BUILDING SERVICES SYSTEMS

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

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Front page illustrations
Top from left:
Tito Maccio Plauto Scuola, Cesena, Italy.
Solitude Gymnasium, Stuttgart, Germany. Photo: Ingenieurbüro Fisch.
Brandengen skole, Drammen, Norway.
Hedegårds skolen, Ballerup, Denmark.

Bottom from left:
Led lighting system in Hedegårds skolen in Ballerup, Denmark,
Decentralised demand controller ventilation in Solitude-Gymnasium in Stuttgart, Germany
Brine-to-water heat pump in the Brandengen School in Drammen, Norway
Modular condensing boiler in Tito Maccio Plauto School in Cesena, Italy

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INTRODUCTION

OBJECTIVES

One of the purposes of the School of the Future project is to provide designers and planners with guidelines for retrofitting concepts and technologies to obtain energy efficiency and good indoor environment quality in school buildings – ranging from simple, but significant energy reduction and indoor environmental improvements to the final target: zero emission schools.

The objective of these guidelines is to develop an overview of the available building and system technologies for energy efficient school buildings including their impact on energy performance and the indoor environment quality as well as their economic feasibility. It is chosen to describe 5 technologies: condensing boilers, heat pumps, ventilation systems, lighting and photovoltaic systems. These technologies have been selected as they are often used when retrofitting school buildings all over Europe. Furthermore there are already written some guidelines in an earlier EU project BRITA in PuBs "Bringing Retrofit Innovation to Application in Public Buildings" (http://brita-in-pubs.eu/). In the BRITA in PuBs project retrofit design guidelines for public buildings have been developed on certain specific innovative technologies and design strategies. These guidelines have been used as the basis and inspiration for the School of the Future guidelines and are still relevant to consider when designing building energy renovation projects.” The following BRITA-in-Pubs guidelines exist concerning building services systems:

- Hybrid Ventilation
- Solar Thermal Systems
- Solar Heating and Cooling
- Integration of PV
- Heat Pumps.

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

The flowchart below illustrates the complete energy renovation planning and design process.

Energy renovation integrated design process.
The energy efficient building has many benefits with regard to indoor conditions and comfort, besides the obvious benefit of low energy consumption if it is designed carefully. These benefits relate first of all to the thermal indoor climate as well as indoor air quality.

When a building has to be retrofitted due to age and wear, it will most likely be economically favourable to include energy measures. The maintenance interval is often 20–40 years, so if energy measures are not included, another 20–40 years will pass before energy upgrading becomes relevant again.

“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 was launched in February 2011 and will run for 5 years. The aim of the “School of the Future” 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. The energy and indoor environment performance of 4 demonstration buildings in 4 European countries and climates will be greatly improved due to a comprehensive 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 have a knock-on effect on other schools and on the residential sector, since the pupils can act as communicators to their families. Tailored training sessions are aimed at improving 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 EU 7FP Call is cost efficiency and knock-on effect. The retrofitting concepts will, however, result in buildings with far lower energy consumption than with regular retrofits with high indoor environmental quality - thus leading the way towards zero emission. They may 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 and the resulting high interest caused a consortium to be formed that included well-known partners from the building industry.
### PARTNERS WITHIN THE “SCHOOL OF THE FUTURE” PROJECT

<table>
<thead>
<tr>
<th>Country</th>
<th>Partner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
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</tr>
<tr>
<td></td>
<td>Landeshauptstadt Stuttgart</td>
</tr>
<tr>
<td>Italy</td>
<td>ENEA (Agenzia Nazionale Per Le Nuove Tecnologie, L’Energia E Lo Sviluppo Economico Sostenibile)</td>
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SUMMARY

This guideline on Building Services Systems is one of four guidelines produced by the School of the Future project. The other three guidelines cover: Building Construction Elements, Improved Indoor Environmental Quality and Concepts for Zero Emission Schools.

This guideline consists of the description of 5 main technologies: condensing boilers, heat pumps, ventilation systems, lighting and photovoltaic systems. For each technology chapter there is the same content list: an introduction, a brief technology description, some advantages and disadvantages, market penetration and utilisation, energy and economic performance, some exemplary applications from the School of Future project, a conclusion and a reference list.

The first technology chapter deals with condensing boilers. Traditional gas boilers can be changed to more energy efficient condensing gas boilers in areas with natural gas. In both new buildings and also when retrofitting condensing gas boilers will be more efficient than traditional boilers. Existing oil burners and electrical panels can be exchanged with condensing gas boilers resulting in significant energy savings. This is applicable in areas with gas and no district heating. If district heating is present it is often a better solution to change to this. The rule applies especially to gas boilers more than 15 years old, as new boilers utilize the energy more efficiently. Conversion from an oil boiler to a natural gas boiler will result in energy savings between 20-40%. Conversion from electricity to natural gas will typically reduce the expenses to heating by 50-60%, and CO₂ emissions will decrease by 60-65%. The conversion from electricity requires, that a water based radiator- or floor heating system is installed. Examples on retrofitting are given from Germany and Italy.

Then a chapter follows on heat pumps. In school buildings, the most commonly used heat pumps are:

- Electrical heat pump, air-to-water
- Electrical heat pump, brine-to-water (ground source heat pump)
- Electrical heat pump, air-to-air (mostly in southern Europe).

Still, a high initial investment cost and a short-term decision horizon and a high electricity cost influence the total cost of ownership of a heat pump system and limit market growth. An example of heat pump installation is given from Norway.

The next chapter presents the results from ventilation systems. The quality of indoor air has a high influence on the health and wellbeing of occupants, in many cases for example in schools and buildings affected by traffic noise, window ventilation cannot achieve comply sufficiently with air quality requirements. To achieve the desired indoor air quality, a mechanical ventilation system is suitable, which provides filtered fresh air continuously and discharges exhaust air and contaminants and helps saving energy by recovering heat from exhaust air and by using energy efficient ventilation equipment. CO₂ demand control ventilation is a real-time, occupancy-based ventilation control approach that can offer significant energy savings over traditional fixed ventilation approaches. Demand controlled ventilation is part of a building's ventilation system control strategy used to both control energy costs and to ensure sufficient ventilation.
The energy efficiency of ventilation systems depends on the heat recovery rate of heat exchangers and the electrical demand of the fans. The electrical efficiency of the ventilation system should be planned very carefully, otherwise the primary energy demand for ventilators could be higher than the primary energy savings of heat recovery.

The building owner, architect and engineer, installer, commissioning agent and building inspector should work together to produce a good ventilation system. Examples of retrofitting of ventilation systems are given from Denmark, Germany, Italy and Norway.

**Lighting systems** are a large and rapidly growing source of energy demand and greenhouse gas emissions. At the same time, the savings potential of lighting electricity is high even with the current technology, and there are new energy efficient lighting technologies coming on the market. There is significant potential for improving the energy efficiency of old and new lighting installations even with the existing technology by the following measures:

- the choice of lamps: incandescent lamps should be replaced with CFLs, infrared coated tungsten halogen lamps or LEDs, mercury lamps by high-pressure sodium lamps, metal halide lamps, or LEDs
- the usage of controllable electronic ballasts with low losses
- the lighting design: the use of efficient luminaires and localised task lighting
- the use of daylight: the control of light with manual dimming, presence sensors, and dimming.

Electric lighting is one of the major energy consumers and particularly in school buildings where it strongly affects visual performance and visual comfort by aiming to maintain adequate, appropriate illumination while controlling reflectance and glare. There are examples on new lighting systems given from Denmark, Germany and Norway.

The development of **photovoltaic systems in EU** basically stopped in 2012. The relevant boost of PV in Europe in 2011 was mainly due to the large number of installations in Italy and Germany. Several types of applications are developing: PV seen as self-consumption (in grid connected or isolated places), highly architectural integrated PV and large-scale PV installations (up to 250 MW) connected to existing grids to "export" electricity to be taken elsewhere. The sharp drop in prices of PV technology, new building efficiency regulations and systems of incentives at the level of individual member states and at EU level has led to keen competition. The future of PV will depend on several factors such as the development of the technology, the decrease of the costs, the transformation of existing grids, the price of electricity, but also on political decisions. Examples of use of PV in retrofitting school buildings are given from Denmark, Germany and Italy.
CONDENSING BOILERS

Introduction

The gas boiler is one of the most commonly used fossil fuel-based technologies for space heating and domestic hot water production in several European countries. Most often a hot water storage tank is used in combination with a gas boiler, but it is possible to install systems that can produce hot water instantaneously. The technology went through significant innovative processes over the past decades in terms of generating efficiency, durability and cost effectiveness. This guideline focuses on the most advanced product: the condensing boiler.

Even if the technology is well established and the products hold a certain share of the market, it is still important to portray its technology potential in the framework of the project School of the Future. There is a significant energy-saving potential obtained by retrofitting the existing school buildings but the energy and economic advantages of the technology are not yet fully exploited, especially in the southern part of Europe where a large portion of such stock is in need of comprehensive static and energy retrofitting. This is particularly true for those school buildings where it is possible to upgrade the heat generation performances with limited investments and renovation work.

Brief technology description

In a gas-fired boiler, gas is burnt in a combustion section. It may occur by means of a traditional flame or via specially designed low NOX combustors. Gas boilers can be wall hung or floor standing. The hot water from the gas boiler is circulated in the radiators of the building. A pump is therefore included in the system or in the boiler itself.

A gas boiler is often called a "central heating (CH) boiler", as it is one of the elements of a central heating installation including boiler(s), a heat distribution system, heat emitters (radiators, convectors etc.) and a control system for the appliances. A view of a typical condensing boiler is shown in Figure 1.1.

Figure 1.1: Schematic drawing of a floorstanding condensing gas boiler (VarmeStåbi®, Nyt Teknisk Forlag)
A condensing boiler is a boiler designed for low-temperature operation. It extracts heat from combustion products in two ways:

1. In the form of sensible heat: heat transmitted from a hotter medium to the cooler return water.
2. By the latent heat due to evaporation.

As a consequence, all the latent heat is wasted through the exhaust vent of traditional boilers, while the water vapour extracted from the exhaust gas in condensing boilers is turned into a liquid condensate in order to exploit the latent heat.

In traditional boilers, the combustion gases pass through the primary heat exchanger and directly into the flue with temperatures ranging approximately between 200 and 250 °C. In condensing boilers, the combustion products are circulated through a secondary heat exchanger, where the heat is extracted from waste gases pre-warming the water coming back into the boiler from the distribution system. A schematic view of the process is presented in Figure 1.2.

The vapour contained in the waste gas reaches the dew point temperature at this stage and cools down and condensates into acid water (which drains away by means of gravity) and is partly discharged through a fan-assisted balanced flue.

![Diagram of a condensing gas boiler operation](microgreening.com)

The performance of boilers is expressed by the boiler efficiency, \( \eta \), being the rate of useful energy extracted from the device to the heat, (in the form of the calorific value of the fuel being consumed) supplied to the boiler. The efficiency of a condensing boiler mainly depends on heat exchanger effectiveness to capture all the available sensible heat from the combustion process as well as part of the latent heat of condensation.

It is important to note that low return water temperatures are essential for obtaining the high condensing efficiencies associated with condensing boilers. It must be emphasised that the lower the temperature of the return loop water, the greater the heat transference to the water.

The ideal temperature at which the water vapour condenses (dew point temperature) is 55 °C: in such a condition the air-to-gas ratio is just about sufficient to cause complete combustion of the gas and the efficiency increases almost exponentially.
Very high efficiencies are attained as the return water temperature drops below 55°C, as can easily be inferred from Figure 1.3. The figure shows the efficiency drop of a boiler (lower than 90%), when the return water temperature is above 55°C.

![Graph showing boiler efficiency dependency on return water temperature](image)

Figure 1.3: Boiler efficiency dependency on return water temperature (RVR Energy Technology Ltd)

The condensate contains traces of nitric and sulphurous acids and must be discharged from the boiler e.g. into a drain or similar; this does not occur in conventional boilers. Connections should preferably be made to internal drainage system.

Attention should concentrate particularly on drain materials: plastic material and clay ware showed a good durability; cast iron is likely to be damaged in the long term; cement and concrete products appeared to be affected even more seriously than other materials. The adverse effects due to condensation are contained as the acid condensate will be diluted very quickly by the discharges from sanitary appliances.

Once the cooled exhaust gases leave the condensing boiler they produce a mist of water vapour. Due to this fact the boiler installer should be careful in choosing the correct location of the flue at installation (not near windows or walkways). The natural buoyancy of the flue products is inadequate at so low temperatures, making it necessary to install a fan to remove them.

**Evaluation - advantages and disadvantages**

Technical lifetime is approx. 15-20 years.

Research and development of heating systems is mainly dedicated to low-NOₓ burn combustion controls enabling appliances to self-adapt to variations in gas composition.

Condensing boilers allow modulating their power as a function of the required load. The efficiency is constant over the range of modulation, and NOₓ emission is low thanks to the NOₓ burner technology. Most of the condensing boilers on the market have reached the highest achievable efficiency (with this technology) and can be considered to be the best available technology.

When evaluating whether to replace a traditional boiler with a condensing type, several factors must be considered. To retrofit existing traditional boilers (typically with an open burner) giving annual efficiencies of only 60-65% is an economically advantageous disposition. If you have
a traditional boiler of the new pattern (with a closed combustion chamber) giving an average annual efficiency of 80%, you will obtain savings on operating costs; but the initial cost of the condensing boiler must be taken into account.

The histograms in Figure 1.4 compare the trends of the efficiency of different generators as a function of load factors (ratio between the generators’ power at partial load and power at nominal load). Up-to-date condensing boilers installed in correctly designed systems with low water return temperatures of 40/30 °C are characterised by efficiency above 100%.

In school buildings, where the continuity of classes have to be ensured, condensing boilers provide the improvement of the heating system efficiency without invasive works inside the building; in fact no or very small measures have to be applied to the control and distribution parts of the heating system and most of the work is carried out in the dedicated technological area of the building.

