studies also include an Austrian school building renovated to become a zero energy school.

Plus energy level

From zero energy to plus energy is a small step. In the end the balance of energy used and energy generated has to be positive, meaning that more energy is generated than used. Since the real energy use of a building often differs at least slightly from the calculated energy use the projects include slightly oversized energy generation systems that can compensate for a bit higher energy uses. The over-dimensioning can make the project a success if the monitoring phase shows somewhat different results than the energy performance calculation or simulation. This makes most of the zero energy buildings in reality plus energy buildings. To hit the mark in the monitored reality with exactly the necessary size of the energy generation system would be very risky. On the other hand the over-dimensioning of systems leads to higher costs.

In Germany there are two ongoing research programmes, one focusing on plus energy houses [4] and the other, and for this guideline most interesting one, on energy efficient school buildings that includes pilot projects of plus energy schools, most of them becoming plus energy after a deep renovation [5]. Some of the projects are presented in this guideline.

Again, the plus energy status can be reached with different boundary conditions (see above) including also energy autarky or a yearly balancing of energy uses and energy generated.

What is more demanding: zero emission, zero energy, plus energy?

Obviously, a plus energy level is slightly more demanding than a zero energy level, but as explained before most zero energy concepts will include a small to considerable buffer concerning the amount of energy generated if compared to the amount of energy used.

If we compare the zero energy with the zero emission level, both on an annual balanced basis, the size of the challenge is clearly dependent on the involved energy carriers and the used CO_2 emission and (non-renewable) primary energy factors.

If zero primary energy is compared with zero final energy, in most cases zero primary energy is easier to achieve since the balance by electricity that is generated from PV or wind will result in higher primary energy benefits due to the high primary energy factor of the general electricity that is counter-balanced.

The following simplified example shows how the results are influenced by the different factors:

Our exemplary school building has a final heating energy use for space heating plus domestic hot water of 40 kWh/m²yr which is generated based on a single energy carrier. In case of the variant "all electrical (heat pump)" a COP of 3 is used to calculate the electricity needed to generate the 40 kWh/m²yr and so 13.3 kWh/m²yr electricity is used by the heat pump. The remaining energy is renewable energy (e.g. geothermal energy). For the other variants (gas condensing boiler, biomass boiler and district heating) a system efficiency of 1.0 is used for simplification. The electricity use of the building is 15 kWh/m²yr and includes auxiliary energy for pumps, controls, fans (ventilation) and lighting. The simple balance shall not take the building equipment into account. A PV system generates 27 kWh/m²yr electricity that is completely fed into the grid. Table 1 includes variants with different energy carriers as heating source and presents the results concerning zero final energy, zero primary energy and zero emission.

Version		1	2	3	4
		All electrical: electrical heat pump	Gas condensing boiler	Biomass boiler	District heating
Final heating energy	kWh/m²yr	13.3	40		
Electricity	kWh/m²yr	15			
PV electricity fed into the grid	kWh/m²yr	-27			
Total final energy	kWh/m²yr	1.3	28		
PEF heating source	-	2.4	1.1	0.2	0.7
PEF electricity	-	2.4			
PEF PV electricity	-	2.4			
Primary energy heating	kWh/m²yr	32	44	8	28
Primary energy electricity	kWh/m²yr	36			
Primary energy PV electricity	kWh/m²yr	-64.8			
Total primary energy	kWh/m²yr	3.2	15.2	-20.8	-0.8
$CO_{2,eq.}$ factor heating source	kg/kWh	0.664	0.253	0.025	0.201
$CO_{2,eq.}$ factor electricity	kg/kWh	0.664			
$CO_{2,eq.}$ factor PV electricity	kg/kWh	0.664			
$CO_{2,eq.}$ emissions heating	kg/m²yr	8.85	10.12	1	8.04
$CO_{2,eq.}$ emissions electricity	kg/m²yr	9.96			
$CO_{2,eq.}$ emissions PV electricity	kg/m²yr	-17.93			
Total $CO_{2,\,eq.}$ emissions	kg/m²yr	0.89	2.15	-6.97	0.07

PEF: (non-renewable) primary energy factor

Table 1: Calculation of the total final energy, total primary energy and total $CO_{2,eq.}$ emissions for four different simplified variants of heating energy systems each in combination with a PV system to balance (part of) the energy.

The included non-renewable primary energy factors and $CO_{2,eq.}$ emission factors are based on German values. Other national factors or another type of district heating system (here: combined heat and power based on fossil fuels) will lead to other, but in many cases similar results. The variants that result in zero (or even plus) levels for final energy, primary energy or $CO_{2,eq}$ emissions are marked in the table (fields highlighted in green).

Together with additional calculations the presented variants show:

- With an all electrical system (heat pump or similar) the building is at the same time a zero final energy building, a zero primary energy building and a $CO_{2,eq.}$ energy neutral building or neither of these. This can however be changed if higher (political) primary energy factors for fed in electricity are used, as it is currently the case in Germany.
- The most difficult characteristic to meet is zero final energy. Both, the non-renewable primary and the $CO_{2,eq.}$ emission factors give a benefit to all other energy carriers in comparison to electricity.
- In the example of Table 1 two variants achieve the zero primary energy level (biomass boiler and district heating), but only one variant, namely the biomass boiler, achieves the zero emission level. However, additional calculations showed that with different configurations it is also possible that a variant can achieve the zero emission level, but not the zero primary energy level. There is no general rule concerning what is more difficult to achieve – zero emission or zero primary energy.

Passive house and 3-liter house schools as major steps towards the zero and plus energy level

While zero emission, zero energy and plus energy buildings let alone school buildings are still very rare in all EU countries, the application of the passive house level to school buildings has been achieved in several buildings in Germany [6] and also in buildings in Italy [7] and Norway [8]. The goal of these energy concepts is not to balance the energy needs by the self-generated energy as explained above, but to strongly limit the energy use by using effective insulation measures and high performance ventilation systems.

Passive buildings, as defined by the German Passivhaus Institut have a defined limit for the net heating energy need (15 kWh/m²a) and the heat capacity (10 W/m²) in order to allow for air-heating via the ventilation system. This shall allow for reduced investment costs as two usually separate building services systems, the heating and the ventilation system, are combined into only one, namely the air-heating system. In order to ensure an acceptable level of indoor comfort, high temperatures of the air-heating are not possible, thus the heat capacity has to be limited. However, there are also passive house buildings that use a separate, then mostly hydronic heating system. Over the years national passive house definitions for other countries and regions like Norway, the Netherlands, the Mediterranean regions etc. have evolved that differ slightly from the original German definition, mostly dependent on the climate.

3-Liter House is a term used in Germany for residential buildings with a low primary energy demand. 3-liter houses and, transferred to school buildings also 3-liter house schools have a maximum primary energy demand of 33.3 kWh/m²a, which corresponds to 3 litre of heating oil. Included in this primary energy demand are the fuels for heating, ventilation, cooling and auxiliary. Within the German research focus Energieeffiziente Schule (EnEff:Schule, [5]) three schools have been refurbished to 3-liter-house level and one new school in this level has been built. The renovated schools of the School of the Future project will result in energy demands slightly above the 3-liter-house level.

TECHNOLOGIES APPLIED IN ZERO EMISSION, ZERO ENERGY AND PLUS ENERGY SCHOOLS

These kinds of "highest" performance buildings have to be optimised in many different areas starting with the building design (architecture) which of course can be influenced less strongly during the renovation of an existing building, the thermal quality of the building envelope and the detailed solutions for avoiding thermal bridges and ensuring airtightness to the choice and quality of the building services systems for heating, hot water, cooling (if necessary), ventilation, lighting and building automation. Energy efficient school equipment has to be chosen and energy has to be generated from renewable energy sources to compensate for the energy use.

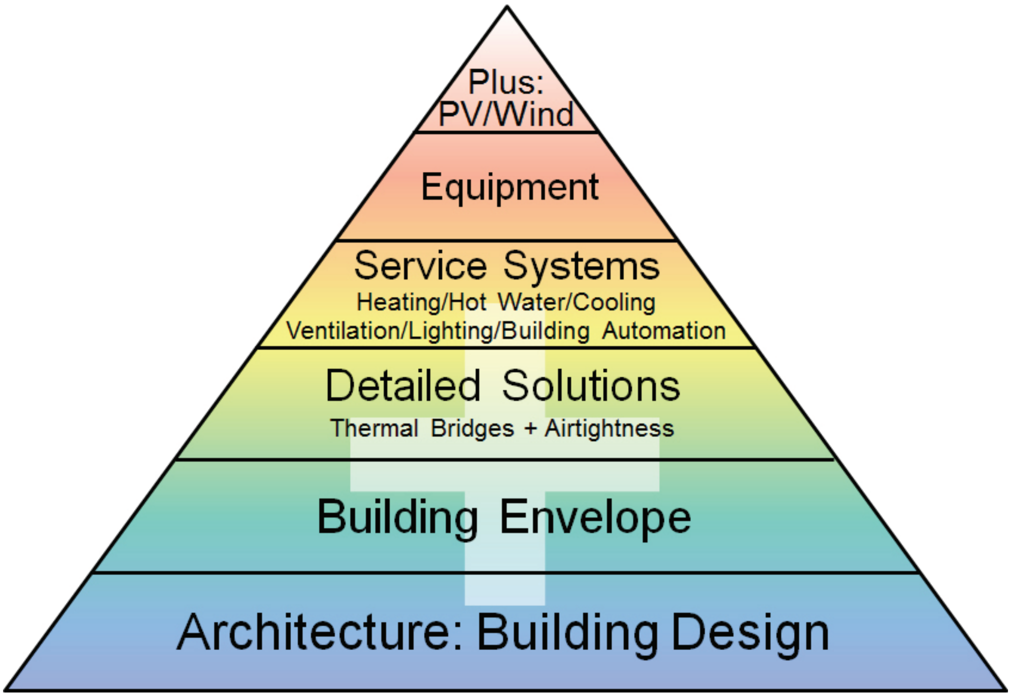


Figure 1: Pyramid of modules contributing to zero emission, zero energy and plus energy school buildings.

Building design

The latest developments in school architecture are mostly not based on energy efficiency but on new teaching forms. The use of classrooms and in general the learning and teaching environment must nowadays be more flexible. The original teaching form with the teacher up front and the pupils directed to him/her in rows is used less and less today. Working groups, animated learning, individual learning time, often connected to the use of computers take over and result in flexible table and chair positioning or even in new sizes and equipment in classrooms.

On the other hand, some of the boundary conditions for classrooms will remain: Enough space for up to about 30 pupils (in some school forms and/or countries this is limited to a smaller number of pupils), high ceilings to provide suitable air volume and together with large window areas placed mostly on one side of the classroom enough daylight, rather high artificial lighting installations to compensate the daylight in the early and late hours or winter, etc. Floors, walls and ceilings need to be covered and painted with healthy (non-toxic) materials and the indoor temperatures, indoor air quality, etc. have to be maintained at a good level. Specific issues in connection with energy are:

- **Compactness of the building:** Classrooms have mostly a defined range of size, which is fixed in national or regional guidelines. E.g. in Baden-Württemberg, a federal state in Germany the size is defined to 54 – 66 m² for up to 31 pupils. In most schools the classrooms are connected to corridors in either side-corridor (classrooms only on one side of the corridor) or central corridor form (classrooms on both sides of the corridor). This and the need for daylight in nearly all rooms limit the possibility for improving the compactness of school buildings. The calculations for the technology screenings in the School of the Future project showed mostly minor differences between the two school building typologies side and central corridor. However, there are some other school building types like the so-called compact school, in which the classrooms are arranged around a central hall. This type can often be found in rather small schools.
- **Daylight:** National school guidelines mostly include daylight requirements (e.g. window area/floor area ≥ 1:10). This results usually in a complete window strip placed along the exterior façade of the classroom up to the ceiling.
- **Solar shading:** The choice of a good shading system should involve the architect and the engineers responsible for the energy concept and the indoor comfort. Further information regarding internal or external shading and the combination with glare protection can be found in the building envelope chapter.
- **Window operation:** In general windows should be designed as openable windows. This can significantly reduce the electricity consumption of mechanical ventilation systems during warmer periods (by turning off mechanical ventilation systems). In combination with clever ventilation strategies (hybrid ventilation or IAQ visualisation) it can also replace mechanical ventilation. However in high performance school buildings the ventilation losses in winter need to be reduced by the use of efficient heat exchangers. This is only possible with mechanical ventilation systems. Openable windows can still be used during peak times; they allow for a lower basic mechanical ventilation rate and are necessary in case the mechanical ventilation system is defect.
- **Cross ventilation:** If window airing is the only form of ventilation, cross ventilation through windows on both sides of the classroom can help to improve the indoor air quality. This is however only possible in side corridor schools (mostly at the top floor) or with the use of the corridors and sometimes atriums for ventilation. During breaks, cross ventilation is also possible by using the classroom door as a second opening.
- **Storey heights:** The usual clear storey height for classrooms is about 3 m. If mechanical ventilation systems are used, high ceilings should be planned.
- **Colouring of walls, floors and ceilings:** The brightness of walls, floors and ceilings can support the use of daylight in classrooms and reduce the necessary electrical lighting. Additionally, the right colouring can reduce the risk of glare. In two School of the Future demonstration projects the painting of the interior has been renewed to increase the daylight rate: Solitude Gymnasium in Stuttgart (classroom walls and ceilings) and Hedegårdsskolen in Ballerup (walls of the central area).
- **Short distribution lengths:** The location of the central heating and ventilation unit can influence the length of the distribution pipes and channels and thus the necessary pump and fan energy as well as the size of the distribution losses. Similarly the location of hot water taps (restrooms and toilets) can influence the distribution losses of centrally generated hot water.

- **Locations for building integrated renewable energy generation:** If the aim of a school design or renovation project is a zero energy school, the designer should have in mind that the necessary renewable energy generation needs suitable space and placement. Mostly this relates to PV panels which should not be mounted on shaded roof and/or façade areas. But also micro wind turbines need to be installed at the right place. Any influence on the daylight in the classrooms (light flicker) or noise from the turbines or vibrations should be prevented. A focus should be on the good architectural integration of the systems into the building. At the Solitude Gymnasium in Stuttgart it was not possible to add large areas of PV due to static limitations on most roof areas. The project also showed that PV can be in competition with parts of ventilation systems on the roof.
- **Locations for informing about the approach:** Displays can be helpful to inform the pupils, but also visitors about the advanced energy level of the school and the current result of monitoring. The location of the displays (electronic or other) should be part of the design.

Building envelope

In addition to the architectural influences indicated in the previous chapter the building envelope quality has a huge impact on the energy performance of a building. The thermal quality (insulation level, low or no thermal bridges and the use of the building mass), the airtightness and the active ventilation losses define the net heating energy demand of the building. Windows have impact on the useful daylight; solar shading can prevent overheating, etc. This chapter presents useful building component technologies and materials for high performance school buildings.

- **Thermal insulation of non-transparent building components:** Roofs, walls, ceilings above unheated zones or outside air and base plates have to be highly insulated in order to reduce the heating energy needs. In very warm climates, the insulation level is usually lower, but investments in substantial roof insulation still prove useful, also to prevent overheating. If you aim for a zero energy school building in a Central European or Northern European climate U-values of about 0.10 to 0.15 W/m²K should be the target for walls and roofs. The analysis of the German efficiency house plus projects has shown that most houses have achieved surplus energy with a thermal quality of the building envelope slightly worse than the passive house requirements. Instead, the area of PV panels was a slightly increased. However, the general approach of the passive house level in building envelope insulation and airtightness can be a good first step towards a zero energy or plus energy building.