Advantages

- Gas boilers offer an efficient way of using primary energy directly. Modern condensing boilers have very small energy losses and are designed to cover the entire heating and hot water needs of end users.
- CO₂- and NOₓ-emissions of gas boilers are the lowest compared with any other fossil fuel boilers.
- The transportation of natural gas to buildings through a gas grid is less "energy costly" than the transportation of oil. Such costs should be evaluated in detail in case actual gas grid is developed or extended.
- In contrast to district heating, there are no network losses related to the transportation of gas in the grid.
- Advanced solutions for heat generation include solar thermal and/or combined heat and power (CHP) systems. These solutions are generally sized to cover only part of the load, and in such cases energy efficient solutions like condensing boilers can be coupled to cover the remaining portion of the heating demand.
Disadvantages

- In some areas, e.g. without district heating or in the case of obsolete heating energy systems, new effective gas boilers can be very competitive. However, the low heating demand in new well-insulated buildings results in condensing boilers not being an economically optimal solution, due to the high investment costs.
- In some areas, e.g. Mediterranean countries, existing buildings are equipped with high temperature radiators, with the consequence that the condensing boilers need to work at a high temperature without reaching the condensation of the vapour. The efficiency of condensing boilers still remains higher than that of conventional ones but the system cannot take advantage of the full potential of the technology. To be noted that the high internal gains due to the pupils occupation in classrooms allow lower temperatures in the radiators during a significant part of the heating season, so that the boiler can work in condensation conditions for that part of the year.

Market penetration and utilisation

Condensing gas boilers are an excellent solution when old and obsolete oil boilers or electric heaters need to be replaced, and these technologies are still widely used in several EU countries but are continuously phased out in favour of gas driven solutions.

The advantages of condensing boilers compared with traditional boilers cause the market to grow throughout Europe. Until five years ago, the spread of condensing boilers for heating systems in France, Italy and Spain was minimal. Nowadays, due to stricter government regulations on energy consumption, condensing boiler technology is in high demand throughout Europe and their market share has reached 37%. The large diffusion began in the Netherlands, UK, Germany and Austria several years ago and today includes the Mediterranean countries of the EU as well. The market penetration of condensing boilers until 2010 is shown in Figure 1.5.

Barriers for not changing a boiler to a more efficient type can be several and they are not necessarily related to the technology, but also to social and economic aspects. The main barriers can be summarised as follows:

- lack of knowledge about the benefits of the technology
- lack of knowledge about the heating system and its sub-systems
- lack of literature and training for installers or designers. Advice should be given at least on how to control flow rates or properly set the boiler reset curve to maximise efficiency
- not all European countries have their own gas reserves or a widespread distribution grid for gas
- additional costs needed for upgrading the whole heating system in order to exploit the full potential of the technology
- condensing boilers need a very clever design since correct sizing of the internal heat exchanger is very important and will strongly impact the final cost
- lack of financial incentives to support the private and public building sector in renovating the building stock.
Energy and economic performance

Due to their efficiency, condensing gas boilers can be used in existing buildings to improve the heating systems and the overall energy performances, which are undeniably higher if compared with existing boilers. Condensing boilers are from 10-30% more energy efficient than traditional boilers, and are also more efficient than other new non-condensing boilers on the market today. This leads to a significant reduction of fuel bills, which is a primary concern in today’s unstable fuel market characterised by steadily increasing prices. Combined with a proper fraction of renewable energy (e.g. active solar collectors), condensing gas boilers can be installed in low energy buildings replacing traditional heating systems and DHW systems, once the technical and economic feasibility is verified. When considering the installation of a condensing boiler, it is necessary to perform and evaluate a detailed building load analysis and to select heating equipment correctly designed to operate at the low water temperatures required for the best performance of the boiler selected. Radiant floor heating systems are found to be typical examples of space heating systems that can operate with water temperatures in the 26 °C to 38 °C range for optimal performance. In heating scenarios where the return temperature is relatively high (as in the case of old radiators), the benefit of a condensing boiler is only in terms of its global efficiency.

Control strategies such as weather compensation and indoor air temperature control can be effectively used by adjusting the central heating flow temperature, accordingly allowing the system temperature to decrease sufficiently for the boiler to condense thereby increasing the overall system efficiency.

The impact of the technology on the performance in school buildings to be renovated was screened in a particular frame work of the Project dedicated to technology screening. The whole calculation set can be downloaded from the project website (http://www.school-of-the-future.eu/index.php/project-results/technology-screening). In the following some exemplary outcomes are presented, including energy, environment and economic issues. The results are achieved under very different boundary conditions, in terms of climatic conditions, reference building characteristics, energy prices, primary energy factors and performance and investment costs of the selected technologies.

In this framework the following results provide a general view of the technology application in improving the performance of existing school buildings in each country rather than comparing the technology impact among different countries. According to this assumption the results are presented separately for each country. The selected climatic zones of the participating countries
are: Denmark (Copenhagen), Germany (Potsdam), Italy (Turin for the north, Terni for the centre and Taranto for the south) and Norway (Oslo).

The impact of this single energy measure is calculated based on a reference building configuration. The reference school building has a typical layout that consists of three storeys with classrooms on one side and a corridor on the other, as represented by the pictogram in Figure 1.6.

It is assumed that the reference school building in Denmark, Germany and Italy has a conventional gas boiler as a heating system. This technology is not relevant in Norway so it was not considered in this analysis.

![Figure 1.6: Pictogram of the reference school building floor](image)

Geometric, technical and economic parameters relating to condensing boiler in the reference building are summarised in Table 1.1. Traditional boilers already installed in existing buildings are characterised by efficiency values up to 0.87 (column 3); new traditional boilers can achieve efficiency values of 0.87-0.94. Current condensing boilers can achieve high efficiencies (0.85-0.97) to cover full loads (column 4). The newer technology allows condensing boilers to be even more efficient (1.00-1.04) at partial loads (as opposed to traditional boilers; column 5) due to their peak efficiency at low-fire rates and low return water temperature (the efficiency of a condensing boiler increases as load decreases).

Annual fuel-utilisation efficiency is the measure of a boiler's seasonal or annual efficiency. It takes into account the cyclic on/off operation and associated energy losses of a heating unit as it responds to changes in load, which, in turn, is affected by changes in weather and occupant controls. Column 6 shows the calculated output of the new installed boilers; column 7 refers to the investment costs, column 8 highlights CO₂ emissions per unit from fuel combustion and column 9 shows the price per unit of produced energy.

### Table 1.1: Condensing boiler characteristics

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<thead>
<tr>
<th>Country</th>
<th>Treated floor area (m²)</th>
<th>Efficiency</th>
<th>Output kW</th>
<th>Investment cost (€)</th>
<th>CO₂ Kg/kWh</th>
<th>Price €/MWh</th>
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<tr>
<td></td>
<td>Existing</td>
<td>New full load</td>
<td>New part load</td>
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<td>Denmark</td>
<td>3,000</td>
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<tr>
<td>Germany</td>
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<td>Turin</td>
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Table 1.2 presents the results of the Danish reference school. The measure is effective, energy savings are greater than 30 kWh/m² per year and the payback time (PBT) is shorter than 4 years. The economic indicators confirm the potentiality of the technology, as inferred by the net present value (NPV) and the investment to saved energy ratio.

Table 1.2: Denmark: Energy and economic results

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<th>Results</th>
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<tr>
<td>Primary energy savings (heating)</td>
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<tr>
<td>CO₂ reduction</td>
<td>[kg/m²]</td>
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<td>Investment/saved energy</td>
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<tr>
<td>Payback time</td>
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</tr>
<tr>
<td>Net Present Value</td>
<td>₹/m²</td>
<td>69.0</td>
</tr>
</tbody>
</table>

Table 1.3 show the results obtained for the application of the condensing boiler in the German School. Energy indicators are positive, being around 25 kWh/m² per year. The initial cost of installation affects the payback time of the investment (about 10 years); however, the NPV is about 30 ₹/m² as a consequence of the expected lifetime of the selected measure.

Table 1.3: Germany: Energy and economic results

<table>
<thead>
<tr>
<th>Results</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final energy savings (heating)</td>
<td>[kWh/m²]</td>
<td>24.1</td>
</tr>
<tr>
<td>Primary energy savings (heating)</td>
<td>[kWh/m²]</td>
<td>26.5</td>
</tr>
<tr>
<td>CO₂ reduction</td>
<td>[kg/m²]</td>
<td>6.1</td>
</tr>
<tr>
<td>Investment/saved energy</td>
<td>₹/(kWh/m²) y</td>
<td>0.94</td>
</tr>
<tr>
<td>Payback time</td>
<td>[years]</td>
<td>10.4</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>₹/m²</td>
<td>31.7</td>
</tr>
</tbody>
</table>

Table 1.4 show the results obtained for the different Italian localities. Energy savings are in line with the severity of the climate: Turin is the best performing (34 kWh/m² per year) while in Taranto the savings are reduce to less than 15 kWh/m² per year. The measure has good PBT in Turin (less than 4 years) and in Terni (less than 6 years), the indicator is still positive in Taranto, even if the PBT gets close to 10 years. The NPV follows the same trend. In this case, even if the cost remains the same, the climatic conditions have a strong impact of the energy end economic performance of the selected measure, even if the installation of the condensing boilers has a general positive impact in Italy, whatever are the climatic conditions.
Table 1.4: Italy - Energy and economic results

<table>
<thead>
<tr>
<th>Results by locality</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TURIN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final energy savings (heating)</td>
<td>kWh/m²</td>
<td>33.9</td>
</tr>
<tr>
<td>Primary energy savings (heating)</td>
<td>kWh/m²</td>
<td>35.6</td>
</tr>
<tr>
<td>CO₂ reduction</td>
<td>kg/m²</td>
<td>6.8</td>
</tr>
<tr>
<td>Investment/saved energy</td>
<td>€/(kWh/m²) year</td>
<td>0.16</td>
</tr>
<tr>
<td>Payback time</td>
<td>years</td>
<td>3.8</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>€/m²</td>
<td>75.6</td>
</tr>
<tr>
<td>TERNI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final energy savings (heating)</td>
<td>kWh/m²</td>
<td>22.2</td>
</tr>
<tr>
<td>Primary energy savings (heating)</td>
<td>kWh/m²</td>
<td>23.3</td>
</tr>
<tr>
<td>CO₂ reduction</td>
<td>kg/m²</td>
<td>4.5</td>
</tr>
<tr>
<td>Investment/saved energy</td>
<td>€/(kWh/m²) year</td>
<td>0.24</td>
</tr>
<tr>
<td>Payback time</td>
<td>years</td>
<td>5.8</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>€/m²</td>
<td>45.4</td>
</tr>
<tr>
<td>TARANTO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final energy savings (heating)</td>
<td>kWh/m²</td>
<td>14.0</td>
</tr>
<tr>
<td>Primary energy savings (heating)</td>
<td>kWh/m²</td>
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</tr>
<tr>
<td>CO₂ reduction</td>
<td>kg/m²</td>
<td>2.8</td>
</tr>
<tr>
<td>Investment/saved energy</td>
<td>€/(kWh/m²) year</td>
<td>0.39</td>
</tr>
<tr>
<td>Payback time</td>
<td>years</td>
<td>9.1</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>€/m²</td>
<td>24.5</td>
</tr>
</tbody>
</table>

Examples of applications in the School of the Future project

The technology is well consolidated and cannot be considered innovative anymore. However, the performance of these boilers is significantly higher than that of traditional ones and for this reason some applications can be found in the School of Future demonstration buildings, where specific situations were suitable for such installations.

Germany

Gas boilers were also installed in the Solitude-Gymnasium in Stuttgart, Germany to feed the heating system in the different school blocks. Two boilers were installed in 2004; one is a condensing boiler with 615 kW power and the other a 515 kW low temperature boiler, both are shown in Figure 1.7.

Figure 1.7: Gas boilers and CHP unit installed in the Solitude-Gymnasium in Stuttgart, Germany
The boilers replaced old constant temperature gas boilers installed during the mid-seventies. During the renovation works, a cogeneration system (CHP) was installed (capacity 15 kWel and 30 kWth). It is planned that under normal operational conditions the space heating will be provided by the cogeneration and by the condensing boiler, while the low temperature boiler will be used only for extreme conditions.

**Italy**

The Plauto School in Cesena, Italy was equipped with two obsolete 35 year-old conventional gas boilers (780 kW in total) and replaced by three condensing boilers working in cascade, able to modulate the power according to the thermal load, with a range from 13.4 to 215 kW. The power was reduced because of the lowered transmission heat losses obtained through the insulation works carried out during the building renovation. The boiler generation efficiencies are: 97.4% at high temperature (80/60 °C) and 106.2% at low temperature (40/30 °C). To take advantage of the boilers’ high efficiency performance electronic pumps and thermostatic valves were installed on all radiators. Figure 1.8 shows the old (left) and the new boilers (right).

![Figure 1.8: Obsolete and new condensing boilers at the Plauto School in Cesena, Italy](image)

**Conclusions**

The gas-fired condensing technology has constantly been advancing, thus ensuring increased comfort and energy efficiency, reduced emissions and noise levels, improved design and reduced size of boilers to fit any building setting. Gas-fired condensing devices can also cope very easily with highly fluctuating requirements for heating and hot water related to variations in patterns of building use.

Particular attention should focus on the system design: over-sizing will result in lower efficiencies and unnecessary extra costs. The size of the boiler depends on the size of building, the type of heating system, as well as how well the building is insulated.

Traditional gas boilers can be changed to more energy efficient condensing gas boilers in areas with natural gas. In both new buildings and also when replacing, condensing gas boilers are more efficient than traditional boilers. Existing oil burners and electrical radiators can be exchanged with condensing gas boilers resulting in significant energy savings. This is applicable in areas with gas and no district heating. If district heating is available, it is often a better solution to change to this. The rule applies especially to gas boilers more than 15 years old, as new boilers utilise energy more efficiently.
The annual energy efficiency for a new condensing gas boiler ranges between 98 and 105% depending on boiler type, energy consumption and the temperature conditions in the heating system.

Conversion from an oil boiler to a natural gas boiler will result in energy savings between 20 to 40%. Conversion from electricity to natural gas will typically reduce the expenses to heating by 50 – 60%, and CO₂ emissions will decrease by 60-65%. The conversion from electricity requires that a waterbased radiator or floor heating system is installed. This energy-saving measure can be even more cost effective in countries where supporting financial schemes favour gas boilers.

**Literature and references**

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- Micro CHP manufacturers on the market, e.g. Remeha and Baxi.
- Recent progress achieved in the way to estimate real performances of domestic boilers once installed Jean Schweitzer Christiansen, and Christian Holm, Danish Gas Technology Centre, Denmark Gastec, Martin Holland Koot and Otto Paulsen, DTI, Denmark. SAVE Workshop Utrecht 2000.
- Test of more than gas 100 boilers tested in laboratory at DGC. Application of BOILSIM model. BOILSIM [http://www.boilsim.com/](http://www.boilsim.com/)
Introduction

A heat pump is a device that provides heat energy from a source of heat or "heat sink" to a destination. Heat pumps are designed to move thermal energy in a direction opposite to that of spontaneous heat flow by absorbing heat from a cold space and releasing it to a warmer one. A heat pump uses some amount of external power to accomplish the work of transferring energy from the heat source to the heat sink.