  Cellar ceilings are usually a bit lower in thermal quality since the installation of distribution pipes etc. limits the thickness of insulation material below the ceiling. In renovation projects this is even more the case since the cellar heights in existing buildings are mostly not high enough for the addition of big insulation panels. The insulation of base plates in existing buildings is also rather difficult as it can only be realised above the plate and thus in limited thickness. Insulation material with very low thermal conductivity such as vacuum insulation can be the solution, but results in considerable investment costs.

  Walls should be insulated on the external side as this ensures the same useful floor area as before the renovation and reduces the risk of thermal bridges. Frequently used insulation materials are mineral wool and polystyrene in combination with covers (plaster or curtain walls). There are also other types of foams on the market that allow for slightly lower thermal conductivities. Insulation packages on walls can have a thickness of 22 cm and more. During the plus energy school renovation in Stuttgart Rot (described in the case studies chapter) 26 cm of resol resin foam have been mounted on the walls. For comparison, the School of the Future renovation of the Solitude Gymnasium, also in Stuttgart includes 18 cm of mineral wool or polystyrene on the external walls. Also for walls the use of innovative insulation materials like vacuum insulation can be considered, it is however installed only rarely, mainly due to cost impacts. There are a few examples where space limits (walls next to a pathway) require such a solution.

Figure 2: 18 cm mineral wool insulation on the external wall of the Solitude Gymnasium Stuttgart.

Roofs, especially flat roofs, are usually renovated with the thickest insulation packages. Thicknesses of up to 30 cm are applied at energy efficient buildings. Also the applied material mostly has a lower thermal conductivity (e.g. expanded polystyrene) than the material used for wall insulation. In case of pitched roofs limitations of insulation thicknesses are possible, or a combination of insulation between the rafters and under or on top of the rafters has to be applied. It might be easier to insulate the ceiling to the unused attic instead of the roof as the Norwegian School of the Future project has shown.

Figure 3: 30 cm mineral wool (flock) insulation on the ceiling to the attic at the Brandengen School in Drammen, a School of the Future demonstration renovation. The ventilation pipes received a thick insulation as well.

The thick insulation packages sometimes demand advanced architectural solutions in order to keep the attractiveness of the building. A good approach is to shift the position of the windows (if part of the renovation) to the external surface of the wall construction. Thus the thick insulation packages will not be readily visible from the outside.

- **High performance windows:** In Central and Northern European climates windows in zero energy schools will mostly have triple-glazing, low-E coating and gas-filling. Window-U-values of 0.7 to 0.9 W/m²K can be realised. Especially in school buildings care must be taken that the light transmittance coefficient τ will remain high, so that a high rate of the visual daylight can be transferred while the g-value of the glazing is rather low and overheating can be reduced. For most learning activities, e.g. art lessons, the colour reproduction of the glazing should be as natural as possible. In Mediterranean climate the possible savings due to triple glazing need to be carefully evaluated and the price difference between double and triple-glazing is still higher. This makes the use of triple glazing in this climatic area very rare.

  As mentioned in the section on architectural design, windows should be openable, even in combination with ventilation systems. In summer time night ventilation (manually or automatically) might be a good solution to decrease the temperatures in the learning and teaching environment over night and start with a cooler school building in the morning.

Figure 4: Triple-glazed window in the School of the Future demonstration building Solitude-Gymnasium, Stuttgart.

- **Care for airtightness:** Especially in high performance buildings, even more in connection with ventilation systems with heat recovery, the airtightness of the building envelope becomes very important. Infiltration losses result in higher heating energy needs. National building regulations usually include airtightness requirements that have to be kept and partly proven by tests. A good airtightness aim for zero energy buildings is the airtightness requirement for passive house buildings with an air change rate $n_{50} < 0.60$ 1/h at 50 Pa pressure rate. The air change rate should at least be lower than 1.0 1/h. The Danish energy frame for Nearly Zero Energy Buildings includes an airtightness requirement of maximum 0.5 l/s per m² floor area at 50 Pa. Careful planning with well-planned details, that are simple to realise on the construction site, good supervision of the craftsmen and organised processes of the different crafts on the construction site allow for airtight connection details. Good exemplary details are available in national standards and guidelines. A blower-door test during critical installation phases can show possible weaknesses. At the end of the building process the blower-door test can provide the airtightness proof. However, if the building includes no mechanical ventilation system after the renovation, a very airtight building envelope will lead to a need for an adapted ventilation behaviour of the users, e.g. opening the windows more frequently in order to secure the required fresh air.

Figure 5: Blower-door test at the Solitude-Gymnasium, Stuttgart.

- **Care for thermal bridges:** Similar to the airtightness also thermal bridge reduction has to be even more in the focus with zero energy buildings. Besides the possible risks of moisture and mould formation on the inside of thermal bridges that applies to all buildings, the thermal losses become more significant when the other shares of the heat demand are really low. Thermal bridges can be reduced by carefully planning the details, applying clever solutions for covering all building parts (edges, etc.) with insulation, and by surveying the construction site. Again, good examples and inspiration can be found in building catalogues, standards and guidelines.

- **Extended use of daylight**: The use of daylight can reduce the electricity consumption for artificial lighting, which results in less energy that needs to be balanced by renewable energy generated at the building. Besides windows of sufficient size and shading systems that allow the use of daylight in the upper part while the lower part is closed (as described in the chapter dealing with architectural influences) and glazing with high light transmittance, there are still other possibilities to redirect daylight into deeper parts of the school building, such as light shelves or similar. The impact of light shelves is however limited and good architectural integration is difficult. Daylight dependent lighting controls (on/off or dimming) can decrease the need for electrical lighting energy in classrooms, corridors, stairs and other areas.

- **Solar shading:** In order to prevent overheating and/or glare shading systems are needed. They can be external or internal. An external shading system keeps large parts of the solar radiation outside the windows while an internal shading system can only reduce the radiation that has already entered the classroom and reflect it to the glazing. Thus external shading systems are usually more efficient. A combination between external shading system and internal glare protection is the best solution, but results in higher investment and maintenance costs. There are different types of shading systems including louvers, roller blinds and shutters. In school buildings louvers are most commonly used. State of the art louver systems have an upper part that can be angled differently from the lower part so that daylight can be redirected in the upper part while the lower part protects from sun and heat. Such a shading system is installed in the Solitude Gymnasium in Stuttgart.

Building services systems

- **Heating systems:** On account to the reduced net energy demand due to the well-insulated building envelope and the low ventilation losses (heat recovery systems), heating systems with low capacities can be installed. The exact values have to be determined by a detailed calculation based on national standards. The plus energy school in Stuttgart has a heating system with a capacity of 22 W/m² net floor area.

  The limited heating energy can also be provided by low heat temperatures, which has two positive consequences for the energy concept:

  (1) the possibility to integrate solar thermal or geothermal contributions into the heating system

  (2) the possibility to keep the (otherwise oversized) existing radiators after the building renovation. With the energy improvement of the building envelope the heat demand in the classrooms and other rooms will be much lower - therefore smaller radiators should be used to deliver the heat to the spaces. Due to the reduction of the heating temperature this effect will be counteracted and the existing radiator size becomes useful again, saving considerable investment costs for new radiators.

  For standard heat generation systems like boilers the heating temperature can be mixed down to lower temperatures. In this way solar thermal energy can be added. Often used heating generation systems in zero energy buildings are heat pumps which can be electrically or gas driven. Electrical driven heat pumps have usually higher COP values and annual efficiencies than gas driven heat pumps. However the energy carrier gas scores with lower primary energy and CO_2 factors. If the targeted annual zero balance is primary energy or CO_2 and not final energy, gas driven heat pumps therefore can make up for the lower efficiencies. Heat pumps can be coupled to the outside air, the exhaust air, to the ground or to the ground water. In the case of renovation projects, coupling to the ground and the ground water can be difficult and more costly because there is no building pit as with new constructions that can be used for the energy pillars or horizontal earth collectors. However there is a good example in the School of the Future project: The Brandengen School in Drammen combined the necessary update of the drainage with the exterior insulation of the external walls in the ground and the installation of collector pipes as shown in figure 6.

Figure 6: Combined digging for drainage, exterior insulation of walls to the ground and collector pipes at the School of the Future school in Drammen.

Combined heat and power units (micro CHPs) allow for the generation of electrical power and heat at the same time. The system can either be designed to best fit the heating needs or to best fit the electricity needs. Excess heat production is usually lost as it can't be fed into buildings that are not connected to a local district heating unit. Excess electricity can be fed into the grid, but the current feed-in tariffs for electricity generated by micro CHPs are not very attractive. Thus many CHP systems are adapted to the electricity needs of the specific building and the remaining heating needs of the building are covered by peak load boilers. During summer, the heat load is very low and so many micro CHPs are turned off. A combination with solar thermal systems can make sense in this case. Micro CHPs are calculated to a rather low primary energy factor, as the benefit of the electricity production is influencing the calculation in a positive way, even more so if the electricity is fed in and replaces electricity in the grid generated by fossil fuels (German calculation method defined in DIN V 18599). At the School of the Future case study Solitude Gymnasium a micro CHP was installed for which the design is based on the electricity load.

Figure 7: The combined heat and power unit and one of the gas boilers kept as back-up in the Solitude-Gymnasium Stuttgart.

Another way to reduce the primary energy consumption of buildings is to use biomass (wood), biogas or biofuel. These energy sources have rather low primary energy factors and also low CO_2 emission factors. They can either be burnt in boilers or CHPs or be a major part of the district heating system of a city, and therefore help to reduce the primary energy factor of the district heating. The Hedegårdskolen in Ballerup, another School of the Future project is connected to the district heating system before and after the renovation. As the district heat is generated by a waste incineration plant, the primary energy factor and the CO_2 emission factor of Ballerup's district heating are rather low (documented are 71 g/kWh) and the installation of a decentral heating system made no sense in this case.

- **Hot water:** Since school buildings are usually rather big buildings with a limited hot water demand (except for showers in sports halls) decentral hot water generation (e.g. electrical or gas-driven hot water boilers in the wash rooms) should be considered as alternative to a combined heating and hot water generation with long distribution pipes and therefore considerable distribution losses. In many schools, for example the plus energy school in Stuttgart-Rot (see Case Studies I) only cold water is provided in the washrooms. In sports halls, especially those that are used by sports clubs in the evening, solar thermal supported hot water generation can be efficient.
- **Ventilation:** Natural ventilation will in most cases need a supporting system to provide an air change rate suitable for class rooms. The supporting system can either be automated window opening controlled by CO_2 or other sensors or a ventilation system for the basic air exchange. One of the buildings of the Solitude Gymnasium uses automated opening of the top windows to the outside and on the opposite side to the corridors during the breaks in combination with a manual switch for the teachers as presented in Figure 8. A CO_2 visualisation system can further support the provision of the required volume of fresh air.

Figure 8: Windows with automated opening during breaks and manual switch for the teacher during classes.

However most renovated school buildings will nowadays include a mechanical ventilation system to ensure a high ventilation rate for good indoor comfort. In combination with a highly efficient heat recovery system a mechanical ventilation system allows for both, energy efficiency (low ventilation losses) and good air quality. Careful consideration is needed during the design phase regarding the noise impact of the fans and during the design and operation concerning the regular cleaning of the filters. Mechanical ventilation systems can be either central systems (with the ventilation ducts being led to one central ventilation unit including heat recovery mostly on the roof of the school building) or decentral systems with one unit supplying and exhausting the air of one or several classrooms. Because of limited space for ducts in existing buildings decentral ventilation systems are an attractive alternative for renovation projects. Figure 9 shows some of the mechanical ventilation systems installed in the School of the Future case studies. For zero energy schools the heat recovery rates should be 85-90% at least. It has to be assessed whether the mechanical ventilation system should run the whole year through or be turned off during summer. With high temperatures the effect of the heat recovery is no longer positive. Many ventilation systems therefore include a bypass of the heat recovery. While heat recovery is not beneficial in summer, the electricity consumption of the fans still increases the energy use of the building. In case the required amount of air can be supplied by window opening and no other restriction (e.g. noise from the streets or similar) applies, the ventilation system can be shut down and turned on again in autumn to save electricity. Based on experiences with the ventilation systems in the School of the Future projects, but also other projects the adjustment of the ventilation rate before or at the hand-over has to be performed and surveyed thoroughly. Too low ventilation rates will lead to bad indoor air quality, whereas too high ventilation rates will cause higher energy consumption and are liable to create noise problems.

Figure 9: Ventilation systems used in the School of the Future case studies: Top left: decentral ventilation system for 4-5 classrooms (Tito Maccio Plauto School, Cesena). Top right: decentral ventilation system for a single classroom (Solitude Gymnasium, Stuttgart). Bottom: Supply system (distribution sail) in a classroom of the central ventilation system at the Brandengen School in Drammen.

- **Cooling:** Cooling systems in schools are not used in the 4 participating countries of the School of the Future project. While Denmark, Norway and Germany have a Northern or Central European climate that tends to get very hot only on a few days per year, Italy has rather warm climatic zones. In Italy the summer break is however longer so that the very hot period occurs during the off time. Also the zero energy/plus energy school concepts presented in the case studies chapter do not include cooling systems. The additional energy consumption of the cooling system would considerably increase the difficulty to achieve a zero energy level. Passive strategies like the use of building mass to delay the heating up of the building or night ventilation strategies can help to decrease the temperatures during summer.

- **Lighting:** Zero- or plus energy schools must ensure low energy consumption also in the area of lighting. Nevertheless high quality lighting is needed in the classrooms, especially in some specific classrooms for teaching fine arts, etc. Thus energy efficient lighting is a prerequisite of these high performance schools. The lamps should be T5 light tubes or better in combination with electronic ballasts. LED lamps are increasingly used also in school buildings. The Hedegårds School in Ballerup, the Danish School of the Future Case Study, features some classrooms with LED lighting as shown in Figure 10.


Figure 10: Two types of LED light fixtures in the renovated Hedegårds School in Ballerup.

Advanced control systems such as occupancy detectors, daylight dependent control and/or dimming can further reduce the lighting energy consumption. The plus energy school in Stuttgart-Rot (see Case Studies I) will include some classrooms in which specific parts of the classroom can be more or less illuminated, depending on where the pupils are grouped.

A general issue is to switch off lamps when the class leaves the room. Signs at the switch near the door can help to raise the awareness of pupils and teachers.

Equipment

The equipment usually found in school buildings include electronic boards, TVs, computers, monitors, printers, copiers, cooking facilities, soda machines and smaller devices such as coffee machines, kettles etc. Many of the devices include energy efficiency classes. The purchase of at least A-rated (A+ or A++) equipment is advised. In many cases even the exchange of existing, still functional equipment with lower efficiency classes can have a short payback and will reduce the energy consumption of the building. Most equipment can be turned off when not in use. Similar to the lighting, signs can remind pupils and teachers to do so. Stand-by times should be as low as possible. An experiment with an electricity meter can make the pupils aware of the stand-by energy use. Seeing is believing.

Instead of the traditional black boards, white boards in combination with projectors or even electronic boards with LED displays are nowadays introduced into the schools. They consume a significant amount of energy. The projector of a white board has a power of 300 to 500 W. Electronic boards with LED displays have a power of approximately 200 W, but they are usually more expensive to buy. In addition a laptop is needed, causing further electricity use.