While air conditioners and freezers are familiar examples of heat pumps, the term "heat pump" is more general and applies to many HVAC (heating, ventilating, and air conditioning) devices used for space heating or space cooling. When a heat pump is used for heating, it employs the same basic refrigeration-type cycle used by an air conditioner or a refrigerator, but in the reverse - releasing heat into the conditioned space rather than the surrounding environment. For this use, heat pumps generally draw heat from the cooler external air or from the ground. In heating mode, heat pumps are three to four times more efficient in their use of electric power than simple electrical resistance heaters.

Heat pumps should be taken into account in energy renovation of school buildings, especially in deep retrofit projects where the whole space heating system has to be re-designed and renovated. Heat pumps, coupled with a suitable heat sink, are an efficient solution especially if part of the electricity uses can be compensated those generated by a PV systems installed on the roof and the façades of the school buildings.

Brief technology description

Heat pumps employ the same technology as refrigerators, moving heat from a low-temperature location to a warmer location. Heat pumps usually draw heat from the ambience (input heat) and convert the heat to a higher temperature (output heat) by means of a closed process; electrically driven compressor heat pumps (Figure 2.1).

The energy efficiency of heat pumps is normally referred to by the COP factor "Coefficient of Performance", describing the delivered heat divided by the consumed electricity. A COP factor of three means that the heat pump delivers three times as much heat as the electricity demand, and two thirds of the delivered heat is collected through the outdoor heat exchanger.

Mechanical heat pumps exploit the physical properties of a volatile evaporating and condensing fluid known as a refrigerant. The heat pump compresses the refrigerant to make it hotter on the side to be warmed, and releases the pressure at the side where heat is absorbed.
The working fluid, in its gaseous state, is pressurised and circulated through the system by a compressor. On the discharge side of the compressor, now hot and highly pressurised vapour is cooled in a heat exchanger, called a condenser, until it condenses into a high pressure, moderate temperature liquid. The condensed refrigerant then passes through a pressure-lowering device also called a metering device. This may be an expansion valve, capillary tube, or possibly a work-extracting device such as a turbine. The low pressure liquid refrigerant next enters another heat exchanger, the evaporator, in which the fluid absorbs heat and boils. The refrigerant returns to the compressor and the cycle is repeated.

It is essential that the refrigerant reaches a sufficiently high temperature, when compressed, in order to release heat through the "hot" heat exchanger (the condenser). Similarly, the fluid must reach a sufficiently low temperature before being allowed to expand, or else heat cannot flow from the ambient cold region into the fluid in the cold heat exchanger (the evaporator). In particular, the pressure difference must be big enough for the fluid to condense on the hot side and still evaporate in the lower pressure region on the cold side. The greater the temperature difference, the bigger the required pressure difference, and consequently the more energy needed to compress the fluid. Thus, as with all heat pumps, the coefficient of performance (amount of thermal energy moved per unit of input work required) decreases with increasing temperature difference.

Insulation is used to reduce the work and energy required to achieve a sufficiently low temperature in the space to be cooled. For operating under different temperature conditions, different refrigerants are available. Refrigerators, air conditioners, and some heating systems are common applications that use this technology.

By definition, all heat sources for a heat pump must be colder than the space to be heated. Most commonly, heat pumps draw heat from the air (outside or inside air) or from the ground (groundwater or soil).

A lot of different types of heat pumps exist, but in school buildings the most commonly used are:

- Electric heat pump, air-to-water
- Electric heat pump, brine-to-water (ground source heat pump)
- Electric heat pump, water-to-water
- Electric heat pump, air-to-air (mostly in southern Europe).

A possible solution for some big buildings could be a gas-driven absorption heat pump.
Electric heat pump, air-to-water

Air-to-water heat pumps draw heat from ambient air and use a water-based heating system to supply the heat to the building (Figure 2.2). The heat pump can also produce the hot water for domestic use.

Air-to-water heat pumps are normally designed to cover between 95 and 98% of the heating demand. The remaining heat demand is covered by electric heating. It is possible to supplement the heat pump by a solar heating system.

Air-to-water heat pumps are normally chosen where there is not enough available outdoor area for ground heat collectors, but where there is a water-based heat distribution system in the building. Air-to-water heat pumps cannot deliver water temperatures higher than 55°C, which means that the radiators have to be able to cover the heat demand with temperatures below this.

In order to obtain these sufficient low supply temperatures, it is in many cases necessary to install a larger heat capacity of the heat emission system, e.g. by installing larger radiators and/or by improving the insulation level of the building envelope. In many cases, however, the improvement of the building envelope may be an economically profitable option anyway, and for new buildings it is a necessity due to requirements in the building regulations.

Some air-to-water heat pumps are designed specifically for supplying only domestic hot tap water. This type of air-to-water heat pumps is used in a number of second homes, especially if there is a large consumption of hot tap water.
Electric heat pump, brine-to-water (ground source heat pump)

Most brine-to-water heat pumps draw heat from the ground through a ground source heat collector. Normally, this type of heat pumps has horizontal pipes about a meter down in the ground with anti-freeze brine collecting the heat from the ground (Figure 2.3). This type is also called a ground source heat pump. Instead of horizontal pipes, it is also possible to use vertical pipes reaching depths up to 250 m.

![Diagram of electric heat pump, brine-to-water](image)

The heat pumps are normally designed to cover between 95% and 98% of the heating demand. The remaining heat demand is covered by direct electric heat sources. It is possible to supplement the heat pump by a solar heating system. It is of great importance to make a correct dimensioning of the heat pump.

Brine-to-water heat pumps have a high average efficiency over the year due to the more stable temperatures in the ground. Brine-to-water heat pumps, in most cases, deliver water temperatures up to 55°C, which means that the radiators have to be able to cover the heat demand of the building with temperatures below 55°C. In the Norwegian demonstration building, however, the heat pump can deliver temperatures up to 70°C. This heat pump solution is described in the chapter 'Example of application in the School of the Future Project'.

It is in many cases necessary to install a larger heat capacity of the heat emission system in order to obtain these sufficiently low supply temperatures, e.g. by installing larger radiators and/or by improving the insulation level of the building envelope. In many cases, however, the improvement of the building envelope may be an economically profitable option anyway, and for new buildings it will be necessary due to requirements in the building regulations.
**Electric heat pump, water-to-water**

Water-to-water heat pumps draw heat from ground water and use a water-based heating system to supply the heat to the building (Figure 2.4). The heat pump can also produce the hot water for domestic use.

Water-to-water heat pumps are normally designed to cover 100% of the heating demand. Just as a backup solution an electrical heating is often installed. As the groundwater temperature in moderate and warm European climates is above 10 °C, a use of brine is not needed. Depending on the high temperature of the source side of the heat pump, a high efficiency can be realized. The installation is not possible in protected ground water zones.

![Electric heat pump, water-to-water](image)

*Figure 2.4: Electric heat pump, water-to-water (picture from Technology Data for Energy Plants).*

**Electric heat pump, air-to-air**

Air-to-air heat pumps draw heat from the ambient air and supply heat locally through air heat exchangers (Figure 2.5).

![Electric heat pump, air-to-air](image)

*Figure 2.5: Electric heat pump, air-to-air (picture from Technology Data for Energy Plants).*
Most air-to-air heat pumps have one outdoor unit and one indoor unit and are often referred to as "split-units". This configuration means that the heat pump can only supply heat from where the indoor unit is placed. This type of heat pump is mostly used in southern Europe.

Air-to-air heat pumps with more than one indoor heat exchanger (multi-split units) are also available, but they only represent a very small percentage of the installed air-to-air heat pumps today.

Many air-to-air heat pumps are reversible so that they can be used for cooling in warm periods (air-condition).

A single air-to-air heat pump normally covers between 60% and 80% of the space heating demand. A high coverage requires that the doors between the room where the air-to-air heat pump is placed and the adjoining rooms are open or an air circulation system is installed. The remaining space heating demand must be covered by other sources, which would normally be electrical heaters or additional air-to-air heat pumps.

**Evaluation - advantages and disadvantages**

**Advantages**

**General for heat pumps**

The general advantage of heat pump technologies is that the technology normally uses a free, low-temperature heat source.

Heat pump efficiency in general depends on the temperatures of the cold (outdoor) and the warm (indoor) side of the heat pump. Lower temperatures on the cold side as well as higher temperatures on the warm side decrease the efficiency. The heat demand is normally higher when outdoor temperatures are low. Therefore, it is important to compare the average annual efficiency instead of the efficiency at a single working point.

Even if characterised by high energy performances and good primary energy conversion factors, the initial cost for school building applications can be high, due to the size of the machine as well as accompanying measures that might be carried out on different part of the space heating system.

**Specifically for air-to-water heat pumps**

- An air-to-water heat pump can deliver heat through the heating system in several rooms, and it is possible to regulate the heat transfer individually in each room, which is an advantage compared with air-to-air heat pumps.

- Compared with brine-to-water heat pumps, the air-to-water heat pump is less efficient because the temperature of the air provided to the outdoor heat exchanger will be lower than the ground temperature when there is a large demand for heating (this could also be a disadvantage). Moreover, in some climatic conditions ice will build up on the outdoor heat exchanger and thereby decrease the evaporation temperature and the efficiency. Therefore, defrosting of the outdoor heat exchanger is needed during cold and humid periods, causing increased energy consumption.

- The main reason for choosing an air-to-water heat pump instead of a brine-to-water heat pump is an easier and cheaper outdoor installation. The outdoor unit will only need a very limited outdoor space, and no digging is needed.

- The overall costs are equally reduced. An air-to-water heat pump will be 20-30% cheaper in investments than a brine-to-water heat pump.
Specifically for brine-to-water heat pumps

- The specific advantage of the ground source heat pump (using the top soil or the ground) is that it performs better than other types of heat pumps because of higher heat source temperature during the heating season.
- The brine-to-water heat pump has the same advantage as the air-to-water heat pump, where the heat is distributed supplying different heat demands in different rooms. The demand for hot water production can be accomplished with this heat pump.
- Moreover, there is no noise problems when the heat pump is running, which can make it the only possible solution in densely built-up areas.
- Vertical pipes can be used instead of horizontal pipes if there is not enough available ground area. This is a more expensive solution, but it is being used more often than previously, which can lower the prices in the future.

Specifically for water-to-water heat pumps

- The specific advantage of the groundwater heat pump is that it has a better performance than other types of heat pumps because of the higher heat source temperature during the heating season.
- The water-to-water heat pump has the same advantage as the brine-to-water heat pump. The need for hot water production can also be supplied with this heat pump.
- Moreover, there is no noise problems when the heat pump is running, which can make it the only possible solution in densely built areas.

Specifically for air-to-air heat pumps

- Air-to-air heat pumps are especially good in rooms and buildings with electric heating. Air-to-air heat pumps absorb heat from outside air and supply it inside the building by means of electricity. On a yearly basis, the ratio between delivered heat and consumed electricity will be around three. This means that the yearly electricity consumption in rooms with electric heating can be reduced to one third by installing an air-to-air heat pump.
- Since the air-to-air heat pumps normally cover only 60-80% of the heating demand of a building, more air-to-air heat pumps or a multi-split system are needed if the overall electricity demand is to be reduced to one third. But one air-to-air heat pump in an electrically heated building will reduce the electricity consumption significantly under any circumstances.
- A special advantage of air-to-air heat pumps is that they do not need a heat distribution system for space heating. In buildings with electric heating, there is normally no heat distribution system, but the air-to-air heat pump can reduce the energy consumption significantly without installation of radiators or floor heating.
- Similarly, the outdoor installation is simple and will only need very limited outdoor space and do not require any digging in the ground.
- An air-to-air heat pump is normally a smaller investment than other types of heat pumps. It costs approximately 25% of the price of a brine-to-water heat pump.

Specifically for gas-driven absorption heat pumps, air-to-water and brine-to-water

- The absorption gas heat pump technology is already a mature product with high efficiency.
- It is adapted for the replacement of existing boilers (minimal change of existing system) and suitable for buildings with radiators that might require higher temperatures.
Disadvantages

Specifically for air-to-water heat pumps

- Noise may be a problem since the noise level has to be below 35 dB(A) on the boundary to other properties. In densely built-up areas, it is sometimes not possible to install air-to-water heat pumps due to this problem.

Specifically for brine-to-water heat pumps

- A disadvantage is that the ground heat source involves digging in the ground or other arrangements to retrieve the necessary heat. The most common solution, which is a horizontal ground collector, needs available ground area corresponding to a maximal consumption of 40 kWh/m² per year where the area is the horizontal area. The investments can be counterbalanced by the reduced costs of energy. A brine-to-water heat pump is approximately 15% more efficient than an air-to-water heat pump. The overall price including digging and pipes is about 20-30% more than for air-to-water heat pumps.

Specifically for water-to-water heat pumps

- A disadvantage is that the groundwater heat source involves digging in the ground or other arrangements to retrieve the necessary heat. A water-to-water heat pump will be approximately 20% more efficient than an air-to-water heat pump. The overall price including water supply wells and pipes is about 20-30% more than for air-to-water heat pumps.

Specifically for air-to-air heat pumps

- The disadvantage of this type of installation is that the heat from the heat pump can only be delivered in the room where the indoor unit is installed. As mentioned before, the air-to-air heat pump can cover 60-80% of the overall heat demand. Other rooms will need supplementary heating, e.g. electric heating or another air-to-air heat pump.
- In cold humid periods, ice will build up on the outdoor heat exchanger and thereby decrease the evaporation temperature and the efficiency. Therefore, de-frosting of the outdoor heat exchanger is needed during cold and humid periods, causing increased energy consumption. There are several heat pumps suited for Nordic climates on the market today.
- Noise from air-source heat pumps may also be a problem. The noise level has to be less than 35 dB(A) on the boundary to other properties. Air-to-air heat pumps of a higher quality will normally have lower noise levels.

Specifically for gas-driven absorption heat pumps, air-to-water and brine-to-water

- There is basically only one product on the market.

Market penetration and utilisation

The number of heat pump units sold in the European heat pump market increased by 3% in 2013. A total of 769,879 units were sold in 2013 in the 21 European countries covered by the EHPA report [EHPA]. During the last 20 years, the total amount of installed heat pumps has exceeded 6.74 million. This amounts to an installed capacity of nearly 224 GW.

Nearly 90% (or 683,985) of the heat pumps of the European market volume was sold in only 10 countries. France led these top-10 markets by sales volume, followed by Italy and Sweden, all of them with annual sales exceeding 100,000 units. These three countries constitute nearly
50% of the total sales in Europe. They have been leading the European markets in different combinations since 2010.

Germany, Norway, Finland and Spain sold over 50,000 units per year. The remaining places on the top-10 list were filled by Denmark, Switzerland and Austria, with Poland and the UK being very strong candidates for a place on the top-10 list in the near future. In terms of absolute change, only the French market increased by more than 10,000 units. Compared with 2012, more markets have returned to growth and this includes in particular major markets like Finland, Spain and Sweden. The fact that only 4 out of 21 markets are still declining leaves room for optimism, especially since the extent of decline has been reduced. It is deemed most likely that the UK, Italy, Netherlands and Norway will return to previous growth rates in 2014 due to an ambitious political environment.

![Figure 2.6: Development of heat pumps sales in 21 European countries – growth rates 2011–12 and 2012–13](image)

The heat pump market continues to be governed by three major trends:

- **Air is and will remain the dominant energy source for heat pumps.**

- **Sanitary hot water heat pumps are the fastest growing heat pump segment across Europe.** This category is the only one showing double-digit growth. Sanitary hot water units combine a heat pump and a hot water storage tank. They are either sold as stand-alone units with heat pump and tank in one casing or as systems combining a heat pump and a separate tank.

- **Larger heat pumps for commercial, industrial and district heating applications are increasingly popular.** They quite often use geothermal or hydrothermal energy. However also here, air is an energy source used by a number of installations.
To sum up, sales production of heat pumps are doing well, but there is still a tremendous potential. This is underlined by a recent study by Ecofys. Looking at the 8 most important markets, the analysis concludes that an ambitious heat pump scenario would lead to a 47% decrease of greenhouse gas emissions in the building sector by 2030 (compared with current levels). However this will require a heat pump-based strategy for heating and cooling with significant government interventions in all Member States of the European Union.

It is worth noting that Member States can implement financial schemes to support the market penetration of the technology. In Italy, as an example, 65% of the cost of installing a heat pump can be deducted from personal taxes. Another scheme (Conto Termico Energia) provides financial incentives to replace old boilers with new boilers or heat pumps up to one thermal megawatt; the scheme is intended for buildings in the Public Administration and to private bodies, directly or through an energy service company.

It seems that competition in the heat pump market segment is more focused on competition among heat pump manufacturers than on competition between heat pump and traditional boiler manufacturers. With the wide introduction of hybrid systems, this may change. Heat pumps are (still) not a mass market product and the perception of heat pumps as “a premium product, which has its price” is still valid.

IEA Annexes

Heat pumps for use in low-energy buildings and nearly zero-energy buildings are investigated in several Annex projects in the Heat Pump Programme of the International Energy Agency (IEA) due to the unique features of heat pumps regarding high system performance, multifunctional use for different building services and load management capacities. In Annex 32 and Annex 40, several new prototypes are developed.

Energy and economic performance

Heat pumps in building renovation are gaining attention for several issues: the technology upscaled the performances in past years; coupling the heat pumps with a cold sink warmer than air (water, ground) improve the efficiency of the system; easier integration of the technology with renewable energy, as electricity generated by wind and PV.

The impact of the technology on the performance in school buildings to be renovated was screened in a particular frame work of the Project dedicated to technology screening. The whole calculation set can be downloaded from the project website (http://www.school-of-the-future.eu/index.php/project-results/technology-screening). In the following some exemplary outcomes are presented, including energy, environment and economic issues. The results are achieved under very different boundary conditions, in terms of climatic conditions, reference building characteristics, energy prices, primary energy factors and performance and investment costs of the selected technologies.

In this framework the following results provide a general view of the technology application in improving the performance of existing school buildings in each country rather than comparing the technology impact among different countries. According to this assumption the results are presented separately for each country. The selected climatic zones of the participating countries are: Denmark (Copenhagen), Germany (Potsdam), Italy (Terni for the centre and Taranto for the south) and Norway (Oslo).

The impact of this single energy measure is calculated based on a reference building configuration. The reference school building has a typical layout that consists of three storeys with classrooms on one side and a corridor on the other, as represented by the pictogram in Figure 2.7. It is assumed that the reference school building in Denmark, Germany and Italy has
a conventional gas boiler as a heating system. An electrical heating system is assumed as reference case for Norway.

![Figure 2.7: Pictogram of the reference school building floor](image)

Geometric, technical and economic parameters relating to heat pump measures in the reference building are summarised in Table 2.1. Traditional boilers already installed in existing buildings are characterised by efficiency values up to 1.00 (column 3); new heat pumps can achieve COP values up to 3.2. In the calculations, it is assumed that the pipes in the building and the radiators are not replaced when changing the heat supply. Heat pumps include pipes in the ground and depend on the power demand of the building.

Table 2.1: Heat pumps characteristics

<table>
<thead>
<tr>
<th>Country</th>
<th>Treated floor area m²</th>
<th>Efficiency</th>
<th>COP</th>
<th>Output kW</th>
<th>Investment Cost €</th>
<th>CO₂ Kg/kWh</th>
<th>Price €/MWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark</td>
<td>3,000</td>
<td>Existing</td>
<td>0.87</td>
<td>New 3.2</td>
<td>457</td>
<td>604,134</td>
<td>0.60</td>
</tr>
<tr>
<td>Germany</td>
<td>3,000</td>
<td>Existing</td>
<td>0.87</td>
<td>New 3.2</td>
<td>239</td>
<td>540,000</td>
<td>0.66</td>
</tr>
<tr>
<td>Italy</td>
<td></td>
<td>1,453</td>
<td>0.85</td>
<td>2.8</td>
<td>118</td>
<td>25,200</td>
<td>0.60</td>
</tr>
<tr>
<td>Terni</td>
<td></td>
<td></td>
<td>0.85</td>
<td>2.8</td>
<td>118</td>
<td>25,200</td>
<td>0.60</td>
</tr>
<tr>
<td>Taranto</td>
<td></td>
<td></td>
<td>0.85</td>
<td>3.0</td>
<td>108</td>
<td>25,200</td>
<td>0.60</td>
</tr>
<tr>
<td>Norway</td>
<td>3,000</td>
<td>1.00</td>
<td>3.2</td>
<td></td>
<td>533</td>
<td>704,436</td>
<td>0.60</td>
</tr>
</tbody>
</table>

Following tables show energy savings (both final and primary saved energy), environmental benefits (CO₂ reduction emissions) and financial implications (simple payback time PBT, net present value NPV and the investment to saved energy ratio).

Table 2.2 presents the results of the Danish reference school and the positive impact on the energy performance can be easily inferred. The high final energy savings, as in Germany and Italy, depend on the high COP of the heat pumps. However the change of the energy source, gas replaced by electricity, implies that primary energy savings should be observed. These are close to 70 kWh/m² per year; however the high initial costs of the ground heat exchange affect the financial results: PBT is 23 years and the NPV is 1€/m² at the end of the investment. To be noted the environmental benefit, with a reduction of 23 CO₂ kg per square meter.
Table 2.2: Denmark: Energy and economic results

<table>
<thead>
<tr>
<th>Results</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final energy (heating/electricity)</td>
<td>[kWh/m²]</td>
<td>151.8</td>
</tr>
<tr>
<td>Primary energy (heating/electricity)</td>
<td>[kWh/m²]</td>
<td>69.6</td>
</tr>
<tr>
<td>CO₂ reduction</td>
<td>[kg/m²]</td>
<td>22.9</td>
</tr>
<tr>
<td>Investment/saved energy</td>
<td>[€/(kWh/m²) year]</td>
<td>2.9</td>
</tr>
<tr>
<td>Payback time</td>
<td>[years]</td>
<td>23.4</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>[€/m²]</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Table 2.3 presents the results of the German school, where high primary energy savings are reached: about 74 kWh/m², with an associated CO₂ reduction of 12 kg/m². Again high initial costs affect the financial suitability of the measure: the payback time exceed the heat pumps life cycle and, as a consequence, a negative NPV is calculated.

Table 2.3: Germany: Energy and economic results

<table>
<thead>
<tr>
<th>Results</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final energy (heating/electricity)</td>
<td>[kWh/m²]</td>
<td>119.5</td>
</tr>
<tr>
<td>Primary energy (heating/electricity)</td>
<td>[kWh/m²]</td>
<td>73.7</td>
</tr>
<tr>
<td>CO₂ reduction</td>
<td>[kg/m²]</td>
<td>12.9</td>
</tr>
<tr>
<td>Investment/saved energy</td>
<td>[€/(kWh/m²) year]</td>
<td>2.4</td>
</tr>
<tr>
<td>Payback time</td>
<td>[years]</td>
<td>58.8</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>[€/m²]</td>
<td>-108.0</td>
</tr>
</tbody>
</table>

In Italy the measures is estimated assuming an heat pump with air as cold sink and, for the climatic characteristics, it is tested for the centre (Terni: Table 2.4) and the south (Taranto: Table 2.5) of the country only, excluding Turin. Due to the milder climatic conditions, primary energy savings are lower but still significant: 78 and 55 kWh/m² for respectively, the centre and the south of Italy. The selected technology has lower costs with consequent excellent financial indicators; PBTs are lower than 4 years and NPVs above 100 €/m² in both cases. The investment to saved energy ratio is also positive.

Table 2.4: Italy - Terni: Energy and economic results

<table>
<thead>
<tr>
<th>Results</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TERNI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final energy (heating/electricity)</td>
<td>[kWh/m²]</td>
<td>113.3</td>
</tr>
<tr>
<td>Primary energy (heating/electricity)</td>
<td>[kWh/m²]</td>
<td>77.7</td>
</tr>
<tr>
<td>CO₂ reduction</td>
<td>[kg/m²]</td>
<td>19.3</td>
</tr>
<tr>
<td>Investment/saved energy</td>
<td>[€/(kWh/m²) year]</td>
<td>0.11</td>
</tr>
<tr>
<td>Payback time</td>
<td>[years]</td>
<td>2.6</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>[€/m²]</td>
<td>171.9</td>
</tr>
</tbody>
</table>
Table 2.5: Italy: Taranto: Energy and economic results

<table>
<thead>
<tr>
<th>Results</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TARANTO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final energy (heating/electricity)</td>
<td>[kWh/m²]</td>
<td>73.8</td>
</tr>
<tr>
<td>Primary energy (heating/electricity)</td>
<td>[kWh/m²]</td>
<td>55.3</td>
</tr>
<tr>
<td>CO₂ reduction</td>
<td>[kg/m²]</td>
<td>10.4</td>
</tr>
<tr>
<td>Investment/saved energy</td>
<td>[€/(kWh/m²) year]</td>
<td>0.15</td>
</tr>
<tr>
<td>Payback time</td>
<td>[years]</td>
<td>3.6</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>[€/m²]</td>
<td>117.6</td>
</tr>
</tbody>
</table>

Table 2.6 presents the results of the Norwegian school, where high final and primary energy savings are reached due to the reference poor performing configuration; also a relevant CO₂ reduction is achieved (22.7 kg/m²). The initial costs are very high with a consequent long payback time (more than years), even if a positive NPV is expected at the end of the life time.

Table 2.6: Norway: Energy and economic results

<table>
<thead>
<tr>
<th>Results</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final energy (electricity)</td>
<td>[kWh/m²]</td>
<td>66.2</td>
</tr>
<tr>
<td>Primary energy (heating/electricity)</td>
<td>[kWh/m²]</td>
<td>165.5</td>
</tr>
<tr>
<td>CO₂ reduction</td>
<td>[kg/m²]</td>
<td>22.7</td>
</tr>
<tr>
<td>Investment/saved energy</td>
<td>[€/(kWh/m²) year]</td>
<td>0.77</td>
</tr>
<tr>
<td>Payback time</td>
<td>[years]</td>
<td>21.1</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>[€/m²]</td>
<td>14.5</td>
</tr>
</tbody>
</table>

**Example of application in the School of the Future Project**

The only application of heat pumps in the School of the Future Project is the installation of a brine-to-water heat pump in the Brandengen School in Drammen, Norway.

In the autumn of 2012, the old oil burner was replaced by a heat pump for space heating and preheating of sanitary hot water.

Figure 2.8 (left): The oil tank on the way to destruction. Figure 2.8 (right): Placement of pipes to collect heat from the ground. Photos: G. Andersen.
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 of the school. The heat pump uses R134a as refrigerant, and is specially designed for variable water flow and temperatures up to 70°C.

The original central heating system was designed as a «high temperature» system requiring 80°C as supply temperature to provide heat on «coldest day». The available heat pumps in market were not suitable for this high temperature level. Temperature level in wells varies between 0 and 8°C. Temperature of leaving hot water from heat pump varies depending on heat demand and ambient temperature; from about 40 to 70°C. Coefficient of performance (COP) of the heat pump is strongly dependent on temperature in energy wells and required supply temperature in the heating circuit. In most of the heating season the required supply temperature for Brandenagen School is 60°C or higher. Traditional heat pump design would lead to rather low COP. It was necessary to design a new concept for heat pumps replacing oil burners in old 80/60°C system, more details [Lunde, Helge and Gjermund, Vittersø].

Compressors are high performance semi hermetic piston type with water chilled tops, speed control and step control. Two identical refrigerant circuits are provided, each with two compressors, evaporator and condenser of extraordinary heat exchanger surface. Water flows are connected in series on the hot side, which reduces temperature level in first condenser, increasing COP for this heat pump circuit. A liquid sub cooler is installed in each refrigerant circuit. This is a heat exchanger where return hot water is able to cool down refrigerant downstream from condenser. Sub cooling of refrigerant increase efficiency of heat pump and improve COP.

A design based on high performance piston compressors with speed control, condensers in series, liquid sub-cooler and ample designed heat exchangers all contribute to 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.

**Conclusions**

In school buildings, the most commonly used heat pumps are:

- Electric heat pump, air-to-water
- Electric heat pump, brine-to-water (ground source heat pump)
- Electric heat pump, air-to-air (mostly in southern Europe).
During the last 20 years, the total amount of installed heat pumps has exceeded 6.74 million. This amounts to an installed capacity of nearly 224 GW. In an individual country perspective, 15 of the 21 markets saw a positive development. The biggest markets such as France and Sweden significantly influence the overall positive results of the market in Europe.