Beamer lamps have to be exchanged after 0.5 to 3 years at about 3,000 usage hours per year. At the plus energy school in Stuttgart-Rot more PV collectors became necessary to balance the electricity demand of additional electronic boards compared to the original design.

Within the School of the Future project the Municipality of Cesena and Energie per la Città have gathered experience with the electricity consumption of soda machines at the Tito Maccio Plauto School. They installed five timers to program the automatic shutdown of the devices after school hours. The machines were on from 7 am to 6 pm on Mondays to Saturdays during all months except for August, when the school was completely closed. Due to the programmed timers between 433 and 1,997 kWh/yr electricity could be saved per soda machine, depending on the type of machine if compared to the electricity use without the timers.

School buildings for further education such as vocational schools can include more and rather specific equipment that is used for specific job-training. In case that the zero energy balance shall include also this kind of energy use, considerably more energy has to be generated on the building.

PV/wind generated energy

As described above, various technologies can reduce the energy needs (e.g. building envelope technologies, ventilation heat recovery), increase the efficiency of energy generation, distribution and delivery (e.g. building services systems technologies) and cover part of the energy needed (e.g. solar thermal systems, CHPs), only few technologies can achieve a balanced or even positive result regarding the energy balance of buildings. These are photovoltaic systems and micro wind electricity generators.

The installation of both systems at school buildings (but also other buildings) is challenging because a focus should be on the good architectural integration of the systems on the school site and for PV even on the building itself.

- **Photovoltaic systems:** In almost all cases, PV collectors have a pre-defined size. This makes the complete coverage of a roof or façade and also the artful integration of the collectors a difficult task. Often this results in PV areas being placed as additional layer on top of part of the roof or even being mounted on a metal fixture. While this engineer approach is fulfilling the initial aim of generating electrical energy it doesn’t satisfy the need for building integration. On the other hand, a good building integration approach often leads to additional costs. PV panels mounted on flat roofs allow for a lower architectural quality of integration since they are usually not visible from the street level.

  In existing buildings the space for PV areas can be limited for reason of statics or because the areas are used by other technical systems, for example by the roof-installed part of central mechanical systems. Both limitations occurred in the School of the Future case study Solitude Gymnasium. Though the school renovation did not aim for zero energy, it still left only the possibility for mounting one column of PV collectors on one of the four buildings.

  The efficiency of photovoltaic systems is not as dependent on the orientation and inclination of the panels as with solar thermal systems. A southern orientation of about 30° inclination is still most effective, but eastern and western orientations can result in acceptable energy generation. Zero and plus energy buildings often aim to generate as much electricity as possible on a certain roof. If the roof is a flat roof it might be more successful to design the PV system with low inclinations in East and West orientation than with 30° to the south, at least in Central Europe. The reason is that the 30° south orientation will lead to one panel shading the other one if they are mounted too close to each other. In the end fewer panels can be mounted and less electricity will be gained. Figure 11 shows the one column of PV panels on the roof of the main building of Solitude Gymnasium which follows the approach of a low inclined east-west orientation.

Several different technologies of PV panels are in use like monocrystalline and multicrystalline silicon cells, thin-film technologies with cadmium telluride and amorphous silicon cells. The first two make up for about 90% of the PV cell market. The efficiencies are not very different from each other and are only slowly developing.

PV panels can be operated in serial and parallel mode. Parallel mode is a bit more expensive, but allows harvesting solar energy even if parts of the panels are currently shaded.

Figure 11: PV panels on the roof of the Solitude Gymnasium in east-west orientation and with low inclination.

- **Micro wind electricity generators**: These systems can either be mounted on the roof of the building or on the ground. Roof-top mounted systems are prone to similar difficulties with statics as the PV cells. Careful design and planning must be done with micro wind generators as they can lead to vibrations of the building constructions and can cause different levels of light or glare in rooms near the installed generators. Besides the well-known 3-armed turbines, new designs include vertical-axis turbines.

  Note: The wind speed on the ground or the roof of a school building can be considerably different from the speed shown on regional wind speed maps.

The choice between PV and wind generated electricity is mostly dependent on the local climate, precisely the available solar radiation and the wind speed. The experience in Germany with plus energy buildings shows that there is a broad tendency towards using PV and not wind generators. Yet, the installation of a wind generator at school buildings can be very educational for the pupils.

Self-generated electrical energy can be either self-used or fed into the electricity grid. As already discussed with CHP systems, the use of the electricity has an influence on the energy price (feed-in tariff versus electricity cost savings due to lower electricity use from the grid) and in some countries also on the energy performance calculation. For example in Germany the electricity that is fed into the grid can be balanced with a higher primary energy factor than the electricity from the grid. This makes the aim of a zero primary energy school more easily achievable for school buildings that feed the generated electricity into the grid. If the aim is to have a zero energy building also on the level of final energy, the benefit in the primary energy factor will not be helpful. On the level of a city, a region or a country, the goal should be to use as much self-generated electricity as possible at the building itself. Batteries can increase the ratio of self-used electricity because they store excess electricity for later use.

Integration in lectures

The energy efficient renovation of buildings is an important political and societal topic. Zero emission or energy buildings and plus energy buildings are highlights of energy efficient buildings, and the application of these levels and technologies in school buildings offers the possibility for raising the awareness of the pupils and their families for this topic. Therefore the design, realisation, evaluation and operation of such high performance buildings should be integrated in lessons and working groups.

- **Standard lessons:** The general need to save energy in order to reduce energy costs, decrease the imported energy and the use of fossil energy carriers can be part of geography or social education. Certain strategies and specific technologies such as insulation, the use of renewable energy, combined heat and power can be part of physics lectures, even more so if the school building offers the possibility of visiting and monitoring these technologies.
- **Working groups:** Working or study groups with different focus areas are available in many schools. Some of them focus on energy savings at the school. The participating pupils act as energy detectives investigating where energy is used and how it can be saved. They monitor the monthly energy use and take care that lights and equipment are switched off after lessons. At a zero energy school they can follow-up the success of the design and construction during the operation phase. How much heating energy and electrical energy is used per month, how much electricity is generated by PV? Will the annual balance be positive or negative?
- **Influence of user behaviour:** Students, teachers and other school users also influence the energy consumption of the school buildings. With a general awareness and some training they can contribute significantly to the success of a zero energy building project. Sensible handling of windows, lighting systems, solar shading systems and electrical equipment can ensure the pre-calculated energy use values.
- **School of the Future training material:** The School of the Future project has developed training material for pupils, teachers and facility managers in 5 languages (Danish, English, German, Italian and Norwegian). The MS Power-Point documents can be easily adapted to the situation at other schools and are available at www.school-of-the-future.eu/index.php/project-results/tailored-training.

  Additionally a simple-to-use calculation tool for the assessment of the energy performance of a school building and the energy and economic impact of various renovation strategies or technologies is offered at the same url. The tool is targeted for school buildings and has been configured with default values for renovation technologies, investment costs and energy prices so that it can also be applied during lectures.

  Other projects offer similar training material for pupils. Search on the internet for national and international projects on energy efficient schools involving the users.

CASE STUDIES I: EXAMPLES OF ZERO EMISSION, ZERO ENERGY AND PLUS ENERGY SCHOOLS

The following chapter presents some pilot projects for zero emission, zero energy and plus energy schools in the 4 participating countries of the School of the Future project and beyond. It describes the architectural designs, the technologies and strategies used, the calculated and - if already available - also the monitored energy use and the energy generated together with the lessons learned.

Germany: Plus energy schools of the German research focus EnEff:Schule

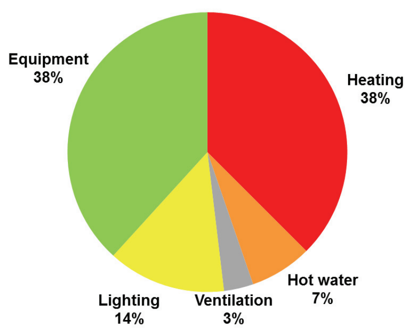
The learning and living environment provided by schools should offer optimum learning conditions. Investments in the learning environment will directly benefit our children's future and, ultimately, all of us. The German research initiative EnOB (energy optimised buildings) is therefore placing a particular focus on 'energy-efficient schools (EnEff.Schule)'. This is intended to develop principles for future-oriented school building concepts based on model projects. For example, solutions that could lead to significantly improved energy efficiency combined with increased comfort will be tried out in test projects.

So-called energy-plus schools are implemented as flagship projects. In terms of their annual energy balance, energy-plus buildings generate more energy than they consume – and can offer an excellent indoor environment. A further group of schools will attain an energy standard equivalent to 3-litre houses – these are buildings that require less than 34 kilowatt-hours of primary energy per square metre of usable area for the heating and ventilation.

An accompanying research team is cross evaluating all pilot projects, both under technological and sociological aspects.

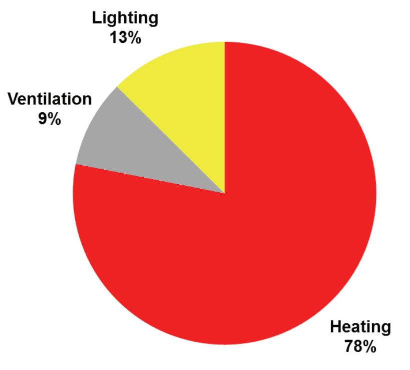
Five plus energy school projects from 'EnEff:Schule' are described on the following pages.

D1: Plus energy school in Stuttgart Rot "Uhlandschule"		
Author(s)	Heike Erhorn-Kluttig, Hans Erhorn, Johann Reiß, Fraunhofer Institute for Building Physics	
Illustration	 Façade of the Uhlandschule before the renovation. Photo: City of Stuttgart	
Project aim	The renovation of schools is one of the main goals of the 10-points-programme of the mayor of Stuttgart. The Uhlandschule will be a highlight retrofit project with the aim of achieving the plus energy level. Thus the school shall generate more energy in the annual balance compared to the total delivered and primary energy consumption.	
Building address	Tapachstraße 4, 70437 Stuttgart, Germany	
Building type	Construction: 1954 (main building pavilion, sports hall), 2004 (annex) Renovation: 2013 - 2016 Side corridor school type Plus energy school: Annual primary and final energy balance of the total energy uses including equipment	
Building size	4748 m² heated net floor area, 21663 m³ heated volume, 450 pupils, 30 classrooms	
Building envelope construction	The concrete and partly brick walls have been insulated with 26 cm of resol resin foam. The concrete roof received a new cover and an insulation of 26 cm expanded polystyrene. The cellar ceiling is insulated by 20 cm of extruded polystyrene from below, whereas the floor to the ground has a vacuum insulation wrapped in expanded polystyrene of a total width of 4 cm on top of the floor. The new windows are made of triple-glazing (diamond glazing with higher light transmission) in passive house frames.	
Building envelope U-values	Wall	0.11-0,14 W/m²K
	Window	0.80 W/m²K
	Roof	0.11-0.15 W/m²K
	Cellar ceiling/ground slab	0.27-0.34 W/m²K

Building services systems	Heating: High efficient electrical ground source heat pumps with a total capacity of 105.5 kW generate the heat for space heating. The supply and return heating temperatures are 37/27 °C. The heat is emitted by capillary tubes in the ceilings and panel heating in the apron walls. There is limited generation of hot water in combination with the heating system, but the wash rooms and classrooms will only be provided with cold water. The sports hall which is used for 3 different school buildings in the area is supplied by a separate system. It is not part of the plus energy concept. Cooling: There is no cooling system. Ventilation: The demand-controlled ventilation system consists of decentralised mechanical ventilation units with 83% heat recovery. The innovative system includes an enthalpy exchanger and was developed especially for the project. The control is based on the CO_2-level (>1500 ppm) and the system is used only in winter. CO_2-indicators (similar to traffic lights) show the pupils when window opening is required. Automatic night ventilation via window actuators ensures cooler classrooms during hot summer days. Lighting: Some of the classrooms received linear LEDs in three zones with daylight- and occupancy-dependent controls. The other classrooms are illuminated in 9 separate zones by linear LEDs that are separately controlled depending on the daylight rate and the presence of persons.			
Included renewable energy technologies	A photovoltaic system on the roofs of the main building and the annex with extends over a total surface of 1120 m^2 (167 kWp, 137 MWh/yr). In the annual balance it covers the total energy demand of the school (heat pumps, ventilation systems, lighting and equipment) and will even result in an energy plus. The heat pump is using geothermal heat.			
Final energy use	Calculated	X	Calculation method	DIN V 18599
	Measured		Monitored in year	
	Heating		9.9 kWh/m^{2}yr	
	Hot water		1.9 kWh/m^{2}yr	
	Cooling		0.0 kWh/m^{2}yr	
	Ventilation		0.9 kWh/m^{2}yr	
	Lighting		3.6 kWh/m^{2}yr	
	Equipment		10.1 kWh/m^{2}yr	
	Total		26.3 kWh/m^{2}yr	
	PV electricity		- 31.8 kWh/m^{2}yr	
	Electricity surplus		- 5.5 kWh/m^{2}yr	
Primary energy use	Grid electricity		68.5 kWh/m^{2}yr	Primary energy factor: 2.6
	Electricity fed in		-82.6 kWh/m^{2}yr	Primary energy factor: 2.6
	Total		- 14.1 kWh/m^{2}yr	
Renewable energy contribution ratio	121% of total final energy			
Improvement compared to average final energy consump-tion of schools	104%		Compared to:	BMBVS Guideline on Measured Energy Consumption: Average for school buildings: 125 kWh/m^{2}yr heating energy consumption + 20 kWh/m^{2}yr electricity consumption

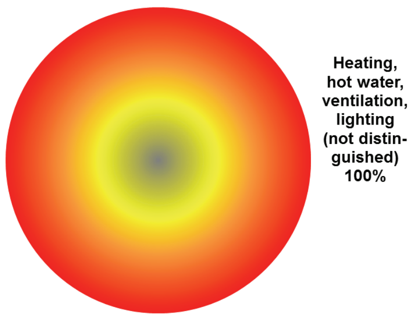
Experiences/ lessons learned	Not yet available.
Costs	The realisation is still under way. Cost estimations are as follows: Construction costs for building elements (KG 300): 4,745,496 € (1,100 €/m²) Construction costs for technical building systems (KG 400): 3,218,212 € (746 €/m²) Ancillary construction costs (KG 700): 2,874,822 € (667 €/m²) Total (KG 300, 400, 700): 10,838,530 € (2,513 €/m²) Note: KG are cost groups as defined in the German standard DIN 276 ("DIN 276", 2008)
Funding	Research Focus "EnEff:Schule" of the German Federal Ministry of Economy and Energy
Links to further information	- website: www.eneff-schule.de/index.php/Demonstrationsobjekte/Plusenergieschulen/plusenergieschule-in-stuttgart-rot.html - book: Reiß, J., Erhorn, H. et al: Energieeffiziente Schulen EnEff:Schule. Fraunhofer IRB Verlag. ISBN 978-3-8167-9034-1