Still, a high initial investment cost and a short-term decision perspective and a high electricity cost influence the total cost of ownership of a heat pump system and limit market growth.

**Literature and references**

VENTILATION FOR ENERGY EFFICIENCY AND INDOOR AIR QUALITY

Introduction

Providing clean air and removing stale air is the primary issue to ensure adequate air quality levels in the built environment. Ventilation systems and strategies to achieve such objectives are based on natural, mechanical or hybrid solutions. Other uncontrolled airflows may cross through a building depending on envelope leakages and on natural driving forces (wind, temperature). These flows as infiltration (entering the space) or exfiltration (loss of air) must still be taken into account in ventilation system design and calibration.

Unnecessarily high rates of air change may affect the building’s heating and/or cooling performances. It is variously estimated that ventilation accounts for 30% or more of the buildings energy demand. Fresh outdoor air is necessary for providing adequate IAQ but, at the same time, it is an additional load on the building’s energy performance.

Designers have to balance these two issues in order to provide adequate air quality as well as energy efficiency related to building use, climate and the emission characteristics of contaminant sources.

Natural ventilation, unlike fan-forced ventilation, uses the natural forces of wind and buoyancy to deliver fresh air into buildings. In summer, wind is used to supply as much fresh air as possible while in winter, ventilation is normally reduced to levels sufficient to remove excess moisture and pollutants. Design of natural ventilation systems will vary based on building type and local climate. The amount of ventilation depends critically on the careful design of internal spaces, and the size and placement of openings in the building. The use of natural ventilation doesn’t only provide fresh outdoor air to ensure safe healthy conditions for building occupants without the use of fans; it also provides free cooling without the use of mechanical systems. Natural ventilation schemes can consist of automatically opening and closing windows and roof-lights, and can range from a simple open/close switch to a fully integrated energy management system with CO₂, temperature, weather sensors and interfaces with building management systems.

Natural ventilation is strictly related to the building design and operation and this guideline is focused on energy system technologies (e.g. hybrid and mechanical ventilation), therefore natural ventilation is not included in this guideline.

The ventilation is particularly important for school buildings, where adequate IAQ values are needed to ensure health and comfort for pupils, as well as to enhance their class performances. This implies accurate design and management of the system, able to provide high fresh air rate where it is needed (classrooms) and reduce the rate in zones with intermittent or null occupancy, to optimise the energy performance of the building in use.

Brief technology description

Mechanical Ventilation

To achieve the desired indoor air quality, a ventilation system is suitable when it continuously provides filtered fresh air and discharges exhaust air and contaminants.

Such systems consist of mechanical air supply ventilation (ducts, grilles, fans, heat exchangers, etc.) or could be part of an air-conditioning system (covering heating and cooling demands). To supply fresh air from the outside to the inside also requires an air intake, an air filter to remove
particles, ductwork and room diffusers. To minimise energy use, fans should be sized and controlled to move only the amount of intake air required.

Regardless of climate, mechanical ventilation is often essential in large, deep plan schools where fresh air must penetrate to the centre of the building and high heat gains can cause overheating. For small buildings, located in a mild climate, installations, operating and maintenance costs of the mechanical systems might outweigh the benefits. In mild climates, natural ventilation by window opening may be satisfactory (no complex system is needed) for buildings with no high heating or cooling loads. On the other hand, under severe climate conditions with relevant conditioning loads, only mechanical systems could balance heating and/or cooling demand and ensure sensible and latent heat recovery that is found to be cost efficient.

Ventilation can also be important for temperature control, particularly in summer. Two main operating modes are the so called “Summer Mode” that turns off the supply air on demand or via a remote thermostat (additional controllable passive ventilation may be required) and the “Summer Bypass mode” automatically controlled, that bypasses the heat exchanger when indoor/outdoor temperature conditions make heat exchange undesirable. This mode could also increases both the supply and extract to full speed when the automatic bypass engages in order to prevent overheating conditions in the enclosed environments.

Units handling the mechanical ventilation can also provide heating cooling, humidification and dehumidification: in these cases they are called HVAC (heating, ventilating, and air conditioning) units.

Mechanical ventilation systems can be integrated with air conditioning or adiabatic cooling to provide a cost-effective and energy-efficient solution when it is necessary to cool below the ambient temperature.

Mechanical ventilation systems could be divided in: central ventilation plants which have one ventilation unit per building (commonly used in office buildings): the air flow in each room can be controlled by variable air volume boxes; decentralised ventilation plants which have one ventilation unit per service unit (class room, apartment), assuring individual time settings for each room, a solution that could be often selected in case of retrofit interventions where it is hard to lead large ducts from a central ventilation unit.

Usually the intake of fresh air and the discharge of exhaust air is decentral as well. But the intake and discharge can also be central and potentially involve supporting ventilators.

HVAC systems can also be combined with heating and heat recovery systems (mechanical heat recovery ventilation (MHRV) to reduce the consumption of energy used for heating efficiently.

Heat recovery systems provide complete balanced ventilation for the whole building. It operates by recovering a large portion of the energy that would normally be lost through open windows, wall vents etc. MHRV thus merges adequate indoor air quality and energy efficiency. A duct system is run from every room to a point where the MHRV unit operates silently and efficiently.

The main components of a MHRV system are:

- insulated ducts for incoming (fresh) and outgoing (stale) air
- ducts to distribute fresh air throughout the building and different ducts to return stale air to the MHRV
- fans to circulate fresh air and exhaust stale air
- a heat-exchanger core, where heat is transferred from one air stream to the another
- filters to keep dirt out of the heat-exchanger core
- a defrost mechanism (some units use a preheater) to prevent freezing and blocking of the heat-exchanger core when the temperature of the intake air is low
- a drain to remove any condensation from inside the MHR
- controls to regulate the MHRV according to ventilation needs.

The use of heat recovery units is an important measure for the energy efficiency of buildings. The impact of Energy Performance Building Directive and its target to reduce the energy demand of technical building systems in gave rise to a significant increase in heat recovery units. What makes a MHRV unique is the heat-exchanger core. A typical heat exchanger unit features two fans—one to remove stale air and another to take in fresh air. It is composed of a series of narrow alternating passages through which incoming and outgoing airflow flow. As the airflows pass through the exchanger, heat is transferred from the warm airstream to the cold, while the airstreams never mix. A MHRV contains filters that keep particles such as pollen or dust from entering the building.

There are two types of heat exchangers depending on their profile:

1. cross flow: plate or cellular
   - vertical flat plate
   - horizontal flat plate
   - cellular
2. circulating: with centrifugal fans and a slow rotating heat exchanger

Figure 3.1: Cross-flow heat exchanger. (Genvex A/S, 2008. Lüftungssysteme – Wohnklima zum Wohlfühlen. Broschüre; http://www.bpcventilation.com)
These units are characterised by the Heat Recovery Rate (HRR) depending on the shape of the exchanger:

- cross-flow heat exchanger: HRR 55-75%
- counter-flow heat exchanger: HRR 60-80%
- circulating heat exchanger: HRR 60-90% (humidity recovery).

During the heating season, a MHRV recovers heat from the outgoing stale household air and uses it to preheat incoming fresh outdoor air. The MHRV then distributes the incoming air throughout the building. The two air streams are always kept separate within the MHRV.

Fresh outdoor air is filtered before it enters the MHRV core, from where a circulation fan distributes the air throughout the home via ductwork. A separate ductwork system draws the stale indoor air back to the MHRV, where it is filtered and pushed by a fan through the heat exchange core.

Strategies and systems based on the effective indoor air quality level requirements are wide spreading. It is the so called demand controlled ventilation (DCV) and it provides filtered fresh air continuously and discharges exhaust air and contaminants, helping save energy often by recovering heat from exhaust air and by using energy efficient ventilation equipment. At every moment, DCV offers an optimisation of heating consumption and indoor air quality, on a fully automated basis.

These systems can be divided into central (only one ventilation unit for the whole building) or de-central ventilation units (one unit per service/zone).

The main DCV systems components are:

- diffusers: supply air to ventilated spaces (care should be taken not to cause draughts)
- air intakes: openings for supply air from outside (not close to contaminant sources)
- air grilles: capture exhaust air from a space
- a group of sensors, designed to monitor pollutants
- a control system for adjusting the ventilation rate in response to need.

DCV is particularly effective when there is a ‘dominant’ pollutant (such as CO₂ in school buildings). The control system relays information from the air quality sensor to the ventilation system: when the sensor indicates a need for ventilation, the fan is switched on. These systems
are particularly beneficial in locations of transient occupancy or where pollutant loads, specific to an environment, vary over time.

The rate of ventilation is automatically controlled in response to variations in the indoor air quality tracked by IAQ sensors (moisture, CO₂, particles, infrared presence, mixed gas sensors). Ventilation is therefore provided only when and where it is needed while, at other times, it may be reduced to minimise space heating or cooling.

At every moment, DCV offers an optimisation of heating consumption and indoor air quality if managed by a fully automated system. This prevents excessive and uncontrolled ventilation (as well as draught) and limits thermal loss due to heating cold ventilation air in winter and cooling warm ventilation air during hot summer nights ensuring a safe and reliable performance of the MHRV.

Modulation parameters should allow adjustment of the air change rate based on actual needs, and for this reason the choice of the control parameters and the design of the appropriate control strategy found to be an investment issue. Sensors are used to measure, monitor and respond rapidly to changes of the indoor environment, according to the governing variable (CO₂ level, PIR movement sensor, and humidity or timer control).

For schools today, humidity, CO₂ and volatile organic compounds control represent the typical priority.

To achieve this, low-consumption fans and a wide range of intelligent elements can be used:

- control elements, speed regulators, frequency inverters
- presence or CO₂ detectors
- temperature and humidity sensors
- pressure sensors
- motorised shutters
- twin-flow inlet valves.

The operating controls may include different functions:

- high-speed and low-speed controls
- a circulation mode setting, which circulates air inside the building but not exchanging indoor and outdoor air
- a dehumidifier that will trigger the HRV into high-speed operation when the humidity level in a room/zone reaches a pre-set level
- a timer that can be set to run the HRV at high speed for specified intervals
- an intermittent exchange mode setting that automatically turns on the HRV at low speed for specified intervals
- pollutant sensors that increase the ventilation rate when pollutant levels rise
- a maintenance light, which comes on automatically when the filters, and other components, need to be cleaned or serviced.

Modulation significantly reduces average airflows, so that the average heat losses are half those of a ventilation system with constant airflow. Heat recovery of 85% achieves energy savings of around 92% compared with a traditional mechanical system without heat recovery.
Hybrid ventilation

Hybrid ventilation combines features of both mechanical and natural ventilation. It's a two-mode system which is designed to minimise energy consumption while providing acceptable indoor air quality and thermal comfort in an energy-efficient way switching automatically from one mode to another at different times of the day, season or year. This principle is based on two fully autonomous systems where the control strategy either switches between the two systems, or uses one system for some tasks and the other system for other tasks.

Fan-assisted natural ventilation

This principle is based on a natural ventilation system combined with an extract or supply fan.

Stack and wind-supported mechanical ventilation

This principle is based on a mechanical ventilation system that makes optimal use of natural driving forces. The control strategy is a crucial issue which aiming to achieve an optimal equilibrium between IAQ and energy use. The level of demand control can vary from manual by occupants, simple timer control, motion detection to direct measurement of IAQ, automatic control of room temperature during occupied hours.

The purpose of the control system is to establish the desired airflow at the lowest energy consumption possible.

The control strategy for a building should at least include a winter control strategy, where IAQ is normally the main parameter of concern, and a summer control strategy, where the maximum room temperature is the main concern. It should also include a control strategy, to be used in the interval between winter and summer, where there might occasionally be a heating demand as well as excess heat in the building.

To facilitate the control of thermal comfort, indoor air quality and airflow in the building, appropriate components can include:

- manually operated and/or motorised windows, vents or special ventilation openings in the facade and in internal walls
- indoor sensors: room temperature and humidity, CO₂ (and/or other pollutants), occupancy, airflow sensors etc.
- outdoor sensors: weather station including: external temperature, wind speed and direction, solar radiation etc.
Evaluation - advantages and disadvantages

Where a natural ventilation strategy does not comply with increased airflow rates required, or a demand for cooling, mechanical ventilation or a full air-conditioning strategy is required. This is much more energy intensive due to the nature of the equipment (e.g. fans) required to move air around the building. It is also possible to mix a natural and a mechanical ventilation strategy to achieve ‘mixed mode’ or hybrid systems, thus striking a balance between energy performance and comfort.

A balanced mechanical ventilation system refers to the system where air supplies and exhausts have been tested and adjusted to meet design specifications. The room pressure may be maintained at either slightly positive or negative pressure, which is achieved by using unequal supply or exhaust ventilation rates. The type of mechanical ventilation used depends on climate: in warm and humid climates, infiltration may need to be minimised to reduce interstitial condensation (an over pressure mechanical ventilation system is often used); conversely, in cold climates, exfiltration needs to be prevented to reduce interstitial condensation (negative pressure ventilation is used).

A demand-controlled ventilation (DCV) system reduces the outside air intake at times when it is not needed. DCV has a number of applications in various types of buildings. Firstly, DCV is applied in buildings where the number of people changes continuously during the whole day. It is also applied in places where occupancy is unpredictable and reaches a high level. In buildings with a more stable occupancy level, DCV provides a sufficient amount of fresh supply air per person all the time. DCV reduces energy costs in areas with a high utility level, high energy demand and energy costs and is also used in spaces where heating and cooling for the most part of the year are required. Energy savings may be less where heat exchangers are used depending on climate, occupancy and a building type. DCV is used in the regions with warm and humid climates or extreme climate conditions, and buildings which have equipment for automated adjusting of the air supply. DCV is applied in spaces where CO$_2$ from human respiration and human activity is the main source of pollution.
Two overall performance indicators are often used. Air exchange efficiency indicates how efficiently fresh air is being distributed in the room; ventilation effectiveness indicates how efficiently the airborne pollutant is being removed from the room. A whole range of different requirements have to be fulfilled before a ventilation system can be considered to have a good performance:

- energy use should be as low as possible to maintain the required airflow rates
- acoustics: noise levels should be below acceptable limits
- costs should be reasonable
- ease of installation
- space use should be limited
- ease of operation, cleaning of filters and controllability
- maintenance should be limited
- durability
- aesthetics: it must be possible to integrate the system in the building in an aesthetic way.