D2: Plus energy school Gymnasium Rostock-Reutershagen	
Author(s)	Heike Erhorn-Kluttig, Hans Erhorn, Johann Reiß, Fraunhofer Institute for Building Physics
Illustration	 Annex to the school on the left, glazed climate buffer zone in the middle and renovated part of the school in Rostock on the right. Photo: Fraunhofer IBP
Project aim	Renovation of a typical school in the eastern part of Germany as role model for similar schools. The energy level aimed for the renovation was plus energy. Parts of the existing school have been torn down and the main building has been changed to a central corridor school. A multi-purpose hall and a glazed buffer zone have been added.
Building address	Mathias-Thesen-Str. 17, 18069 Rostock, Germany
Building type	Construction: 1960/61, 2013 (new annex and glazed buffer zone) Renovation: 2009 - 2016 Before the renovation: Side corridor school type After the renovation: Central corridor school type Plus energy school: Annual primary energy balance of the energy uses except equipment
Building size	After the renovation: 4159 m² heated net floor area, 26629 m³ heated volume, ~ 700 pupils, 50 classrooms
Building envelope construction	The brick walls have been insulated by adding prefabricated wooden façade modules filled with 24 cm of mineral wool. The new walls (annex) were also built with prefabricated wooden modules including 24 cm mineral wool. The formerly pitched roof was replaced by a flat roof including 24 cm of fibre insulation material between rafters and sloped insulation. The new roof includes 28 cm of fibre insulation material. The buffer zone has received a foil roof. The existing base plate was insulated with 2 cm vacuum insulation while the new base plate

	includes 10 cm extruded polystyrene. The windows of the main building are box-type windows with 2-times double glazing (low-E coated). The windows in the new building parts are made of triple-glazing (low-E coated) in wood-aluminium frames.			
Building envelope U-values	Wall	0.15 W/m^2K		
	Window	0.80 W/m^2K		
	Roof	0.12 W/m^2K (buffer zone: 1.96 W/m^2K)		
	Cellar ceiling/ground slab	0.27-0.34 W/m^2K		
Building services systems	Heating: The district heating system is kept because of the favourable primary energy factor (0.256). Pedestal heating and radiant ceiling panels deliver the heat to the rooms. The system works at 40 °C/30 °C supply and return temperature. An Organic Rankine Cycle (ORC) system is generating heat and electricity (2.5 kW) based on the district heating. Cooling: There is no cooling system. Ventilation: 4 central ventilation systems with a heat recovery rate of 79% supply the classrooms with fresh air. The air supply is realised in the classrooms via textile tubes. The extract is located in the central corridor. The ventilation systems are controlled by temperature and humidity sensors and partly by CO_2 sensors. Lighting: Daylight-redirection systems have been integrated in the box-type windows of the classrooms. The atrium is used to distribute daylight with light scoops and holographic-optical elements. The electrical lighting is realised by T5 tubes in two rows with electronic ballasts. They are controlled by daylight and occupancy sensors.			
Included renewable energy technologies	In the annual balance, the electricity generation of a photovoltaic system with a total of 665 m^2 (75 kWp, 67 MWh/yr), 3 wind generators (18 MWh/a) and the electricity production of the ORC cover the total primary energy demand of the school (heating, ventilation, lighting) but not that of the equipment and will even result in an energy plus.			
Final energy use	Calculated	X	Calculation method	DIN V 18599
	Measured		Monitored in year	
	Heating		56.0 kWh/m^2yr	
	Hot water		0.0 kWh/m^2yr	
	Cooling		0.0 kWh/m^2yr	
	Ventilation		6.7 kWh/m^2yr	
	Lighting		9.0 kWh/m^2yr	
	Equipment		unknown	
	Total		71.7 kWh/m^2yr	
	Wind electricity		- 4.3 kWh/m^2yr	
	PV electricity		- 16.1 kWh/m^2yr	
	ORC electricity		- 0.7 kWh/m^2yr	
	Annual balance		50.6 kWh/m^2yr	
Primary energy use	District heat		14.4 kWh/m^2yr	Primary energy factor: 0.256
	Grid electricity		40.6 kWh/m^2yr	Primary energy factor: 2.6
	Electricity fed in		-55.1 kWh/m^2yr	Primary energy factor: 2.6
	Total		- 14.5 kWh/m^2yr	
Renewable energy contribution ratio	29% of total final energy			

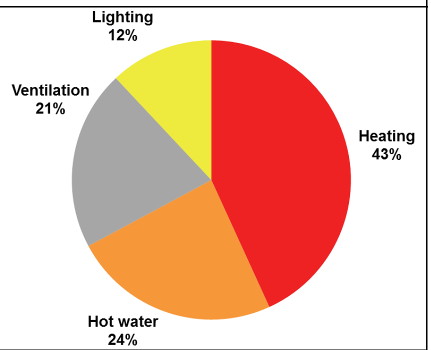
Improvement compared to average final energy consump-tion of schools	65% (but equipment is not included)	Compared to:	BMBVS Guideline on Measured Energy Consumption: Average for school buildings: 125 kWh/m²yr heating energy consumption + 20 kWh/m²yr electricity consumption
Experiences/ lessons learned	Not yet available. Monitoring ongoing.		
Costs	Total gross construction costs: 7,790,000 € = 1,873 €/m²		
Funding	Research Focus "EnEff:Schule" of the German Federal Ministry of Economy and Energy and funding by the federal state.		
Links to further information	- website: www.eneff-schule.de/index.php/Demonstrationsobjekte/Plusenergieschulen/plusenergieschule-reutershagen-rostock.html - book: Reiß, J., Erhorn, H. et al: Energieeffiziente Schulen EnEff:Schule. Fraunhofer IRB Verlag. ISBN 978-3-8167-9034-1		

D3: Plus energy school Hohen Neuendorf		
Author(s)	Heike Erhorn-Kluttig, Hans Erhorn, Johann Reiß, Fraunhofer Institute for Building Physics	
Illustration	 Façade of the elementary school in Hohen Neuendorf. Photo: Fraunhofer IBP	
Project aim	The need for additional places in elementary schools in the growing region in the north of Berlin led to the construction of a new school building together with a sports hall. The school was required to have low energy consumption and energy costs, be sustainable and provide a good indoor comfort. It was therefore decided to build a plus energy school.	
Building address	Goethestraße 1, 16540 Hohen Neuendorf, Germany	
Building type	Construction: 2011 Side corridor school type Plus energy school: Annual primary energy balance of the energy uses except equipment	
Building size	6563 m² heated net floor area, 53205 m³ heated volume, 540 pupils, 18 classrooms	
Building envelope construction	The building envelope was designed in passive house standard. The walls, ceilings and static interior walls are constructed with reinforced concrete. The cavity walls include 20 cm mineral wool. The balustrades include vacuum insulation to reduce width. The green roof includes 36 cm insulation. The base plate is insulated above and below the plate. The windows consist of triple glazing in wood/aluminium frames. The upper parts of the windows have daylight re-directing glazing. Skylights in the classrooms of the top floor contain light-diffusing nanogel-glazing. The facade of the canteen consists of electrochromic glazing.	
Building envelope U-values	Wall	0.14 W/m²K
	Window	0.80 W/m²K (skylights: 0.80 W/m²K)
	Roof	0.11 W/m²K
	Ground slab	0.10 W/m²K

<table>
<tr><td>Building services systems</td><td colspan="4">Heating: A combination of a wood-pellet combined heat and power unit (CHP, 10 kW$_{th}$/3 kW$_{el}$) and a wood-pellet boiler (220 kW) generates the heat. Three buffer storages (2 x 1650 l and 1000 l) are placed in between the generators and the radiators.
Note: The wood-pellet combined heat and power unit is not yet available on the German market. Currently the building is heated by the wood-pellet boiler only.
Cooling: There is no cooling system.
Ventilation: A hybrid ventilation system was realised consisting of a decentralised mechanical ventilation systems (one for each school wing) with heat recovery and a support by automated window opening during the breaks. The air is supplied in the classrooms and extracted in the washrooms. The ventilation system allows for two levels of air supply (6 m^3/person and 12 m^3/person). The automated windows can also be used for night ventilation in summer. Occupancy sensors are used to control the ventilation.
Lighting: Fluorescent light tubes (T5) controlled by the room depth, daylight sensors and occupancy sensors are installed in the classrooms. In the corridors LED is used for the basic lighting to which T5 tubes can be added.</td></tr>
<tr><td>Included renewable energy technologies</td><td colspan="4">Biomass is used for the boiler and the CHP. Together with the electricity produced by a 400 m^2 PV system (55 kWp), the CHP generated renewable electricity results in a negative primary energy balance (= plus energy).</td></tr>
<tr><td rowspan="9">Final energy use</td><td>Calculated</td><td>X</td><td>Calculation method</td><td>DIN V 18599</td></tr>
<tr><td>Measured</td><td>(X)</td><td>Monitored in year</td><td>2013 - 2015</td></tr>
<tr><td colspan="2">Heating, hot water, ventila-tion, lighting</td><td>42.9 kWh/m^{2}yr</td><td rowspan="7">
</td></tr>
<tr><td colspan="2">Cooling</td><td>0.0 kWh/m^{2}yr</td></tr>
<tr><td colspan="2">Equipment</td><td>unknown</td></tr>
<tr><td colspan="2">Total</td><td>42.9 kWh/m^{2}yr</td></tr>
<tr><td colspan="2">PV electricity</td><td>- 6.9 kWh/m^{2}yr</td></tr>
<tr><td colspan="2">CHP electricity</td><td>- 2.3 kWh/m^{2}yr</td></tr>
<tr><td colspan="2">Annual balance</td><td>33.7 kWh/m^{2}yr</td></tr>
<tr><td rowspan="4">Primary energy use</td><td colspan="2">Wood pellets</td><td rowspan="2">23.6 kWh/m^{2}yr</td><td>Primary energy factor: 0.2</td></tr>
<tr><td colspan="2">Grid electricity</td><td>Primary energy factor: 2.6</td></tr>
<tr><td colspan="2">Electricity fed in</td><td>-24.1 kWh/m^{2}yr</td><td>Primary energy factor: 2.6</td></tr>
<tr><td colspan="2">Total</td><td colspan="2">- 0.5 kWh/m^{2}yr</td></tr>
<tr><td>Renewable energy contribution ratio</td><td colspan="4">21% of total final energy</td></tr>
<tr><td>Improvement compared to average final energy consump-tion of schools</td><td colspan="2">77%
(but equipment is not included)</td><td>Compared to:</td><td>BMBVS Guideline on Measured Energy Consumption: Average for school buildings: 125 kWh/m^{2}yr heating energy consumption + 20 kWh/m^{2}yr electricity consumption</td></tr>
</table>

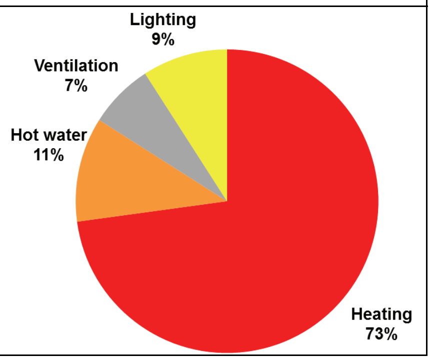
Experiences/ lessons learned	The design focused on designated home areas for the pupils. Each classroom has its own restroom and wardrobe area on the other side of the corridor. This works well for young children. The electrochromic glazing in the canteen façade resulted in warm interior surfaces. It was uncomfortable to sit near the façade. The hybrid ventilation system worked satisfactorily. The switches for the manual control of ventilation, lighting and solar shading in the classrooms were too complicated for the users. The automated windows generated noise while opening and closing that distracted the pupils. The planner was chosen according to a competition, the construction companies according to the cheapest offer. The latter proved to be problematic. In this context, experience and former projects should also be considered. The school is a national lighthouse project.
Costs	Construction costs for building elements (KG 300): 6,729,500 € (1,025 €/m²) Construction costs for technical building systems (KG 400): 2,080,962 € (317 €/m²) Total (KG 200 - KG 700): 10,853,001 € (1,654 €/m²) Note: KG are cost groups as defined in the German standard DIN 276 ("DIN 276", 2008)
Funding	Research Focus "EnEff:Schule" of the German Federal Ministry of Economy and Energy
Links to further information	- website: www.eneff-schule.de/index.php/Demonstrationsobjekte/Plusenergieschulen/low-tech-und-low-cost-plusenergie-grundschule-hohen-neuendor.html - book: Reiß, J., Erhorn, H. et al: Energieeffiziente Schulen EnEff:Schule. Fraunhofer IRB Verlag. ISBN 978-3-8167-9034-1

D4: Plus energy elementary school with day care center in Halle	
Author(s)	Heike Erhorn-Kluttig, Johann Reiß, Micha Illner, Fraunhofer Institute for Building Physics
Illustration	 Façade of the elementary school in Halle. Photo: Fraunhofer IBP
Project aim	The new building provides additional learning and teaching space for two existing school buildings in the neighbourhood and includes an elementary school and a day care centre. The building owner, a catholic foundation, attaches importance to sustainability and ecology. Therefore the building was realised in passive house standard and, based on this, as a plus energy school in order to be a model for other school building owners.
Building address	Katholische Grundschule und Hort “St. Franziskus”, Murmansker Straße 13, 06130 Halle/Saale, Germany
Building type	Construction: 2014 Central corridor / side corridor school type Plus energy school: Annual final and primary energy balance of the energy uses except equipment
Building size	2966 m² heated net floor area, 11990 m³ heated volume, 190 pupils/children, 20 classrooms/care rooms
Building envelope construction	The building envelope was designed in passive house standard. The timber frame construction of the wall is filled with 11 cm plus 25.5 cm cellulose insulation. Parts of the south-oriented wall are covered by solar thermal modules (35 m²). These walls are insulated with 11 cm plus 13.5 cm cellulose insulation. The flat roof is also a timber frame construction, insulated by 28 cm plus 18 cm cellulose material. Even the base plate consists of timber, which is insulated by 28 cm cellulose and 15 cm foam glass granulates. Below the plate there are ground-coupled heat exchanger pipes. The box-type windows include a solar shading system made of slats

<table>
<tr><td></td><td colspan="4">inserted between the glazings. The slats have two different surfaces, a metallic reflective surface for the summer and a black absorbing surface for the winter. The surfaces can be oriented according to the season. At the main entrance and the assembly hall a mullion and transom façade replaces the box-type windows due to the size of the glazed area.</td></tr>
<tr><td rowspan="4">Building envelope U-values</td><td colspan="2">Wall</td><td colspan="2">0.11 / 0.16 W/m^{2}K (regular wall / solar wall)</td></tr>
<tr><td colspan="2">Window</td><td colspan="2">0.60 / 0.75 W/m^{2}K (box-type / mullion and transom)</td></tr>
<tr><td colspan="2">Roof</td><td colspan="2">0.10 W/m^{2}K</td></tr>
<tr><td colspan="2">Ground slab</td><td colspan="2">0.13 W/m^{2}K</td></tr>
<tr><td>Building services systems</td><td colspan="4">Heating and ventilation: The building is heated by an air-heating system connected to the ground-coupled pipes and a mechanical ventilation system with 90% heat recovery rate. The inner parts of the box-type windows are opened towards the classrooms in winter and contribute to the space heating. If the supply air temperature is not high enough a temperature rise is possible, based on a district heating system used by the neighbour school building.
Hot water: The three thermal solar modules of 5, 12 and 18 m^2 that are integrated in the south façade feed into a solar storage of 2000 l, including an electrical heating element and a possibility to use district heating for warming the hot water.
Cooling: Phase change material at the walls and ceiling of the auditorium offer the possibility to have a slower rise of the indoor temperature in summer in combination with night ventilation.
Lighting: Fluorescent light tubes (T5) controlled by daylight sensors are installed in the classrooms. The luminance in the classroom is compared to the required level set by the user. If necessary, additional electrical lighting is added. For external lighting solar lamps connected to a battery are used.</td></tr>
<tr><td>Included renewable energy technologies</td><td colspan="4">A PV system with an array of 441 m^2 was mounted on the roof of the school building. The generated electricity is mainly used by the school; the remaining electricity is fed into the grid. An additional PV system (58 m^2 in size) was mounted on the roof of the carports. Together with a micro wind turbine placed in front of the main entrance, the small PV area feeds into a battery. In combination with solar lamps, the stored electricity shall ensure autarky of the external lighting as far as possible.
The ground-coupled pipes serve to pre-heat (in winter) and pre-cool (in summer) the supply air for the building.
The 35 m^2 thermal solar system that covers parts of the façade contributes to generating hot water.</td></tr>
<tr><td rowspan="11">Final energy use</td><td>Calculated</td><td>X</td><td>Calculation method</td><td>DIN V 18599</td></tr>
<tr><td>Measured</td><td></td><td>Monitored in year</td><td></td></tr>
<tr><td colspan="2">Heating</td><td>23.4 kWh/m^{2}yr</td><td rowspan="9">
</td></tr>
<tr><td colspan="2">Hot water</td><td>13.0 kWh/m^{2}yr</td></tr>
<tr><td colspan="2">Cooling</td><td>0.0 kWh/m^{2}yr</td></tr>
<tr><td colspan="2">Ventilation</td><td>11.3 kWh/m^{2}yr</td></tr>
<tr><td colspan="2">Lighting</td><td>6.5 kWh/m^{2}yr</td></tr>
<tr><td colspan="2">Equipment</td><td>unknown</td></tr>
<tr><td colspan="2">Total</td><td>54.2 kWh/m^{2}yr</td></tr>
<tr><td colspan="2">PV electricity</td><td>-68.2 kWh/m^{2}yr</td></tr>
<tr><td colspan="2">Annual balance</td><td>-14.0 kWh/m^{2}yr</td></tr>
</table>

Primary energy use	District heating	10.3 kWh/m²yr	Primary energy factor: 0.29	
	Grid electricity	45.4 kWh/m²yr	Primary energy factor: 2.4	
	Electricity fed in	-191.0 kWh/m²yr	Primary energy factor: 2.8	
	Total	-135.3 kWh/m²yr		
Renewable energy contribution ratio	126% of total final energy			
Improvement compared to average final energy consump-tion of schools	110% (but equipment is not included)	Compared to:	BMBVS Guideline on Measured Energy Consumption: Average for school buildings: 125 kWh/m²yr heating energy consumption + 20 kWh/m²yr electricity consumption	
Experiences/ lessons learned	Not yet available.			
Costs	Not yet available.			
Funding	Research Focus "EnEff:Schule" of the German Federal Ministry of Economy and Energy			
Links to further information	website: http://www.eneff-schule.de/index.php/Demonstrationsobjekte/Plusenergieschulen/plusenergie-grundschule-mit-hort-in-halle.html			

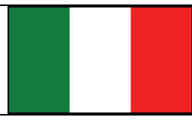
D5: Plus energy vocational school in Detmold	
Author(s)	Heike Erhorn-Kluttig, Johann Reiß, Micha Illner, Fraunhofer Institute for Building Physics
Illustration	 Façade of the vocational school in Detmold. Photo: H. Semke (pape oder semke ARCHITEKTURBÜRO)
Project aim	The five buildings of the vocational school 'Felix Fechenbach' and 'Dietrich Bonhoeffer' were to be retrofitted to achieve the plus energy standard. Increased energy efficiency was be combined with improved indoor comfort. The annual primary energy balance was aimed to yield a positive result, i.e. the amount of energy generated was designed to exceed the energy use. Additionally, the school was intended to comply with the 3-liter-house standard and the passive house standard.
Building address	Felix-Fechenbach-Berufskolleg, Saganer Straße 4, 32756 Detmold, Germany
Building type	Construction: 1954 – 1962 Renovation: 2010 - 2015 Comb-shaped school, featuring central corridor and side corridor school types Plus energy school: Annual primary energy balance of the energy uses except equipment
Building size	9373 m² heated net floor area, 38076 m³ heated volume, 3600 pupils, 58 classrooms
Building envelope construction	The use of sustainable building material and pre-fabricated elements contributes to realising a cost-effective and environmentally friendly building. Prefabricated timber-frame constructions filled with 36 cm blow-in cellulose material were mounted on the existing masonry wall. The ceiling to the attic was insulated with similar wood-frame constructions

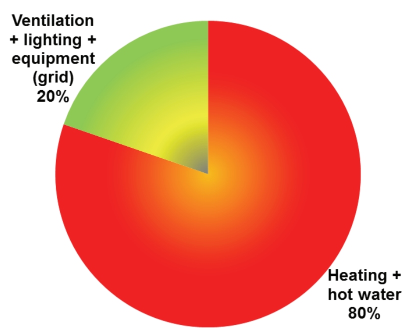
<table>
<tr><td></td><td colspan="4">with equally 36 cm thick cellulose insulation. The counter bearing of the PV elements on the roof was insulated with vacuum insulation.
The ground slab did not undergo any intervention.
The windows were replaced by passive house windows with triple low-E coated glazing in wooden frames with an aluminium cover on the outside.</td></tr>
<tr><td rowspan="4">Building envelope U-values</td><td colspan="2">Wall</td><td colspan="2">0.10 W/m²K</td></tr>
<tr><td colspan="2">Window</td><td colspan="2">0.73 W/m²K</td></tr>
<tr><td colspan="2">Ceiling to the attic</td><td colspan="2">0.12 W/m²K</td></tr>
<tr><td colspan="2">Ground slab</td><td colspan="2">2.95 W/m²K</td></tr>
<tr><td>Building services systems</td><td colspan="4">Heating and hot water: The renovated buildings are still connected to the district heating network of the municipal energy supplier. The district heat is mainly generated by combined heat and power based on biomass. The district heating pipes received improved insulation during the earthworks.
Cooling: There is no cooling system. During summer manually controlled ceiling fans shall improve the indoor comfort in two test classrooms. Night ventilation cools down the building mass and is used as a passive cooling system.
Ventilation: A hybrid ventilation system was realised, combining decentralised mechanical ventilation units with 85% heat recovery and manual window opening. The air is supplied in the classrooms through textile material that can be washed and thus reduce the dust deposit. Additionally, these devices reduce the noise emitted by the ventilation systems. The control of the ventilation system is dependent on a combination of a timer and CO_2 sensors.
Lighting: To optimise daylight use, the windows have received narrow frames. Vacuum insulation was applied to window pillars to reduce shading. The new bright-coloured paint of the classroom walls and ceiling increases indoor comfort. In previous years, the electric lighting system had been changed to T5 tubes with occupancy and daylight control. In some areas where the lighting had not yet been renovated (small sports hall and some corridors) LED lamps were installed.
A central building energy management system (BEMS) allows for optimising the building management provide the basis for monitoring.</td></tr>
<tr><td>Included renewable energy technologies</td><td colspan="4">On the roofs of three buildings and the small sports hall PV modules with a total module size of 2768 m² and 352 kWp have been installed with an increased ventilation space on the rear side.</td></tr>
<tr><td rowspan="11">Final energy use</td><td>Calculated</td><td>X</td><td>Calculation method</td><td>DIN V 18599</td></tr>
<tr><td>Measured</td><td></td><td>Monitored in year</td><td></td></tr>
<tr><td colspan="2">Heating</td><td>46.4 kWh/m²yr</td><td rowspan="9">
</td></tr>
<tr><td colspan="2">Hot water</td><td>7.1 kWh/m²yr</td></tr>
<tr><td colspan="2">Cooling</td><td>0.0 kWh/m²yr</td></tr>
<tr><td colspan="2">Ventilation</td><td>4.4 kWh/m²yr</td></tr>
<tr><td colspan="2">Lighting</td><td>5.8 kWh/m²yr</td></tr>
<tr><td colspan="2">Equipment</td><td>unknown</td></tr>
<tr><td colspan="2">Total</td><td>63.7 kWh/m²yr</td></tr>
<tr><td colspan="2">PV electricity</td><td>-26.3 kWh/m²yr</td></tr>
<tr><td colspan="2">Annual balance</td><td>37.4 kWh/m²yr</td></tr>
</table>

Primary energy use	District heating	0.8 kWh/m^{2}yr	Primary energy factor: 0.015
	Grid electricity	30.8 kWh/m^{2}yr	Primary energy factor: 2.6
	Electricity fed in	-68.5 kWh/m^{2}yr	Primary energy factor: 2.6
	Total	- 36.9 kWh/m^{2}yr	
Renewable energy contribution ratio	58% of total final energy		
Improvement compared to average final energy consump-tion of schools	74% (but equipment is not included)	Compared to:	BMBVS Guideline on Measured Energy Consumption: Average for school buildings: 125 kWh/m^{2}yr heating energy consumption + 20 kWh/m^{2}yr electricity consumption
Experiences/ lessons learned	Not yet available		
Costs	Construction costs for building elements (KG 300): 6,623,000 € (707 €/m^2) Construction costs for technical building systems (KG 400): 1,825,000 € (195 €/m^2) Total (KG 300 + KG 400): 8,448,000 € (902 €/m^2) Note: KG are cost groups as defined in the German standard DIN 276 (“DIN 276”, 2008)		
Funding	Research Focus “EnEff:Schule” of the German Federal Ministry of Economy and Energy		
Links to further information	Website: http://www.eneff-schule.de/index.php/Demonstrationsobjekte/Plusenergieschulen/sanierung-zur-plusenergieschule-berufskolleg-detmold.html		

Italy: Plus electricity school

In Italy no zero emission, zero energy or plus energy school could be found. However, the Tito Maccio Plauto School generates more electricity on an annual basis than it consumes. Therefore it could be called a plus electricity school. The PV electricity is primarily used by the building; the remainder is fed into the grid. Note: for the official energy performance calculation only the self-used PV electricity can be included in Italy.

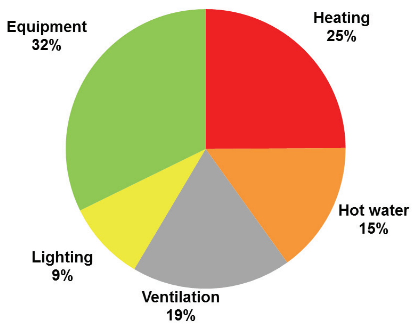
I1: Plus electricity school Tito Maccio Plauto School in Cesena (Demonstration building of the School of the Future project)	
Author(s)	M. Zinzi, G. Battistini, G. Bernabini
Illustration	 Renovated façade and main entrance of the school.
Project aim	Full energy renovation of the building. Minimum requirements were the reduction of space heating energy use by factor 4 and of the total final energy by factor 3. The building generates more electrical energy than it consumes if compared in an annual balance.
Building address	Via T. M. Plauto, 175 – CESENA (FC)
Building type	Construction: 1960s Renovation: 2011-2014 Secondary school, L-shaped with side corridor and adjacent gym hall
Building size	6027 m^2
Building envelope construction	Formerly exposed clay bricks and reinforced concrete beams and pillars. Tilted roof covered with clay tiles. Single-glazed windows with metal frames. The renovation included: - School: External thermal insulation system (ETICS) on the façade, insulated attic, insulation on the floor between the ground floor and the unheated basement. Particular care was taken to minimise thermal bridges in all the building. - Gym: internal insulation of walls and external roof insulation. - Low-e coated double glazing units in windows with thermally insulated PVC frame. - External moveable shading devices to prevent glare and overheating during the intermediate season

Building envelope U-values	Wall		0.28 - 0.30 W/m^{2}K	
	Window		1.2 W/m^{2}K	
	Roof		0.18 W/m^{2}K	
	Cellar ceiling/ground slab		0.28 – 1.3 W/m^{2}K	
Building service systems	Modulating condensing gas boilers (power from 13.4 to 215 kW) serving the heating and hot water systems. Thermostatic valves on radiators and thermostats in selected classrooms. Programmable thermostats installed in zones with specific operating hours: gym, office area, music hall. Separation of hydraulic loops to independently operate in the different zones of the school. Decentralised mechanical ventilation system with heat recovery serving all the classrooms that are continuously used. Five units installed inside the suspended ceiling of the toilets. Remote BEMS controlling the heating system performances in 60 buildings of Cesena Municipality, including the Plauto School. Lighting systems consist of luminaries equipped with T8 lamps in all the building, no specific measures were implemented due do the limited electricity energy uses of the building. No cooling system is installed, because the building is not used during the summer season (June to mid-September).			
Included renewable energy technologies	Polycrystalline PV system installed on the east and south pitches of the roof. The plant consists of 433 m^2 with 64.5 kWp. The production was 78,185 kWh in 2014.			
Final energy use	Calculated	(X)	Calculation method	Series UNI TS 11300
	Measured	X	Monitored in year	2014 ($HDD_{20\,°C}$ = 1605 Kd)
	Heating + hot water		23.6 kWh/m^{2}yr (climate corrected: 29.6 kWh/m^{2}yr)	
	Cooling		-	
	Grid electricity: ventilation + lighting + equipment		5.8 kWh/m^{2}yr	
	Total energy *		29.4 kWh/m^{2}yr	
	Self-used electricity from PV: ventilation + lighting + equipment		3.8 kWh/m^{2}yr	* These totals are only theoretical, since the Italian calculation method for the energy performance of buildings does not allow the accumulation of energy from different energy sources. Also, only self-used PV electricity can be part of the official energy performance calculation. *(Decreto 26 giugno 2015 Adeguamento del decreto Ministero dello sviluppo economico, 26 giugno 2009 – Linee guida nazionali per la certificazione energetica degli edifici)*.
	(Total electricity used		9.6 kWh/m^{2}yr)	
	Electricity from PV fed into grid		-9.1 kWh/m^{2}yr	
	Annual balance of electricity		-3.3 kWh/m^{2}yr	
	Total annual energy balance *		20.3 kWh/m^{2}yr	
Primary energy use	Gas		26.0 kWh/m^{2}yr	Primary energy factor: 1.1
	Grid electricity		12.6 kWh/m^{2}yr	Primary energy factor: 2.17
	Electricity fed in		-19.7 kWh/m^{2}yr	Primary energy factor: 2.17
	Total *		18.9 kWh/m^{2}yr	

Renewable energy contribution ratio	100% of total final electricity 29% of the total final energy		
Improvement compared to average final energy consump-tion of schools	82% 84%	Compared to:	Reference thermal energy uses for schools in Italy Reference total final energy uses for schools (thermal + electricity) in Italy
Experiences/ lessons learned	This case study demonstrates the potentialities of the energy renovation in existing public buildings, where full refurbishment can ensure about 80% of energy savings. National and international funding schemes can provide significant economic back up to the energy measures to be implemented. Construction works went through delays at some point due to the economic crisis, which affected the contractors and the original work plan; the final deadlines were respected in any case. The installation of the mechanical ventilation system significantly improved the indoor air quality, which is not ensured by the simple operation of windows during classes.		
Costs	The net costs for the energy-relevant retrofitting measures including required certificates and fees amount to € 954,800 or 158 €/m². This amount includes all measures that were performed at the building envelope and the building services systems (e.g. the boilers, the ventilation system, and the photovoltaic system).		
Funding	EU FP7, Italian "Conto Termico Energia"		
Links to further information	- http://www.school-of-the-future.eu/ - http://www.energieperlacitta.it/progetti/progetti-europei - report: Zinzi, M. et al.: Final Demonstration Building Report. EU FP7 School of the Future deliverable 6.3. Available at www.school-of-the-future.eu		

France: Plus energy school in Montpellier

F1: Ecole Maternelle et Elémentaire F. Mitterrand	
Author(s)	Heike Erhorn-Kluttig (Fraunhofer IBP), based on information during a visit and a poster presentation.
Illustration	 Façade of the Francois Mitterrand school in Montpellier. Photo: Fraunhofer IBP.
Project aim	The school was built with the aim of achieving a plus primary energy level (BEPOS).
Building address	1330 rue Henri Lagattu, 34080 Montpellier, France
Building type	Construction: 2011-2012 Nursery and elementary school. Central corridor school but classrooms only on one side. Plus energy school: Annual primary energy balance of the energy uses including equipment
Building size	3558 m², 2 buildings
Building envelope construction	The external walls are made of concrete and insulated with 20 cm mineral wool. The concrete roof includes 28 cm polyurethane insulation. The floor to the ground and the floor above outside air is made of concrete and 10 cm (to ground) respectively 15 cm (above outside air) polyurethane insulation. The double glazed low e-coated windows are filled with argon, have thermally separated aluminium frames and result in a U-value of 1.1 W/m²K for the glazing and 1.76 W/m²K for the window. There is a fixed but rotable solar shading system made of wooden slats with an either horizontal or vertical axis depending on the orientation.