Evaluations of the benefits and drawbacks of each ventilation system follow below.

**Advantages**

**Mechanical ventilation**

- Improves IAQ by removing allergens, pollutants, moisture (avoiding mould problems).
- Ensures more control, providing fresh airflow along with appropriate locations for intake and exhaust.
- Allows a constant flow of outside air and can also provide filtration, dehumidification, and conditioning of the incoming outside air ensuring improved comfort conditions.

**DCV**

- Energy consumption reduction for ventilation, heating and cooling.
- Appropriate amount of fresh air and temperature control.
- Reduction of outside air intake at times when it is not needed.
- User acceptance of the ventilation system, providing the occupants with a sense of confidence in the system.
- The customer should not have to interact with the system.
- The system can manage a wide range of occupancy rates and respond accordingly saving energy as well as providing good ventilation during peak periods.

**Hybrid ventilation**

- Uses the best of natural and mechanical ventilation.
- Great control of ventilation requirements.
- Can fulfill the requirements for indoor performance and the need for energy systems.
- Adaptable to changes in climate.
- Great user satisfaction due to the high degree of personal control.
- Reduction of energy use.
- Cheaper to run than dedicated mechanical ventilation.
Disadvantages

Mechanical ventilation
- System devices (valves, sensors, controllers etc.).
- Extra maintenance due to the measurement devices.
- HVAC systems are affected.
- Additional sensors, design calculations, programming needs, maintenance requirements.

DCV
- Excess use of outside air due to the drifting of CO₂ sensors may lead to a waste of energy.
- Operating costs related to CO₂ sensor calibration and maintenance.
- Concerns over insufficient ventilation for non-human pollutants.

Hybrid ventilation
- Difficulty to design the system without a complete knowledge of future user patterns.
- Requires complex programming and controls.
- Difficult to repair and maintain.
- Expensive to buy and set up.
- Limited by regulations with regard to fire and acoustics.

Market penetration and utilisation

Gathering data and statistics about the market of ventilation systems is a complex task since a common product/system definition is not agreed at EU level. Eurostat and national statistics bodies classify ventilation systems either as fans or air-conditioning machines not containing a refrigeration unit; central station air handling units; variable air volume boxes and terminals, constant volume units and fan coil units. Likely also air handling units and central heat recovery are to be included in the category.

In such a complex category, the market is polarised by Italy for the fan coil unit production and Germany for air handling units; together the two countries represent more than 60% of the EU27 market. Figure 3.4 shows the market evolution between 2003 and 2009. The strong increase of the unit/system production (blue curve) until 2006 rapidly dropped in the following years, due to the economic crisis; no data are available since 2009. The economic value of the technology (red curve) was apparently not affected by the crisis; data available until 2012 show a constant trend in line with the values reached in the 2007-2009 period.
The market shows a significant penetration of the technology in Europe, even if the penetration rate significantly varies between southern and central/northern regions of the continent. Barriers still exist at several levels in existing buildings, and schools in particular.

The most relevant is found in existing schools designed to be naturally ventilated through window openings. Installing a mechanical ventilation system is an invasive solution due to necessary interventions requiring the building to be unoccupied and the architectural and structural restraints of the building for the installation of ducts, ventilation units, heat recovery systems, etc.

Another critical issue is related to the definition, setting and management of the control strategy and the identification of the control parameters during the design phase and, in particular, during the operating phase. This problem is often caused by inadequate knowledge and skill of the person in charge of the system management. A more tangible problem was found on the cost of the components and their maintenance (such as sensors, filters, fans etc.), especially in those areas where mild climatic conditions do not allow significant energy savings through the installation of mechanical ventilation systems.

**Energy and economic performance**

Energy codes in EU countries treat mechanical ventilation in different ways for various building categories. The technology is mandatory in some cases; other regulations require adequate air exchange rates without giving an indication of whether they can be achieved by mechanical or natural means/strategies.

The technical and economic assessment strictly address the energy performance of the technology and it is worth remembering that this technology is also relevant for the environmental quality of the built environment. This aspect is crucial in schools, where a high quality standard should be adopted for pupils who spend many hours of the day in the same enclosed space.

The impact of the technology on the performance in school buildings to be renovated was screened in a particular frame work of the project dedicated to technology screening. The whole
calculation set can be downloaded from the project website (http://www.school-of-the-future.eu/index.php/project-results/technology-screening). In the following some exemplary outcomes are presented, including energy, environment and economic issues. The results are achieved under very different boundary conditions, in terms of climatic conditions, reference building characteristics, energy prices, primary energy factors and performance and investment costs of the selected technologies.

In this framework the following results provide a general view of the technology application in improving the performance of existing school buildings in each country rather than comparing the technology impact among different countries. According to this assumption the results are presented separately for each country. The selected climatic zones of the participating countries are: Denmark (Copenhagen), Germany (Potsdam), Italy (Turin for the north, Terni for the centre and Taranto for the south) and Norway (Oslo).

The impact of this single energy measure is calculated based on a reference building configuration. The reference school building has a typical layout that consists of three storeys with classrooms on one side and a corridor on the other, as represented by the pictogram in Figure 3.5.

![Figure 3.5: Pictogram of the reference school building floor](image)

The energy savings due to MVHR application as saved final energy and total primary energy consumptions as the economic parameters are intended in comparison to the reference buildings. This is described in the following for each country and summarised in Table 3.1. In Denmark, Germany and Norway, the classroom area is 60 m² and used by 30 pupils and a teacher. This requires a ventilation rate of 2.2 l/(s m²) to comply with category 2 of DS/EN15251. The reference school building is characterised by natural ventilation and no cooling system for the Denmark and Germany cases, a mechanical exhaust air system is considered for the Norway reference building. Balanced mechanical ventilation with a good efficient heat recovery (MVHR) is considered a retrofitting measure. The heating energy consumption of the reference school building is slightly higher than the average heating consumption of Danish schools, also because the ventilation rate is set to fulfil the optimised hygienic recommendations.

The Italian classroom is assumed to be 50 m² and used by 25 persons. The reference building is assumed to be naturally ventilated and neither mechanical ventilation nor cooling system exists. Since no standard data exist for these operational conditions, it is assumed to have an infiltration/ventilation rate of 0.42 l/(s m²), according to common experience. The mechanical ventilation measure assumes an increased inlet rate, set to 1.60 l/(s m²), during the system operation; an infiltration rate of 0.20 l/s m² used in this case. Balanced mechanical ventilation with a good efficient heat recovery (MVHR) is considered a retrofitting measure.
Table 3.1: MHRV Characteristics

<table>
<thead>
<tr>
<th>Country</th>
<th>Treated floor area</th>
<th>SEL</th>
<th>Efficiency</th>
<th>Air tightness</th>
<th>Investment Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m²</td>
<td>kJ/m²</td>
<td>%</td>
<td>(50 Pa) l/sm²</td>
<td>€</td>
</tr>
<tr>
<td>Denmark</td>
<td>3,000</td>
<td>1.2</td>
<td>90</td>
<td>0.6</td>
<td>570,000</td>
</tr>
<tr>
<td>Germany</td>
<td>3,000</td>
<td>0.7</td>
<td>80</td>
<td>0.6</td>
<td>570,000</td>
</tr>
<tr>
<td>Italy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turin</td>
<td>1,453</td>
<td>1.2</td>
<td>90</td>
<td>0.2</td>
<td>116,240</td>
</tr>
<tr>
<td>Terni</td>
<td>1,453</td>
<td>1.2</td>
<td>90</td>
<td>0.2</td>
<td>116,240</td>
</tr>
<tr>
<td>Taranto</td>
<td>1,453</td>
<td>1.2</td>
<td>90</td>
<td>0.2</td>
<td>116,240</td>
</tr>
<tr>
<td>Norway</td>
<td>3,000</td>
<td>1.2</td>
<td>90</td>
<td>0.6</td>
<td>245,902</td>
</tr>
</tbody>
</table>

Following tables show energy savings (both final and primary saved energy are presented), environmental (CO₂ reduction emissions) and financial (simply payback time and net present value) results for Denmark (Table 3.2), Germany (Table 3.3), Italy (Terni, Taranto) (Table 3.4) and Norway (Table 3.5).

Table 3.2 presents the results of the Danish school, where the measure leads to relevant energy savings (greater than 70 kWh/m²) and CO₂ reduction (about 15 kg/m²). The installation and maintenance costs, however, lead long PBT (about 28 years) and negative net present values.

<table>
<thead>
<tr>
<th>Results</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final energy (heating/electricity)</td>
<td>kWh/m²</td>
<td>72.0</td>
</tr>
<tr>
<td>Primary energy (heating/electricity)</td>
<td>kWh/m²</td>
<td>73.4</td>
</tr>
<tr>
<td>CO₂ reduction</td>
<td>kg/m²</td>
<td>14.7</td>
</tr>
<tr>
<td>Investment/saved energy</td>
<td>€/(kWh/m²) year</td>
<td>2.59</td>
</tr>
<tr>
<td>Payback time</td>
<td>years</td>
<td>27.9</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>€/m²</td>
<td>-63.5</td>
</tr>
</tbody>
</table>

Table 3.3 presents the results of the German schools, where positive results are achieved in terms of energy savings (25 kWh/m²) and CO₂ reduction (6 kg/m²). The maintenance costs, in this case, are higher than those saved thanks to the mechanical ventilation systems; hence negative payback time and negative net present are calculated.

<table>
<thead>
<tr>
<th>Results</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final energy (heating/electricity)</td>
<td>kWh/m²</td>
<td>24.1</td>
</tr>
<tr>
<td>Primary energy (heating/electricity)</td>
<td>kWh/m²</td>
<td>26.5</td>
</tr>
<tr>
<td>CO₂ reduction</td>
<td>kg/m²</td>
<td>6.1</td>
</tr>
<tr>
<td>Investment/saved energy</td>
<td>€/(kWh/m²) year</td>
<td>7.2</td>
</tr>
<tr>
<td>Payback time</td>
<td>years</td>
<td>Negative</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>€/m²</td>
<td>-280.1</td>
</tr>
</tbody>
</table>

Table 3.4 presents the results of the Italian schools. In this case final and primary energy savings are very small or negative, which can be explained by the increase of the air change rate when the natural ventilation is replaced by a mechanical system at the mild Mediterranean latitudes.
and the increase of electricity uses for fans. PBTs and NPVs are obviously negatives in all the cases.

**Table 3.4: Italy - Turin: Energy and economic results**

<table>
<thead>
<tr>
<th>Results</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final energy (heating/electricity)</td>
<td>[kWh/m²]</td>
<td>4.3</td>
</tr>
<tr>
<td>Primary energy (heating/electricity)</td>
<td>[kWh/m²]</td>
<td>0.2</td>
</tr>
<tr>
<td>CO₂ reduction</td>
<td>[kg/m²]</td>
<td>-0.01</td>
</tr>
<tr>
<td>Investment/saved energy</td>
<td>[€/(kWh/m²) year]</td>
<td>175.3</td>
</tr>
<tr>
<td>Payback time</td>
<td>[years]</td>
<td>Negative</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>[€/m²]</td>
<td>-100.4</td>
</tr>
</tbody>
</table>

**TERNI**

<table>
<thead>
<tr>
<th>Results</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final energy (heating/electricity)</td>
<td>[kWh/m²]</td>
<td>1.4</td>
</tr>
<tr>
<td>Primary energy (heating/electricity)</td>
<td>[kWh/m²]</td>
<td>-2.5</td>
</tr>
<tr>
<td>CO₂ reduction</td>
<td>[kg/m²]</td>
<td>-0.5</td>
</tr>
<tr>
<td>Investment/saved energy</td>
<td>[€/(kWh/m²) year]</td>
<td>-15.6</td>
</tr>
<tr>
<td>Payback time</td>
<td>[years]</td>
<td>Negative</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>[€/m²]</td>
<td>-107.6</td>
</tr>
</tbody>
</table>

**TARANTO**

<table>
<thead>
<tr>
<th>Results</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final energy (heating/electricity)</td>
<td>[kWh/m²]</td>
<td>-1.1</td>
</tr>
<tr>
<td>Primary energy (heating/electricity)</td>
<td>[kWh/m²]</td>
<td>-5.0</td>
</tr>
<tr>
<td>CO₂ reduction</td>
<td>[kg/m²]</td>
<td>-1.0</td>
</tr>
<tr>
<td>Investment/saved energy</td>
<td>[€/(kWh/m²) year]</td>
<td>-7.7</td>
</tr>
<tr>
<td>Payback time</td>
<td>[years]</td>
<td>Negative</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>[€/m²]</td>
<td>-113.6</td>
</tr>
</tbody>
</table>

The Norwegian school has a significant reduction of final and primary energy (more than 60 kWh/m²), as well as of CO₂ reduction. The economic analysis shows that the payback time investment is 17 years which leads to a positive net present value (around 15 €/m²). The positive results depend on the lower maintenance costs being a mechanical system already installed in the reference case; while in the other countries it is assumed to have only natural ventilation.

**Table 3.5: Norway: Energy and economic results**

<table>
<thead>
<tr>
<th>Results</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final energy (heating/electricity)</td>
<td>[kWh/m²]</td>
<td>61.9</td>
</tr>
<tr>
<td>Primary energy (heating/electricity)</td>
<td>[kWh/m²]</td>
<td>63.2</td>
</tr>
<tr>
<td>CO₂ reduction</td>
<td>[kg/m²]</td>
<td>12.6</td>
</tr>
<tr>
<td>Investment/saved energy</td>
<td>[€/(kWh/m²) year]</td>
<td>1.3</td>
</tr>
<tr>
<td>Payback time</td>
<td>[years]</td>
<td>16.9</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>[€/m²]</td>
<td>15.8</td>
</tr>
</tbody>
</table>

It is important to outline that the impact of mechanical ventilation in school building retrofitting cannot be addressed only in terms of energy and economy, since it improves the environmental quality in a critical environment, such as a classroom with pupils. The right system strongly depends on the required minimal and maximal ventilation rate, the local situation like outside noise, outdoor air pollution and outdoor climate. The potential for using controlled ventilation is discussed in the following.
Natural ventilation by manual window ventilation is the traditional ventilation system in many existing schools in European countries. The system has a broad acceptance by the users, because they open and close windows by themselves to ensure optimal indoor conditions.