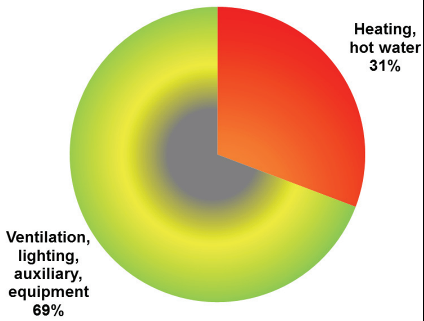
Building envelope U-values	Wall	0.159 W/m²K		
	Window	1.76 W/m²K		
	Roof	0.08 W/m²K		
	Cellar ceiling/ground slab	0.157 – 0.177 W/m²K		
Building services systems	Heating: Two gas condensing boilers with 70 kW each generate the heat for the low temperature radiators with thermostats in the rooms. The heating pumps are speed regulated. The heat is distributed from 8 am to 6 pm. The hot water is generated separately by small electrical boilers in the restrooms and by a gas boiler in the kitchen. Cooling: There is no cooling system, but night ventilation is used to prevent overheating. Ventilation: A simple flux ventilation system (extract ventilation driven by only one fan) is used in all main rooms and the restrooms and controlled by humidity sensors. There is no heat recovery included. The ventilation systems run from 9 am to 6 pm. Lighting: T5 tubes with two zone control (window area and corridor area) and occupancy sensors. Installed are 8 W/m² for the main rooms and 5 W/m² for the other areas. A central building energy management system (BEMS) controls the heating and ventilation systems, and allows detecting of malfunctions and surveying of the energy use.			
Included renewable energy technologies	400 m² of polycrystalline PV panels with 57 kWp generate about 69 MWh/yr electricity on two roofs. The generated electricity is fed into the grid.			
Final energy use	Calculated	X	Calculation method	Dynamic thermal simulation
	Measured	(X)	Monitored in year	2013: 45 kWh/m²yr total primary energy use 53 kWh/m²yr primary energy generation from PV
	Heating	5.4 kWh/m²yr		
	Hot water	3.3 kWh/m²yr		
	Cooling	0.0 kWh/m²yr		
	Ventilation	4.0 kWh/m²yr		
	Lighting	2.0 kWh/m²yr		
	Equipment	7.0 kWh/m²yr		
	Total	21.7 kWh/m²yr		
	PV electricity	-16.4 kWh/m²yr		
	Annual balance	5.3 kWh/m²yr		
Primary energy use	Gas	8.7 kWh/m²yr	Primary energy factor: 1	
	Grid electricity	33.7 kWh/m²yr	Primary energy factor: 2.58	
	Electricity fed in	-50.0 kWh/m²yr	Primary energy factor: 2.58	
	Total	-7.6 kWh/m²yr		
Renewable energy contribution ratio	89% of total final energy			
Improvement compared to average final energy consump-tion of schools	unknown	Compared to:	Even without taking into account the electricity generated by PV, the building already achieves Class A energy performance.	

Experiences/ lessons learned	- The building is a light-house building for the city of Montpellier. Two city departments (architecture and energy + technical installations) have worked closely together to perform integrated planning work that was based on dialogue and simulations - Simple and robust solutions have been sought and found, for example the shading system and the gas condensing boilers. - A blower door test was performed during the construction phase to ensure good airtightness of the building. - A guideline for the operation was produced that supports the user with practical guidance concerning the correct use of lighting, shading and window opening. Blue stickers on the window frames remind the users to open the windows in summer for night ventilation.
Costs	Total costs including planning: 11,200,000 € (3,148 €/m²) Construction costs: 5,529,000 € (1554 €/m²) Costs of PV system (400 m²): 219,060 €
Funding	Ville de Montpellier: 11,023,384 € Region: 126,616 € ADEME: 50,000 €
Links to further information	- Website: Observatoire BBC: Groupe scolaire F. Mitterand http://www.observatoirebbc.org/site/bepos/?FicheDuBatiment=44 - Summary leaflet: http://www.montpellier.fr/include/viewFile.php?idtf=12751&path=97%2FWEB_CHEMIN_12751_1305012963.pdf

Austria: Zero energy school (for heating and hot water) in Wolfurt

A1: Elementary school in Wolfurt Mähdle

Author(s)	Heike Erhorn-Kluttig (Fraunhofer IBP), based on information of IEA SHC Task 40 presented in Voss, K.; Musall, E.: Net zero energy buildings – International projects of carbon neutrality in buildings. Detail Green Books. 2013. ISBN 978-3-920034-80-5.	
Illustration	No photo available.	
Project aim	Renovation of the 35 year old school buildings with the aim of meeting current and future demands. Passive house standard and building-related (heating + hot water) zero final energy balance.	
Building address	Mähdlestraße 27, 6922 Wolfurt, Austria	
Building type	Construction: 1974 Renovation: 2007 Elementary school. Central and side corridor school. Net zero energy school: Annual final energy balance of the building related energy uses (together with a neighbouring new built fire station)	
Building size	3367 m² net floor area, 15006 m³ gross volume, school and sports hall, 180 users	
Building envelope construction	The formerly open space between the school and the sports hall was closed, resulting in additional 580 m² of usable space and a more compact building. The existing reinforced concrete walls have been insulated with in total 30 cm mineral wool as part of a wood frame construction with double wood shingle cladding. The new façade was partly prefabricated in elements. The old double-glazed windows were replaced by a post and lintel construction. The strip windows were replaced by triple-glazed casement windows. The existing roof structure (consisting of reinforced concerte and 14 cm insulation) was provided with an additional layer of 16 cm expanded polystyrene hard foam. The insulation of the floor slab could not be enhanced, but extruded polystyrene hard foam insulation was added as perimeter insulation.	
Building envelope U-values	Wall	0.13 W/m²K
	Window	0.85 W/m²K
	Roof	0.12 W/m²K
	Ground slab	0.95 W/m²K

Building services systems	Heating and hot water: A ground water heat pump (56 kW, one borehole with an 18 m deep well) in combination with 80 m^2 of solar collectors provide both heating and hot water. The solar collectors are integrated in the southern façade of the school, feeding a 6000 l combined buffer storage tank. A separate heat pump is used for the fire station. Cooling: There is no cooling system. Solar protection systems with mixed control (automatic tilting according to the sun position and manual override) prevent overheating. Ventilation: A controlled supply and exhaust ventilation system with a heat recovery rate of 85% was installed. For the school hall and the sports hall this was realised by a centrally located ventilation plant. In the classrooms, decentralised ventilation systems with supply air via the façade were installed. The classroom ventilation systems are controlled by presence sensors, but they can also be operated manually. Lighting: Energy-efficient lighting was installed.			
Included renewable energy technologies	80 m^2 of solar collectors on the south façade of the school building. Ground-water heat pump of 56 kW. According to the calculations, a rooftop-mounted 188 m^2 PV array with 26 kWp can offset the 26000 kWh/yr electricity use of all building service systems. The PV system feeds electricity into the national grid.			
Final energy use	Calculated	(X)	Calculation method	unknown
	Measured	X	Monitored in year	2010
	Heating + hot water	8 kWh/m^{2}yr		
	Cooling	-		
	Ventilation, lighting, auxiliary, equipment	18 kWh/m^{2}yr		
	Total	26 kWh/m^{2}yr		
	PV electricity	-8 kWh/m^{2}yr		
	Annual balance	18 kWh/m^{2}yr		
Primary energy use	Grid electricity	34 kWh/m^{2}yr		Primary energy factor: 1,3
	(of which heating and hot water related) *	(10 kWh/m^{2}yr)		
	Electricity fed-in	-11 kWh/m^{2}yr		
	Total	23 kWh/m^{2}yr		
	(in relation to heating and hot water) *	(-1 kWh/m^{2}yr)		* At the time of the energy performance calculation Austria assessed heating and hot water as building related energy use. The zero energy balance is related to this energy use.
Renewable energy contribution ratio	30% of total final energy			
Improvement compared to average final energy consumption of schools	unknown		Compared to:	-

Experiences/ lessons learned	- In the first year of measurements (documented here) the net zero primary energy balance goal was nearly missed because of:
	  - increased use of heat to dry the building
	  - different user behaviour
	  - initially uninsulated heating pipes
	  - lower solar yields due to a sensor problem and shading by a big tree
	- A very short construction period of eleven weeks for the school buildings and eight months for the infrastructure was made possible because of excellent communication and use of prefabricated façade modules.
	- The technical fine-tuning and harmonisation of the space heating system, the ventilation system and the sun protection took nearly one year.
	- The changes to the energy concept became part of the curriculum.

Costs	Construction and technical systems costs (net): 950 €/m²
Funding	20% subsidy from the State of Vorarlberg.
Links to further information	Voss, K.; Musall, E.: Net zero energy buildings – International projects of carbon neutrality in buildings. Detail Green Books. 2013. ISBN 978-3-920034-80-5.

Overview table of zero emission, zero energy or plus energy school buildings and the applied technologies

Characteristic				D1: Stuttgart	D2: Rostock	D3: Hohen Neuendorf	D4: Halle	D5: Detmold	I1: Cesena	F1: Montpellier	A1: Wolfurt
Type of high performance building	Zero Emission										
	Zero Energy	Primary energy									heating + hot water only
		Final energy									
	Plus energy	Primary energy							electricity only		
		Final energy							electricity only		
Type of balance	Annual										
	Dynamic (autarky)										
Included energy uses in the balance	Heating										
	DHW										
	Ventilation										
	Cooling			not used	not used	not used	not used	not used	not used	not used	not used
	Lighting										
	Equipment										
Used technologies/qualities	Building envelope	Wall	U-value > 0.15 W/m²K								
			U-value ≤ 0.15 W/m²K								
		Win-dows	Double glazed low-E								
			Triple glazed low-E								
			Box-type: 2x double								
		Roof	U-value > 0.15 W/m²K								
			U-value ≤ 0.15 W/m²K								
		Floor	U-value > 0.20 W/m²K								
			U-value ≤ 0.20 W/m²K								
	Heating	Boiler				biomass					
		Heat pump									
		District heating									
		Solar thermal support									
		Geothermal support									
		Low temperature distribution									
		Radiators									
		Floor heating									
		Panel heating at wall or ceiling									

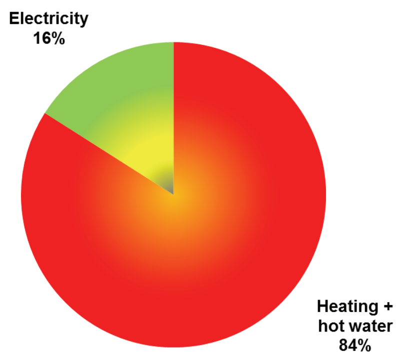
Characteristic			D1: Stuttgart	D2: Rostock	D3: Hohen Neuendorf	D4: Halle	D5: Detmold	I1: Cesena	F1: Montpellier	A1: Wolfurt
		Pedestal heating								
		Air heating								
	DHW	Combined w. heating								
		Decentralised electrical								
		Solar thermal support								
		Only cold water								
	Cooling		not used	not used	not used	passive, PCM	not used	not used	not used	not used
	Venti-lation	Natural								
		Central mechanical w/o HR								
		Central mechanical w. HR								
		Decentral mechanical w. HR						5 units		
		CO_2-control								
		Temperature/humidity control								
		Night ventilation								
	Lighting	T8								not part of energy concept
		T5								
		LED								
		Daylight dependent								
		Occupancy dependent								
		Daylight re-direction								
	Equip-ment	Blackboards		not part of energy concept	not part of energy concept	not part of energy concept	not part of energy concept			
		Whiteboards with projectors								
		Electronic whiteboards								
		Low energy computers								
		Low energy cooking								
	Electricity generation	PV								
		Wind								
		Combined heat and power								
		Organic Rankine Cycle								
Integration in lectures		Standard lessons								
		Working groups								
		Information on user influence								

CASE STUDIES II: ON THE WAY TOWARDS ZERO ENERGY

In this chapter the renovation projects of the School of the Future projects are presented in relation to the zero energy level. That means that the four projects are described and at the end of the overview it is indicated which necessary additions must be made to achieve the zero energy level. For consistency it is calculated in each case how many square meters of horizontally applied photovoltaic panels (5% inclination to East/West) would have to be added.