In Figure 3.6 the first five histograms present simulation results for conventional window airing in schools for 10 minutes rush airing between 45 minutes lessons for various climatic zones. This strategy does not provide adequate air quality (the CO₂ concentration increases above 1500 ppm), as inferred by the cumulate distribution bars reported for each locality in the natural ventilation mode. Windows have to be opened also during lessons but in winter outdoor air is cold and windows are closed earlier or even not opened at all, noisy or dusty streets limit even more the possibility for window opening. Another critical issue is that ventilation rates depend on natural driving forces like wind and temperature differences between inside and outside. Therefore it is not possible to keep ventilation rates constant over time without controlling the openings in an automated way. This is a crucial aspect in winter to guarantee good indoor climate and minimise heating energy consumption. As a consequence, the environmental quality will in practice be more critical than shown in the picture.

Window opening is simulated ideally only between lessons until outdoor carbon dioxide is reached or the operative indoor temperature falls below 17°C. A constant airflow rate can only be reached with mechanical ventilation. Demand-controlled ventilation with regard to CO₂ levels can either be reached by continuously automated windows or mechanical ventilation, but natural ventilation is restricted to comfort issues in winter.

![CO₂ levels in classrooms in winter for different ventilation strategies](image)

Figure 3.6: Simulated carbon dioxide levels in classrooms during occupancy in winter (December-February). The occupancy hours are: 392 in Copenhagen, 450 in Potsdam and 494 in Turin, Terni and Taranto. Occupancy hours for constant and demand controlled ventilation simulations are 450.

Mechanical ventilation guarantees a defined ventilation rate and can be combined with preheating, precooling filtering and sound insulation, thus achieving good air quality without waiving thermal comfort in winter. The impact on the environmental quality in a standard classroom can be seen from the last five columns of Figure 3.6. By using a minimum air change rate ACH of 2.5/3.5/4.5, the CO₂ level never rises above 1500/1200 ppm. The last 2 columns
refer to the Demand Controlled (DC) ventilation, strategy based on an air quality sensor, which activate the natural and/or ventilation systems when the CO$_2$ concentration reaches the design target. This approach is useful since, being demand based, activate the ventilation as a function of the occupation density and ensure good results as shown in the graph.

It is important to remember that mechanical ventilation cannot always provide high comfort. This depends on the individual performance of systems. Placing outlets at the wrong place or providing supply air with too high air speed can cause draught due to the high ventilation rate required. In addition, mechanical ventilation systems are not always silent. In order to preserve the system-inherent advantages of mechanical ventilation the mechanical ventilation systems have to be designed carefully with respect to ventilation rate, supply air temperature, type and positioning of inlets and noise protection (especially for decentralised systems). Supply air should always be fresh air and not be mixed up with exhaust air. A well-designed mechanical/hybrid ventilation system will significantly improve the environmental quality of the classrooms.

**Examples of applications in the School of the Future**

Ventilation is crucial for energy efficiency and environmental quality in school buildings and therefore it was carefully addressed in the School of Future demonstration projects, with solutions that reflect the climatic conditions.

**Denmark**

A hybrid ventilation system was installed at Hedegårdsskolen in Ballerup: fresh air enters through pipes in the building envelope and pre-heats the radiators of the heating system. The natural ventilation is supported by fans when more fresh air is needed, according to the CO$_2$ levels, registered by dedicated sensors. However, the existing system was found to be noisy and poorly controlled. To solve such problems, it was decided to revive the existing mechanical ventilation systems, installed during the construction of the buildings and then dismissed in favour of the hybrid system. Energy performances are expected to increase with the installation of a highly efficient heat exchanger for heat recovery of the ventilation air, with an improvement of the air and acoustic quality. Performances also improve thanks to an advanced BEMS: the ventilation will be managed by the CO$_2$-sensors and occupation profiles that will modulate the air exchange rate.

**Germany**

The Solitude-Gymnasium in Stuttgart, Germany consists of several blocks and some of them were equipped with ventilation systems. However the existing solutions were either obsolete or inadequate for ensuring proper air quality levels, while in other cases the natural ventilation results proved to be insufficient. The retrofitting required the implementation of several strategies/technologies to improve the ventilation systems:

- Installation of heat recovery systems, where possible
- CO$_2$ controls to ensure adequate indoor air quality
- Natural ventilation through time controlled actuators for opening/closing of windows
- Temperature, humidity and CO$_2$ sensors installed in about 2-3 selected rooms of each building to check the environmental quality
- Visualisation systems for indoor air quality (comfort-o-meter by Exhausto) in selected classrooms.

Some works were complex because of the inclusion of new systems in an existing structure, as an example in the gym, because of the limited space between the roof and the intermediate...
ceiling of the hall. There are four inspection chambers, the access is about 3 to 4 meter high and it takes place through a shift boss. Also the static load of the gym roof left no possibility of adding a heat recovery system.

Figure 3.7: Ventilation system inside the classrooms

**Italy**

The Plauto School in Cesena, Italy was naturally ventilated before energy retrofitting. The low insulation level and air tightness coupled with the manual operation of the windows did not cause severe discomfort conditions – covering both overheating in intermediate seasons and uncomfortable indoor air quality. However the two issues became relevant after the building renovation, with increased insulation levels and air tightness standards. A mechanical ventilation system with heat recovery was installed to feed the classrooms with adequate fresh air; other spaces, not continuously in use, remain provided with natural ventilation. Delocalised units and ducts, each covering 4 to 5 rooms were installed because of structural and architectural restraints: one unit, placed in the toilet false ceiling, for each corridor (flows ranging from 1,800 to 3,250 m$^3$/h). Figure 3.12 shows the main duct running in the corridor and the branches serving the individual classrooms. Silencers were mounted to keep noise at acceptable levels.
Norway

The Brandengen School in Drammen already had variable air volume ventilation systems with heat recovery (rotating heat exchanger) in two of its buildings, while no heat recovery was installed on the activity building’s ground floor and in the gym.

It should be noted that the performance of the ventilation system will be continuously monitored owing to the local and/or remote energy management systems installed by the buildings’ owners/managers in all the schools.

Conclusions

The quality of indoor air has a high influence on the health and wellbeing of occupants, in many cases for example in schools and buildings affected by traffic noise, window ventilation cannot comply sufficiently with air quality requirements.
To achieve the desired indoor air quality, a mechanical ventilation system is suitable, which provides filtered fresh air continuously and discharges exhaust air and contaminants and helps saving energy by recovering heat from exhaust air and by using energy efficient ventilation equipment.

CO₂ demand control ventilation is a real-time, occupancy-based ventilation control approach that can offer significant energy savings over traditional fixed ventilation approaches.

DCV is part of a building's ventilation system control strategy used to both control energy costs and to ensure sufficient ventilation. It may include hardware, software, and control strategy and is an integral part of a building's ventilation design.

The energy efficiency of ventilation systems depends on the heat recovery rate of heat exchangers and the electrical demand of the fans. The electrical efficiency of the ventilation system should be planned very carefully, otherwise the primary energy demand for ventilators could be higher than the primary energy savings of heat recovery.

To increase energy efficiency and comfort, it is therefore very important to adapt and control airflows different issues:

- Actual number of occupants (maximum, minimum number of occupants, presence/absence).
- Sufficient hygrothermal comfort in heating period.
- Energy demand in summer period and transition periods.
- Balance of incoming (with air-speed control) and outgoing air.
- A high filter quality.
- Fulfilling requirements for inspection, cleaning, control and maintenance of ventilation systems.

The building owner, architect and engineer, installer, commissioning agent and building inspector should work together to produce a good ventilation system.

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LIGHTING SYSTEMS

Introduction

The main goals of lighting design consist in providing the visibility required based on the task to be performed by providing an adequate illuminance level, achieving quality and aesthetic objectives and by minimising the negative effects of direct and reflected glare. At the same time, it is important to choose luminaires complimentary to the installation and with maintenance characteristics designed to minimise operational costs.

The recent lighting system concepts have to meet the functional and comfort requirements of building occupants. At present, important factors concerning lighting are energy efficiency, such as daylight use, individual control of light, quality of light, emissions during the life cycle, and total costs.

Lighting is a large and rapidly growing source of energy demand and greenhouse gas emissions. At the same time, the savings potential of lighting energy is high so that lighting can be considered a cost-effective way to reduce CO$_2$ emissions. To achieve energy savings, reducing CO$_2$ emissions, assuring high comfort levels to occupants of indoor environments the primary goal is to identify and to accelerate the widespread use of appropriate energy efficient high-quality lighting technologies and their integration with other building systems.

The impact of the electric lighting use on the overall energy performance in school buildings is a function of several architectural and technological parameters; however latitude and climatic conditions are among the most relevant variables. The high daylight availability in the southern and Mediterranean EU countries limits the electric lighting bill, which in turn is higher in central and Nordic countries for the opposite reason, especially in winter. Economic analyses, coupled to energy savings, give a more complete frame for the technology potentialities.

Brief technology description

Light can be categorised in two shades: a natural one produced by sun while the other is artificial light produced by electricity. Daylighting optimises natural sunlight entry into a building to minimise the need for artificial lighting. Energy-efficient lighting is the use of artificial light to achieve the optimal level of light at the lowest energy investment. The central concern associated with daylighting is the heat gain that can result when natural light is brought into a building during the cooling season, while the heat gain from natural light can be useful during the heating season. Proper sizing of the light to correspond with the needs of the location and the tasks that will be performed were found to be of primary relevance both from a health point of view and as an energy-saving strategy.

The primary goal to reach consists in supplying enough light with proper lighting distribution in space, with good spectral qualities and little or no glare, and at reasonable costs. To accomplish this, overhangs on windows, which are a primary means of daylighting, must be sized to prevent direct light (light that is in direct line to the sun) from entering except, where desired, in the heating season.

Daylighting

Daylighting is the controlled admission of natural light (direct sunlight and diffuse skylight) into a building to reduce electric lighting, saving energy and to ensure a direct link to the natural outdoor illumination. Daylight is a free and sustainable source of light and the supply of daylight is typically at its highest during the hours with peak electric energy loads. Usually, there is enough daylight to meet the demand for lighting of a building during most of the working hours. Moreover poor indoor natural lighting could be a cause of many of the health
and performance-related problems in indoor environments. This is the so-called ‘ill-lighting syndrome’ (the human physiological system is regulated by a circadian rhythm affected by natural lighting) which is a mechanism that can result in many different negative health/performance effects for individuals showing a dependence on environmental lighting. Daylighting is an effective way to both decrease your building’s energy use and make the interior environment more comfortable for people.

The level of permanent artificial lighting, which is necessary for an acceptable brightness balance between the levels of daylight artificial lighting, is directly proportional with the level of exterior daylight.

It is important how light is let into indoor environments without any undesirable side effects. The fenestration shape, size, spacing, glass selection and the location of windows in a building, must be carefully designed in such a way as to avoid the admittance of direct sun on task surfaces or in occupants’ eyes. Generally, buildings should be oriented east-west rather than north-south. This orientation lets you harness daylight and control glare consistently along the long faces of the building. It also lets you minimise glare from the rising or setting sun discovered to be better for daylighting and visual comfort. The side of the building facing the sun’s path (the equator-facing side) can generally be easily shaded with overhangs or light shelves.

Daylighting requires an integrated design approach to be successful, because it can involve decisions about the building form, siting, climate, building components (such as windows and skylights with particular attention to their orientation), lighting controls, and lighting design criteria. Carefully balanced heat gain and heat loss, glare control, and variations in daylight availability must be taken into account. Since daylighting components are normally integrated with the original building design, in general they should not be considered for a retrofitting project, so we focused the following description on artificial lighting that could be coupled with a daylight-responsive lighting control system.

**Artificial Lighting**

A lighting system is defined as an array of luminaires having a characteristic lighting distribution that can be divided into:

- **Direct lighting**: luminaires direct 90 to 100% of their output downward. The distribution may vary from widespread to highly concentrate depending on the reflector characteristics; reflected glare and shadows may be a problem
- **Semi-direct lighting**: the distribution is predominantly downward (60 to 90%) but with a small upward component; the upward component will tend to soften shadows and improve room brightness
- **General diffuse lighting**: downward and upward components of light from luminaires are about equal (each 40 to 60%)
- **Direct-indirect** is a special category within this classification for luminaires that emit very little light at angles near the horizontal distributing the light about equally in all directions
- **Semi-indirect lighting**: emits 60 to 90% of their output upward
- **Indirect lighting**: directs 90 to 100% of the light upward to the ceiling that becomes the primary source of illumination (shadows and glare will be virtually eliminated); these surfaces must have high reflectance to light on the work plane.

A lighting system comprises three main components:
- Lamps: devices that generate light
- Ballast/controller: connection between energy supply and light source (current transformer, starter device)
- Luminaires: lighting unit consisting of a lamp or lamps together with the parts designed to distribute the light, to position and protect the lamps, and to connect the lamps to the power supply (socket).

Lamp selection is based on efficacy (lumens per Watt), colour temperature, colour rendering index, life and lumen maintenance, availability, switching, dimming capability, and cost. Light sources are technical devices that convert usually electric energy into radiation - partly to light. Artificial light sources are categorised by the technology used to produce the light. The five most common light sources are as follows:

**Incandescent lamp**

Until a few years ago, the most common electric light bulb was the incandescent lamp which consists of a screw-in base that holds two wires attached to a coiled tungsten filament, and a glass enclosure that is filled with argon gas to reduce the evaporation of the tungsten and increasing the life of the bulb. An electric current carried through the wires heats the tungsten filament (characterised by a high melting point), causing it to glow. The working temperature of tungsten filaments in incandescent lamps is about 2700 K. Therefore the main emission occurs in the infrared region. Its relatively low energy efficiency and short lamp life has led to its progressive replacement by other more efficient types of lamps (such as the CFL). They are available in a variety of colours, shapes, sizes and wattages, their colour temperature is low, (2500-3000 K), so the light is warm and the colour rendering is excellent.

**Fluorescent lamps**

Fluorescent lights are a type of gas discharge lamp and are formed as a long thin glass cylinder with electrodes at either end that provide the electric connection. The tube contains argon and a small amount of mercury vapour at low pressure, (the inner surface of the glass is coated with fluorescent powders known a phosphors that react to ultra-violet radiation) (Figure 4.1). When electricity is passed through the vapour, it emits UV radiation that is converted to visible light by the phosphor. The majority of the emission (95%) takes place in the ultraviolet region. The final spectral distribution of emitted light can be varied by different combinations of phosphors. These kinds of lamps can only operate with the help of auxiliaries (ballasts, starters, luminaires and controls) which ensure the starting and the continuity of gas discharge.