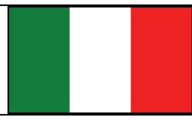
Germany

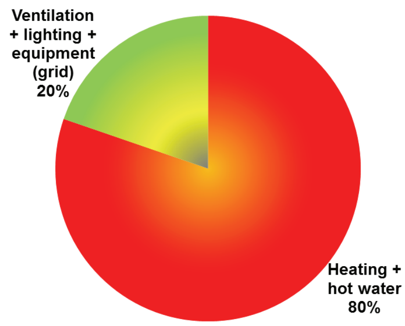
School of the Future: Energy-efficient Renovation of the Solitude Gymnasium in Stuttgart	
Author(s)	Heike Erhorn-Kluttig, Hans Erhorn, Fraunhofer Institute for Building Physics Christoph Höfle, Stephan Kempe, Jürgen Görres, City of Stuttgart
Illustration	 Façade of the Solitude Gymnasium after the renovation. Photo: Fraunhofer Institute for Building Physics
Project aim	Energy efficient renovation beyond the usual approach but with limitation of the investment cost. The heating energy use should be reduced by 75% and the total energy use by factor 3. In parallel the indoor climate should be improved. The school is one of the demonstration projects within the EU 7FP School of the Future project.
Building address	Spechtweg 40, 70499 Stuttgart, Germany
Building type	Construction: 1966 (big pavilion)/1975 (main building and gym) Renovation: 2012 - 2014 Central corridor school type. Highly energy-efficient renovation

<table>
<tr><td>Building size</td><td colspan="4">8924 m² heated net floor area, 46500 m³ gross volume, 710 pupils,
27 classrooms + additional rooms for science classes, etc.</td></tr>
<tr><td>Building envelope construction</td><td colspan="4">The concrete and partly brick walls have been insulated with 18 cm of mineral wool or polystyrene. On the concrete flat roof insulation of up to 22 cm expanded polystyrene was applied. The cellar ceiling did not undergo any renovation. The new windows are made of triple glazing, in few areas double glazing was used.</td></tr>
<tr><td rowspan="4">Building envelope U-values</td><td colspan="2">Wall</td><td colspan="2">0.18-0,23 W/m²K</td></tr>
<tr><td colspan="2">Window</td><td colspan="2">0.90/1.3 W/m²K</td></tr>
<tr><td colspan="2">Roof</td><td colspan="2">0.15-0.20 W/m²K</td></tr>
<tr><td colspan="2">Cellar ceiling/ground slab</td><td colspan="2">1.5 W/m²K (no intervention)</td></tr>
<tr><td>Building services systems</td><td colspan="4">Heating: A combination of a cogeneration plant (CHP, 15 kW_{el}/30 kW_{th}) and the use of the two existing boilers for peak load and redundancy was calculated to obtain a short payback period. Together with a heat storage, this combination covers the heat demand for space heating and hot water. The produced electricity is used by the school and excess electricity will be fed into the grid. The existing hydraulic system was upgraded by state-of-the-art heating pumps and valves.
Cooling: There is no cooling system.
Ventilation: The main building includes a central ventilation system with 90% heat recovery for the auditorium and decentral ventilation systems with 80% heat recovery in the classrooms. The existing ventilation system of the scientific classrooms was improved by heat recovery unit with 90% recovery rate. All mechanical ventilation systems are CO_2-controlled. The classrooms in the big pavilion feature a hybrid ventilation system with window opening and actuators that open the upper part of the windows during breaks and if activated by the teachers. The ventilation system of the gym could not be improved due to lack of space. However a CO_2-control was added.
Lighting: During the renovation old T8 compact fluorescent lamps (CFL) have been replaced by T5 CFLs. Electronic ballasts replace conventional ballasts. The classroom lighting is controlled by presence detectors. Daylight-dependent control of the lighting was installed in the staircases.</td></tr>
<tr><td>Included renewable energy technologies</td><td colspan="4">Due to static limitations and the installation of the ventilation system on the building for scientific classes, most roofs could not be used for the addition of photovoltaic panels. However, a 7.5 kWp PV system consisting of 30 panels (~ 50 m²) was installed on the roof of the main building, directly above a static wall.</td></tr>
<tr><td rowspan="12">Final energy use</td><td>Calculated</td><td>X</td><td>Calculation method</td><td>DIN V 18599</td></tr>
<tr><td>Measured</td><td></td><td>Monitored in year</td><td></td></tr>
<tr><td colspan="2">Heating</td><td rowspan="2">53.1 kWh/m²yr</td><td rowspan="10"></td></tr>
<tr><td colspan="2">Hot water</td></tr>
<tr><td colspan="2">Cooling</td><td>-</td></tr>
<tr><td colspan="2">Ventilation</td><td rowspan="3">10.1 kWh/m²yr</td></tr>
<tr><td colspan="2">Lighting</td></tr>
<tr><td colspan="2">Equipment</td></tr>
<tr><td colspan="2">Total</td><td>63.2 kWh/m²yr</td></tr>
<tr><td colspan="2">PV and CHP gen. electricity</td><td>-5.5 kWh/m²yr</td></tr>
<tr><td colspan="2">Annual balance</td><td>57.7 kWh/m²yr</td></tr>
</table>

Primary energy use	Heating	52.6 kWh/m²yr	Primary energy factor: 1.1, $f_{HS/HI}$=1,11
	Grid electricity	27.3 kWh/m²yr	Primary energy factor: 2.7
	Electricity fed into grid	-16.5 kWh/m²yr	Primary energy factor: 3.0
	Total	63.4 kWh/m²yr	
Renewable energy contribution ratio	1% of total final energy		
Improvement compared to average final energy consumption of schools	54% (74% of consumption before the renovation)	Compared to:	BMBVS Guideline on Measured Energy Consumption: Average: 125 kWh/m²yr heating energy consumption + 20 kWh/m²yr electricity consumption
Experiences/ lessons learned	Energy retrofitting of existing buildings cannot always be realised as easily as planned for in the first concept. Static or spatial restrictions can prevent energy-saving measures such as the initially intended bigger PV array and the heat recovery in the gym. During commissioning, special care has to be taken to ensure correct adjustment of the air change rate of the ventilation systems. The lowest ventilation level must meet the hygienically necessary ventilation rate. Windows have to be operable in classrooms also in the presence of ventilation systems. The indoor air quality was significantly improved due to the renovation.		
Costs	The total cost of the renovation including non-energy related measures and planning costs have been about 12 million € or 1.340 €/m².		
Funding	EU 7FP: Project "School of the Future" (260102)		
Links to further information	- Website: http://www.school-of-the-future.eu/index.php/stuttgart-germany - Report: Zinzi, M. et al.: Final Demonstration Building Report. EU FP7 School of the Future deliverable 6.3. Available at www.school-of-the-future.eu		
Necessary addition to achieve a zero energy level	Zero primary energy (all energy uses incl. equipment): ~ 2006 m² PV (multicrystalline) on horizontal area Zero final energy (all energy uses incl. equipment): ~ 5231 m² PV (multicrystalline) on horizontal area		

Italy

School of the Future: Energy-efficient renovation of theTito Maccio Plauto School in Cesena		
Author(s)	M. Zinzi, G. Battistini, G. Bernabini	
Illustration	 Renovated façade and main entrance of the school.	
Project aim	Full energy renovation of the building. Minimum requirements were the reduction of space heating energy use by factor 4 and of the total final energy by factor 3. The building generates more electrical energy than it consumes if compared in an annual balance.	
Building address	Via T. M. Plauto, 175 – CESENA (FC)	
Building type	Construction: 1960s Renovation: 2011-2014 Secondary school, L-shaped with side corridor and adjacent gym hall	
Building size	6027 m^2	
Building envelope construction	Formerly exposed clay bricks and reinforced concrete beams and pillars. Tilted roof covered with clay tiles. Single-glazed windows with metal frames. The renovation included: - School: External thermal insulation system (ETICS) on the façade, insulated attic, insulation on the floor between the ground floor and the unheated basement. Particular care was taken to minimise thermal bridges in all the building. - Gym: internal insulation of walls and external roof insulation. - Low-e coated double glazing units in windows with thermally insulated PVC frames. - External moveable shading devices to prevent glare and overheating during the intermediate season	
Building envelope U-values	Wall	0.28 - 0.30 W/m²K
	Window	1.2 W/m²K
	Roof	0.18 W/m²K
	Cellar ceiling/ground slab	0.28 – 1.3 W/m²K

<table>
<tr><td>Building services systems</td><td colspan="4">Modulating condensing gas boilers (power from 13.4 to 215 kW) serving the heating and hot water systems. Thermostatic valves on radiators and thermostats in selected classrooms. Programmable thermostats installed in zone with specific operating hours: gym, office area, music hall. Separation of hydraulic loops to independently operate in the different zones of the school.
Decentralised mechanical ventilation system with heat recovery serving all the classrooms that are continuously used. Five units installed inside the suspended ceiling of the toilets.
Remote BEMS controlling the heating system performances in 60 buildings of Cesena Municipality, including the Plauto School.
Lighting systems consists of luminaries equipped with T8 lamps in all the building, no specific measures were implemented due do the limited electricity energy uses of the building.
No cooling system installed, because the building is not used during the summer season (June to mid September).</td></tr>
<tr><td>Included renewable energy technologies</td><td colspan="4">Polycrystalline PV system installed on the east and south pitches of the roof. The plant consists of 433 m^2 with 64.5 kWp. The production was 78,185 kWh in 2014.</td></tr>
<tr><td rowspan="11">Final energy use</td><td>Calculated</td><td>(X)</td><td>Calculation method</td><td>Series UNI TS 11300</td></tr>
<tr><td>Measured</td><td>X</td><td>Monitored in year</td><td>2014 ($HDD_{20\,°C}$ = 1605 Kd)</td></tr>
<tr><td colspan="2">Heating + hot water</td><td>23.6 kWh/m^{2}yr (climate corrected: 29.6 kWh/m^{2}yr)</td><td rowspan="9">

* These totals are only theoretical, since the Italian calculation method for the energy performance of buildings does not allow the accumulation of energy from different energy sources. Also only self-used PV electricity can be part of the official energy performance calculation. (Decreto 26 giugno 2015 Adeguamento del decreto Ministero dello sviluppo economico, 26 giugno 2009 – Linee guida nazionali per la certificazione energetica degli edifici).</td></tr>
<tr><td colspan="2">Cooling</td><td>-</td></tr>
<tr><td colspan="2">Grid electricity: ventilation + lighting + equipment</td><td>5.8 kWh/m^{2}yr</td></tr>
<tr><td colspan="2">Total energy *</td><td>29.4 kWh/m^{2}yr</td></tr>
<tr><td colspan="2">Self-used electricity from PV: ventilation + lighting + equipment</td><td>3.8 kWh/m^{2}yr</td></tr>
<tr><td colspan="2">(Total electricity used</td><td>9.6 kWh/m^{2}yr)</td></tr>
<tr><td colspan="2">Electricity from PV fed into grid</td><td>-9.1 kWh/m^{2}yr</td></tr>
<tr><td colspan="2">Annual balance of electricity</td><td>-3.3 kWh/m^{2}yr</td></tr>
<tr><td colspan="2">Total annual energy balance *</td><td>20.3 kWh/m^{2}yr</td></tr>
<tr><td rowspan="4">Primary energy use</td><td colspan="2">Gas</td><td>26.0 kWh/m^{2}yr</td><td>Primary energy factor: 1.1</td></tr>
<tr><td colspan="2">Grid electricity</td><td>12.6 kWh/m^{2}yr</td><td>Primary energy factor: 2.17</td></tr>
<tr><td colspan="2">Electricity fed in</td><td>-19.7 kWh/m^{2}yr</td><td>Primary energy factor: 2.17</td></tr>
<tr><td colspan="2">Total *</td><td>18.9 kWh/m^{2}yr</td><td></td></tr>
<tr><td>Renewable energy contribution ratio</td><td colspan="4">100% of total final electricity
29% of the total final energy</td></tr>
</table>

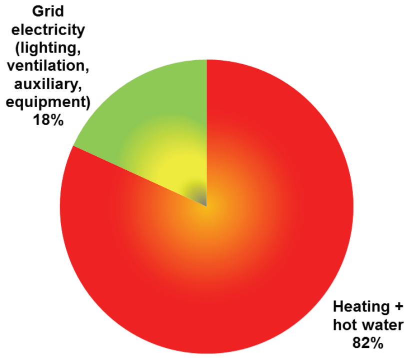
Improvement compared to average final energy consump-tion of schools	82% 84%	Compared to:	Reference thermal energy uses for schools in Italy Reference total final energy uses for schools (thermal + electricity) in Italy
Experiences/ lessons learned	This case study demonstrates the potentialities of the energy renovation in existing public buildings, where full refurbishment can ensure about 80% of energy savings. National and international funding schemes can provide significant economic back up to the energy measures to be implemented. Construction works went through delays at some point due to the economic crisis, which affected the contractors and the original work plan; the final deadlines were respected in any case. The installation of the mechanical ventilation system significantly improved the indoor air quality, which is not ensured by the simple operation of windows during classes.		
Costs	The net costs for the energy-relevant retrofitting measures including required certificates and fees amount to € 954,800 or 158 €/m². This amount includes all measures that were performed at the building envelope and the building services systems (e.g. the boilers, the ventilation system, and the photovoltaic system).		
Funding	EU FP7, Italian "Conto Termico Energia"		
Links to further information	- http://www.school-of-the-future.eu/ - http://www.energieperlacitta.it/progetti/progetti-europei - report: Zinzi, M. et al.: Final Demonstration Building Report. EU FP7 School of the Future deliverable 6.3. Available at www.school-of-the-future.eu		
Necessary addition to achieve a zero energy level **	Zero primary energy (all energy uses incl. equipment): ~ 500 m² PV (multicrystalline) on horizontal area Zero final energy (all energy uses incl. equipment): ~ 1120 m² PV (multicrystalline) on horizontal area ** These calculations are only theoretical, since the Italian energy performance of buildings calculation method does not allow the accumulation of energy from different energy sources.		

Denmark

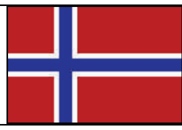
School of the Future: Energy-efficient renovation of the Hedegårds School in Ballerup

Author(s)	Ove Mørck, Cenergia & Kirsten Engelund Thomsen, Danish Building Research Institute, Aalborg University
Illustration	 The east façade of the renovated school. Photo: Ove Mørck, Cenergia.
Project aim	Part F of Hedegaards School in Ballerup, Denmark has been energy-retrofitted as one of the four demonstration buildings within the EU 7FP project “School of the Future”. The energy-efficient renovation had to be beyond the usual approach but with a limitation of the investment costs. The heating energy use should be reduced by 75% and the total energy use by factor 3. In parallel, the indoor climate should be improved. The school is more than 35 years old and a renovation was needed. The roof was not weather tight, the windows were punctured and leaky and the insulation levels of the walls and ceilings were low. In addition, the lighting system in the corridors was old-fashioned and consumed too much energy. The renovation includes the following elements: insulation of the thermal envelope, new windows, new lighting system in corridor and two classrooms, renewables (PV) and an advanced control management system (BEMS).
Building address	Magleparken 8, 2750 Ballerup, Denmark
Building type	Construction: 1972 Renovation: 2012 - 2014 Side corridor school type with internal common areas Highly energy-efficient renovation
Building size	The total floor area is 3850 m^2. It has 15 ordinary classrooms, two rooms for physics/science classes, one auditorium, one teachers’ room, and a student cafeteria in the basement.

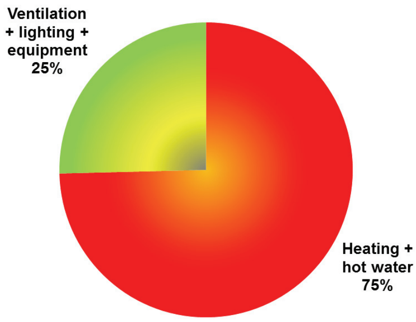
<table>
<tr><td>Building envelope construction</td><td colspan="2">The exterior walls were double brick walls. Between the two layers of bricks there was a layer of insulation – 7 cm thick and at several points massive and thus with substantial thermal bridges. The windows were double-glazed windows placed in a band extending almost all around the building. Many of the windows were punctured and the frames in need of paint.
As an average, 25 cm of insulation has been added on the roof, so the average thickness now is 45 cm. All around the building, the existing insulation and the exterior wall layer has been replaced by new insulation and a new exterior layer. All the windows were replaced by new windows. The new wall is insulated with 33 cm of mineral wool with a value of thermal conductivity equal to 0.034 W/mK. The windows have three layers of glass and a frame system with very low thermal transmittance.</td></tr>
<tr><td rowspan="4">Building envelope U-values</td><td>Wall</td><td>0.10 W/m^{2}K</td></tr>
<tr><td>Window</td><td>0.70 W/m^{2}K</td></tr>
<tr><td>Roof</td><td>0.08 W/m^{2}K</td></tr>
<tr><td>Cellar ceiling/ground slab</td><td>0.40 W/m^{2}K (no intervention)</td></tr>
<tr><td>Building services systems</td><td colspan="2">The district heating system and the ventilation systems are kept.
Part F of Hedegaards School has been coupled to the existing BEMS system that controls the other parts of the school. The energy meters for electricity and heating automatically feed data to the BEMS system. The electricity production of the PV system is also monitored by the new BEMS system.
The existing lighting systems in the classrooms are quite efficient and a replacement in all classrooms cannot be justified today by energy savings. However, the municipality is interested in gathering experiences with new (LED) lighting systems and therefore a side-by-side test of two different LED systems (round and square) in two classrooms was carried out. In both classrooms the lamps are controlled based on presence and daylight sensors. Also the lighting of the blackboards has been improved in the two classrooms by installing LED-based lighting systems. Here a band of LED light diodes has been installed in a reflector above and in front of the blackboards. LED downlights were installed in the corridors. The two rows of light fixtures are controlled individually according to daylight level.
There is no cooling system.</td></tr>
<tr><td>Included renewable energy technologies</td><td colspan="2">A PV system was installed on the south facing sloping roof of one of the roof light systems of the school building. The area is 152 m^2 and the total installed power is 22.5 kWp. The expected yearly production will be 22.5 MWh/yr, corresponding to 5.8 kWh/m^{2}yr.</td></tr>
</table>

Final energy use	Calculated	(X)	Calculation method	ASCOT (EN 13790)
	Measured	X	Monitored in year	2014 - 2015
	Heating + hot water		76.1 kWh/m^{2}yr	
	Cooling		-	
	Grid electricity: ventilation + lighting + auxi-liary +equipment		16.9 kWh/m^{2}yr	
	PV energy generated and self-used		5.1 kWh/m^{2}yr	
	(Total electricity use incl. PV)		22.0 kWh/m^{2}yr)	
	Total energy		93.0 kWh/m^{2}yr	
Primary energy use	District heat		76.1 kWh/m^{2}yr	Primary energy factor: 1.0
	Grid electricity		42.3 kWh/m^{2}yr	Primary energy factor: 2.5
	Total		118.4 kWh/m^{2}yr	
Renewable energy contribution ratio	5% of total final energy			
Improvement compared to average final energy consump-tion of schools	36%		Compared to:	Heating: 120 kWh/m^{2}yr Electricity: 25 kWh/m^{2}yr
Experiences/ lessons learned	Applying external wall insulation in the way chosen was a positive experience. The renovation process – stepwise renovation of two classrooms - went very well. Pb and PCB were found in the old windows. This increased the cost and delayed the replacement. Renewal of the existing classroom ventilation system was too costly. Energy savings were close to the estimations – and goals - of the project.			
Costs	The total investment for the energy-related part of the renovation was 4.1 million DKK without VAT and the simple pay-back time is 17.6 years.			
Funding	The Municipality of Ballerup – own funding. EU 7FP: Project "School of the Future" (260102)			
Links to further information	- www.school-of-the-future.eu - Report: Zinzi, M. et al.: Final Demonstration Building Report. EU FP7 School of the Future deliverable 6.3. Available at www.school-of-the-future.eu			
Necessary addition to achieve a zero energy level	Zero primary energy (all energy uses incl. equipment): ~ 1100 m^2 PV (multicrystalline) on horizontal area Zero final energy (all energy uses incl. equipment): ~ 1260 m^2 PV (multicrystalline) on horizontal area			

Norway

School of the Future: Energy-efficient renovation of the Brandengen School in Drammen	
Author(s)	Karin Buvik, SINTEF Building and Infrastructure Geir Andersen, Drammen Municipality Real Estate Sverre Tangen, Glass, Glazing and Facade Association
Illustration	 South and east façade after retrofitting. Photo: SINTEF.
Project aim	Reduction of delivered energy by 67%. Improvement of indoor thermal conditions; avoiding cold drafts in winter and overheating in summer. Restoration of the facades' aesthetics to be close to their original historic look. The school is one of the demonstration projects within the EU 7FP School of the Future project.
Building address	Iver Holters gate 48, 3041 Drammen, Norway
Building type	Construction: 1914 Renovation: 2012 - 2013 The school's facilities consist of three buildings in bricks, linked together with arcades. The buildings are of historical value, designed by architect Arnstein Arneberg. The main building has a side-corridor plan layout with classrooms facing south and west.
Building size	7.079 m^2 gross area. Number of classrooms: 30 (25+3+2) including gym and activity rooms. 520 pupils in 2015.
Building envelope construction	The exterior walls are made of brick, without insulation between the two sidewalls. The windows were mainly from the 1960s. Neither the mansard roof of wooden construction, nor the concrete basement walls, had additional insulation. To decrease energy consumption and increase indoor comfort, the building envelope was retrofitted, including additional insulation in the attic, mansard walls and basement walls, and replacement/restoration of windows. Windows from the 1960s were replaced by 'passive house' windows. Windows on south and west façades got glazing with low solar energy transmittance (g-value 27%). Thus the exterior sunscreen devices could be removed from the façades, in order to restore the facades' aesthetical appearance to be as close as possible to that of the original

	historic look. Arched, original windows from 1914 were restored and provided with new interior sashes with double-glazed units.	
Building envelope U-values	Wall	0.81 W/m²K
	Window, new	0.80 W/m²K
	Window, restored	1.0 W/m²K
	Roof	0.20 W/m²K
	Cellar ceiling/ground slab	0.15 W/m²K
Building services systems	Space heating: In the two largest buildings the heating system is water based, with radiators controlled by thermostats. The energy carrier was oil, now replaced by geothermal heat. The small building has electric heaters. Ventilation: In 2003 balanced ventilation systems, with variable air volume and heat recovery of outlet air, were installed in the main building and the small building for leisure time arrangement. The gym building still has its old heating air ventilation system. Replacement of this system is postponed, due to uncertainty regarding the future activities in the building. The gym building will, most likely within a few years, be transformed to general work places for classes (classrooms), as a new sports hall is planned to be built in the neighbour plot. Electric lighting: The lighting system was also modernised in 2003, with T5 low energy lighting fixtures and presence detectors in all classrooms, larger occupied zones and corridors. The users have to manually switch on the light, while shutting down is automated. Sanitary hot water: In the two largest buildings the tap water is heated through double-jacketed hot water boilers, based on the heating system with supplementary electrical coils for summer operation. In the small building electrical coils heat the tap water.	
Included renewable energy technologies	The original heating system was based on two oil burners in combination with an electrical boiler. The rebuilt system uses a heat pump connected to ground-source energy wells. One of the old oil burners is modified for bio oil for peak load. This burner and the old electrical boiler serve as backup. 19 energy wells for collectors were drilled in the schoolyard, each about 250 m deep. The heat pump has 4 compressors and is dimensioned to cover 85% of the energy demand. The heat pump uses R134a as refrigerant, and is specially designed for variable water flow and temperatures up to 70 °C. The heat pump is connected to the existing pipelines in the main building. New pipelines were built to connect the activity building (gym) to the heat pump. The original central heating system was designed as a 'high temperature' system requiring 80 °C as supply temperature to provide enough heat at design outdoor temperature. Commercially available heat pumps were not suitable for this high temperature level. Traditional heat pump design would lead to a rather low coefficient of performance (COP). It was necessary to design a new concept for heat pumps replacing oil burners in old 80/60 °C. A design based on high performance piston compressors with speed control, condensers in series, liquid sub-cooler and amply designed heat exchangers all contribute to an improved COP. Heating capacity for the heat pump is 200 kW at 55 °C leaving hot water temperature. After tuning the heat pump the efficiency is monitored to 3.1 COP [ref. Lunde and Vittersø].	

Final energy use	Calculated	(X)	Calculation method	Simien
	Measured	X	Monitored in year	2014 (HDD: 3468 Kd)
	Heating		94 kWh/m^2yr (HDD corrected for heating)	
	Hot water			
	Cooling		-	
	Ventilation		32 kWh/m^2yr	
	Lighting			
	Equipment		unknown	
	Total		126 kWh/m^2yr	
	Geothermal input to heat pump		-55 kWh/m^2yr	
	Annual balance		71 kWh/m^2yr	
Primary energy use	District heat		There are no official conversion factors in Norway.	
	Grid electricity			
	Electricity fed-in			
	Total			
Renewable energy contribution ratio	43% of total final energy			
Improvement compared to average final energy consump-tion of schools	Reliable statistics on average energy use are not available.		Compared to:	After retrofitting, this 100-year old building uses just as little energy as a new building according to Norwegian Standard for Low Energy Buildings; NS 3701:2012
Experiences/ lessons learned	Heat pump: Usually a heat pump cannot deliver supply temperatures beyond 55 °C. Thanks to an improved concept design, the new heat pump at Brandengen School can deliver up to 70 °C. This design attracts a lot of attention, as it can replace old oil burners in 80/60 °C systems. The heat pump at Brandengen School has one common alarm for the five functional areas: condenser pressure, engine temperature, frequency converter, regulator sensor and two pressure switches. Troubleshooting would be easier if there was one alarm for each functional area. Daylighting: As a rule of thumb, permanent structural shading should be avoided at northern latitudes. However, solar control glass is applied on the south and west facades to avoid external, movable shading, which is unwanted in school buildings, due to tear and wear. Electro chromic glass, with variation spectre for visual light and solar energy transmission, is considered to be the best solution when external, movable shading is undesirable. But this kind of high-performance glazing is too expensive for most school budgets, at the time being.			
Costs	Additional insulation, windows, new pipelines to connect the activity building (gym) to the heat pump, and heat pump 220 kW with 19 drilled energy wells for collectors: ~ 1,093,000 € ex VAT (154 €/m^2)			
Funding	EU 7FP: Project "School of the Future" (260102)			
Links to further information	- Lunde, Helge and Gjermund Vittersø. New design of Heat Pump System. Memo from Thermoconsult, consulting company in heat pumps and refrigeration. 2014. Website: www.school-of-the-future.eu/images/files/MemoHeatPumpSolutionBrandengenSchool.pdf - Report: Zinzi, M. et al.: Final Demonstration Building Report. EU FP7 School of the Future deliverable 6.3. Available at www.school-of-the-future.eu			

Necessary addition to achieve a zero energy level	Zero final energy (all energy uses incl. equipment): ~ 4,000 m² PV (multicrystalline) on horizontal area or ~ 3,000 m² PV on an area tilted 30 degrees facing south.

MOST COMMONLY USED SOLUTIONS SETS AND REASONABLE ALTERNATIVES

Chapter "Case Studies I: Examples for zero emission, zero energy and plus energy schools" includes detailed descriptions of 8 school buildings with such ambitious energy goals and an overview table of the technologies applied in these buildings. The solution sets that are described here are derived from these case studies but also from experiences with other types of zero energy and plus energy buildings. The sets are divided into building envelope technologies, heating and hot water systems technologies, cooling technologies, ventilation technologies, lighting technologies and renewable energy technologies to provide for the balance of the otherwise remaining energy uses.

Please note that most examples are from Central Europe (Germany and Austria), with only the plus energy school in Montpellier and the plus electricity school in Cesena being case studies from the Mediterranean area. This circumstance probably has an influence on the insulation thicknesses and the necessary size of the RES contribution. It should be taken into account that the German case studies are part of a research initiative that has a focus on the application of innovative technologies. For the time being, however plus energy buildings are generally innovative buildings, pursuing very ambitious energy goals that often can only be achieved by using advanced (innovative) technologies.

Building envelope

There is a clear tendency towards well-insulated building envelopes with

- **wall U-values of 0.15 W/m²K** or lower (exemptions are the two southern schools)
- **roof U-values below 0.15 W/m²K**
- **floor or cellar ceiling U-values in new buildings below 0.20 W/m²K**.

In the examples that were renovated to become a plus energy school, considerably higher floor U-values are listed, but most of them only up to 0.35 W/m²K.

Windows are mostly realised as **low E-coated triple glazing** in wooden or even **insulated frames**. The two southern school buildings include low E-coated double-glazed windows. Two examples have (partly) box-type windows with two double glazing.

Particular attention is given to **improved airtightness** and a **strong reduction of the thermal bridge impact**, even in the Italian school.

Heating and hot water

The applied heating systems show a wide range of technologies. While the **two southern school buildings rely on rather conventional gas boilers**, the German and the Austrian school buildings feature **geothermal heat pumps, biomass boilers and in three cases district heating**, especially when the available district heating network is characterized by very low non-renewable primary energy factors. The heat distribution is often based on **low temperatures** in connection with **panel or floor heating, sometimes with radiators**.

For two school buildings it was decided to **offer only cold water** in the washrooms. Five schools generate **hot water in combination with the space heating system**. Two schools include solar thermal support for hot water generation (one of them also uses solar thermal support for the space heating). In case of low hot water demand, a decentral solution for electrical hot water generation might make sense in order to save circulation energy as demonstrated in the French plus energy school.

Cooling

None of the presented schools includes an active cooling system. This is partly due to the Central European climate in combination with **effective shading systems** and strategies like **night ventilation and pre-cooling of the supply air**. In Italy the summer months include a longer break compared to other countries. This also helps to prevent the need for cooling.

Ventilation

None of the schools relies on window opening only, however it can be part of a **hybrid ventilation strategy** and the possibility to open the windows whenever the users feel a need to do so was pointed out in nearly all cases. The **mechanical ventilation systems used are balanced systems**, which achieve **highly efficient heat recovery rates (> 80%)**. There are examples of **central and** examples of **decentral ventilation systems**. Sometimes it is easier to installe decentral systems in existing schools buildings that are undergoing renovation. Most of the systems are controlled based on **CO_2 sensors**, others are based on temperature or humidity control, sometimes in combination with a timer.

Lighting

Nearly all plus energy buildings use **T5 compact fluorescent lamps** in combination with **electronic ballasts** to save electricity. Several schools have installed **LED lamps**, in some cases in specific areas only or as a test. In the future there will most probably be a change towards LED lighting as it became less expensive during the last years. Lighting control is often depending on the available daylight supply (**daylight sensors**) and/or on the **occupancy** of a certain room or area. Two school buildings include daylight-redirection features.

Electricity generation to balance the remaining energy use

All school buildings include **large photovoltaic areas** to generate electricity that is either used in the building or fed into the local electrical grid. The size of the PV area **depends** mainly on the **size of the school**, the **remaining final energy use** by the building, the **energy goal** and **which energy uses are included** and on the **available solar radiation**. The presented examples have **between 188 m² and 2768 m² of PV** installed, mainly on the roof. Two examples additionally include **micro wind** turbines. Their contribution to the self-generated electricity is however small and their focus is **most probably educational**. One school planned to produce electricity via a biomass-fuelled combined heat and power unit. This advanced system is however currently not available on the market.

Conclusions

The collected examples show that a zero or plus energy building needs to include highly efficient technologies in all of the areas mentioned. There is no example that has only regular building envelope qualities but an immensely efficient heating system or ventilation system, neither one that relies only on minimalistic U-values. The sizing of insulation thickness, the heat recovery rates and the efficiency of the heating system in combination with the type of energy carriers are directly linked to the necessary PV area that balances the energy uses. For each school, with each specific user profile and occupancy pattern the most cost-efficient combination of building envelope, heating, ventilation and lighting systems and the necessary PV collector area has to be found. Sometimes the PV area is limited by the size of the roof and the lack of suitable façade surfaces. The use of carport roofs, however, can extend the potential PV area.

Last but not least a plus energy concept should not stop at the purely technological approach. It should also include the users, here the pupils and teachers, by analysing their expectations, by offering information on how to correctly use the technologies like lighting, ventilation and shading systems and by explaining in which way they can contribute to reducing the energy use.

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