The most efficient fluorescent tubes are T8 and T5 (T stands for tubular and the number refers to the diameter of the lamp in eighths of an inch). Their diameter being smaller than the older T12, T8 and T5 allow the light to be redirected in a more effective way also due to the use of electronic ballasts. These lamps work well in luminaires that provide the general ambient lighting for a space and are available in different shapes. The long and diffuse nature of these lamps provides excellent surface lighting. T5 has a very good luminous efficacy (100 lm/W) and optimal operating point at high ambient temperatures.
Compact fluorescent lamp

The compact fluorescent lamp (CFL), a variant of the fluorescent one, was designed as a more efficient replacement for the incandescent lamp. It is supplied with the same fixing system (screw or bayonet), and can be used in many light fittings designed for incandescent lamps, while pin-base models plug directly into ballasts (Figure 4.2). Due to their diffuse nature and small size, CFL lamps are used in recessed luminaires, wall- and ceiling-mounted fixtures, and even for track lighting and task lighting. CFLs use less energy and last much longer than conventional incandescent bulbs. However, they cost more to purchase and contain a small amount of mercury sealed within the glass tubing so that it is necessary to expand recycling and disposal options. The luminous efficacy of CFL is about four times higher than that of incandescent lamps, which makes it possible to save energy and the cost of lighting by replacing them with CFLs.
Discharge lamps

Discharge lamps work by starting an electric arc between two electrodes, which ionise the gases and allows a continuous energy transmission to flow between the conductors causing the filler gas to give off light (Figure 4.3). They can be divided into: *low pressure lamps* (e.g., Mercury vapour, metal halide); *high pressure lamps* (e.g., Sodium lamps), *high intensity discharge* (HID) (e.g., mercury, ceramic, sodium, xenon). These lamps have two envelopes. The inner quartz envelope is an arc tube. The radiation generated by the electric current through mercury vapour is only partly light, its invisible part is transformed into light by the fluorescent powder on the inside surface of the outer envelope. Mercury lamps need auxiliaries (ballast or starter-transformer) for their operation. They provide high luminous efficacy and are characterised by long life, resulting in the most economical light source available. HID makes it possible to use gas discharges (plasmas) to generate optical radiation predominantly in the form of single spectral lines. Discharge lamps generate light of a different colour quality, according to how the spectral lines are distributed in the visible range.

![Discharge lamp](http://weed-ellas.blogspot.it/2012/04/grow-lights.html)

Light emitting diode (LED)

Solid-state lighting (SSL) commonly refers to lighting with light-emitting diodes (LED). LEDs use semi-conductors (aluminium-gallium-arsenide) to convert electric energy directly into light and are highly efficient and long lasting. LED is a small chip of silicon treated with chemical elements that create a positive-negative interaction (Figure 4.4). The positive side contains electron holes, while the negative side contains free electrons. When connected to a power source, the holes and electrons are forced together, releasing energy in the form of a light photon. Modern LED components cover peak wavelength regions from the ultraviolet to the infrared region with spectral emission from the red to the yellow region of the visible spectrum. White LEDs can be realised by mixing the emission of different coloured LEDs or by the utilisation of phosphors. Phosphor-converted white LEDs are usually based on blue or ultraviolet LEDs. Unlike conventional light sources, which emit light in all directions, LEDs emit visible light in a very narrow spectral band and they can produce "white light". This is accomplished with either a red-blue-green array or a phosphor-coated blue LED lamp. LED lamps last 40,000 to 100,000 hours depending on colour.

Several parameters are used to characterise LEDs optically. The main parameters depending on the LED type (i.e., coloured or white LED) are the spectral power distribution (SPD), spatial light distribution, viewing angle, colour rendering index (CRI), correlated colour temperature (CCT), peak wavelength, dominant wavelength, luminous flux, luminous intensity and
luminous efficacy. The operation temperature influences the optical and electrical characteristics of an LED so that thermal management is an important aspect to be taken into account.

Theoretically, unlike all the other light sources an LED source can achieve a conversion efficiency of 100%. The luminous efficacy of a white light LED depends on the desired wavelengths and colour rendering index (CRI). LED-based lighting systems have an important advantage due to their easy controllability. Intelligent features combined with the inherent high energy-saving potential of LEDs are a strong competitive combination in a wide range of applications such as:

- Light bulbs
- Lanterns
- Streetlights
- Large-scale video displays
- Architectural lighting
- Light source for machine vision systems
- Motorcycle and bicycle lights
- Flashlights, including some mechanically powered models
- Emergency vehicle lighting
- Backlighting for LCD televisions and displays.

![Figure 4.4: LED device (http://www.lednews.org/)](http://www.lednews.org/)

Light sources can be characterised by different technical data. Table 4.1 provides an overview and a comparison of some of the performance and operating characteristics (efficacy, colour rendition, estimated operating lifespan etc.) of each lighting type. Colour rendition is quantified on a colour rendering index (CRI) scale of 1 to 100, where 100 CRI is equivalent to sunlight.

Incandescent lights have excellent colour rendition, but have the lowest efficacy and lifespan. Fluorescent lights are much more efficient and have a longer lifespan, but cannot match incandescent lamps in colour rendition. HPS lamps compare favourably to metal halides in efficacy and have a much longer operating life, but possess a very poor colour rendition. LED lights combine a long lifespan and good colour rendition but are still catching up on efficiency. As technology advances, the use of LEDs in a variety of applications should continue to grow.
Table 4.1 Technical characteristics of lighting systems

<table>
<thead>
<tr>
<th></th>
<th>Incandescent lamp</th>
<th>Fluorescent tube</th>
<th>CFL</th>
<th>HID</th>
<th>LED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminous flux</td>
<td>Φe(lm)</td>
<td>200-40,000</td>
<td>1,000-5,400</td>
<td>250-2,900</td>
<td>1,800-5,800</td>
</tr>
<tr>
<td>Colour temperature</td>
<td>T [K]</td>
<td>2,500-3,000 light is warm</td>
<td>2,900-6,500 K, light may be warm, neutral or cool</td>
<td>2,900-6,500 may be warm, neutral or cool</td>
<td>3,350-4,000 may be warm or neutral</td>
</tr>
<tr>
<td>Colour rendering</td>
<td>CRI [%]</td>
<td>1A</td>
<td>1A, 1B, 2A, 2B, 3</td>
<td>1A, 1B</td>
<td>3</td>
</tr>
<tr>
<td>Luminous efficacy</td>
<td>[lm/W]</td>
<td>6-20</td>
<td>50-75 for Φ 38 mm 70-95 for Φ 26 mm 95-105 for Φ 16 mm</td>
<td>36-65 with ballast 50-90</td>
<td>30-60</td>
</tr>
<tr>
<td>Life time</td>
<td>[hr]</td>
<td>750-1,500</td>
<td>7,500-15,000</td>
<td>8,000-10,000</td>
<td>8,000-20,000</td>
</tr>
<tr>
<td>Starting time</td>
<td>[s]</td>
<td>&lt; 0.1</td>
<td>1</td>
<td>1</td>
<td>2-5 min</td>
</tr>
<tr>
<td>Restarting time</td>
<td>[s]</td>
<td>&lt; 0.1</td>
<td>1</td>
<td>1</td>
<td>10 min</td>
</tr>
</tbody>
</table>

Note: Colour rendering: Very good: 1A 90-100; 1B 80-89; Good: 2A 70-79; 2B 60-69; Acceptable: 3 40-59

**Ballasts** are devices providing sufficient voltage to start the lamps and regulating the current for their operation. Since the lighted fluorescent tube has a low resistance, the ballast serves as a current limiter. This kind of lamps needs a starter too: a timed switch that allows current to flow through the filaments at the ends of the tube. The current causes the starter's contacts to heat up and open, thus interrupting the flow of current so that the tube lights.

**Luminaires** generally consist of lamps, lamp holders or sockets, ballasts or transformers (where applicable), reflectors to direct light into the task area, and/or shielding or diffusing media to reduce glare and distribute the light uniformly. An enormous variety of luminaire configurations exist. Luminaires direct lamp output to where it is needed, while shielding the lamp from the eyes at normal angles of view. Luminaires are classified according to the percentage of light output above and below the horizontal. The main types of luminaires can be classified in: recessed (lay-in troffers and downlights), suspended (indirect or direct/indirect), suspended high ceiling, surface-mounted luminaires.

**Integrated lighting Systems**

An integrated lighting system utilising both daylight and electrical lighting.

Being difficult to apply all the principles of natural lighting to existing buildings, integrated lighting systems can be usefully applied in combination with dedicated control systems.

An integrated lighting system usually consists of the following major elements:
- A daylighting system (providing natural light)
- An electric lighting system (providing artificial light, if required)
- A lighting control system (enhancing energy performance).
Lighting controls have the benefit of reducing energy use when lighting is not required. Daylight-responsive electric lighting controls are absolutely essential to any daylighting system. The controller regulates the level of artificial light by increasing/decreasing the level of daylight when the sensed daylight level is below/above a set threshold. No daylighting design will save any energy unless the electric lights are dimmed or turned off when there is sufficient illumination from daylight. Daylight-responsive lighting controls consist of continuous dimming- or stepped-ballasts in the light fixtures, and one or more photocells to sense the available light and to dim or turn off the electric lighting in response. Three types of controls are commercially available:

- Switching controls: on-and-off controls that simply turn the electric lights off when there is ample daylight
- Stepped controls: control individual lamps within a luminary to provide intermediate levels of electric lighting
- Dimming controls: continuously adjust electric lighting by modulating the power input to lamps to complement the illumination level provided by daylight.

As control requirements become more complex with increasing demand for flexibility and control strategies, control zoning becomes very important. In different controlled zones, one or more lamps are turned on and off by a single controller or allocated to a given control strategy depending on daylight levels and the position of different workplaces with respect to windows. If daylight is present, zoning should be delineated around daylight availability: one zone per row of luminaires mounted parallel to windows. In the case of side-lighting applications with vertical fenestration such as windows, these are daylight zones extending deeper into the space, controlled separately from primary daylight zones and other general lighting in the space. Such a capability requires the lighting to be divided into smaller zones, each assigned to a different conveniently located override switch. A critical decision is to establish lighting control zones, identifying lighting loads to be separately controlled.

When automated shading is provided to control glare and unwanted heat gain from daylighting, it would be necessary to coordinate daylighting controls with automated shading controls.

In addition to daylight controls, other electric lighting control strategies should be incorporated where they are cost effective, including the use of:

- Occupancy controls: using infrared, ultrasonic, or micro-wave technology, occupancy sensors respond to movement or object surface temperature and automatic turn-off or dim-down luminaries when rooms are left unoccupied. Vacancy sensors automatically turn the lights off after a predetermined period in which no human activity is sensed. Typical savings have been reported to be in the 10% to 50% range depending on the application
- Timers: these devices are simply time clocks that are scheduled to turn lamps or lighting off on a set schedule. If spaces are known to be unoccupied during certain periods of time, timers are extremely cost-effective devices.

Typical energy savings pay for control devices in approximately 3-7 years. This payback time makes lighting control an attractive energy-saving strategy.
Evaluation - advantages and disadvantages

Globally, almost one fifth of the total amount of electricity generated is consumed by the lighting sector. Lighting consumes about 19% of the total generated electricity (IEA 2010). It accounts for 30% to 40% of the total energy consumption in office buildings. The annual electricity consumption of lighting per square meter of the building varies between 20 to 50kWh/m², a (SEA 2007, STIL 2007). There is a trend in the international community to reduce the electricity consumption of lighting with new technology to below 10 kWh/m² per year. The possible ways to reduce electricity consumption for lighting include: lowest possible power density, use of light sources with high luminous efficacy, use of lighting control systems and utilisation of daylight. The quality of light must be maintained when installed power for lighting is reduced. In commercial buildings, electric lighting accounts for 35-50% of total electric energy consumption. The improvement in energy efficient lighting was to be a primary issue related to the need to reduce global energy consumption and the emissions of greenhouse gases. The energy savings from reduced electric lighting through the use of daylighting strategies can directly reduce a building’s cooling demand by an additional 10% to 20%.

When selecting from the wide array of new technologies, four major objectives have to be considered:

1. Provide the visibility required based on the task to be performed and the economic objectives.
2. Furnish high quality lighting by providing a uniform illuminance level, where required, and by minimising the negative effects of direct and reflected glare.
3. Choose luminaires aesthetically complimentary to the installation with mechanical, electric and maintenance characteristics designed to minimise operational expense.
4. Choose sustainable products that minimise energy use while achieving the visibility, quality and aesthetic objectives.

Traditional light source types except incandescent sources contain some level of mercury. These light sources should be recycled to avoid release of any mercury into landfills. The cost of recycling light sources should be included in any life-cycle cost analysis.

These main goals have been taken into account to evaluate benefits and drawbacks of each lighting technology considered.

LED is going to drive the electric lighting market in new and existing buildings, however a crucial issue in school buildings is the quality of light that LED and other sources provide in the built environment. Non energy issues (e.g. the quality of vision, the impact on the circadian cycle) need to be taken into account for the users and, in particular, for pupils and students in young age.

Advantages

**Incandescent lamps**

- Low initial cost
- Small size
- Excellent colour rendition
- Turns on instantly
- Not ambient temperature
- dependent
- No ballast requirement
- Variety of shapes
- Ease of dimming.

**Fluorescent lamps**
- Improved efficacy and longer life than incandescent lamps
- Efficacies for fluorescent lamps range anywhere from 50 to 100 lumens per watt
- Low surface brightness and heat generation (ideal for offices and schools).

**HID (high intensity discharge)**
- High efficacy
- Long lamp life
- Point-source characteristic for good light control.

**LEDs**
- High luminous efficacy (LEDs are developing fast and their range of luminous efficacies is wide): produce more light per watt than incandescent bulbs
- Can emit light of an intended colour without the use of colour filters which traditional lighting methods require
- The solid package of the LED can be designed to focus its light (no need of external reflectors)
- When used in applications where dimming is required, LEDs do not change their colour shade as the current passing through them is lowered
- LEDs are ideal for use in applications that are subject to frequent on-off cycling, (unlike fluorescent lamps that burn out more quickly when cycled frequently, or HID lamps that require a long time before restarting)
- LEDs light up very quickly (could achieve full brightness in microseconds)
- LEDs do not contain mercury
- Physically robust
- Long lifetime expectancy (with proper thermal management)
- Contains no mercury
- Excellent low ambient temperature operation
- New luminaire design possibilities
- Possibility of changing colours
- No optical heat on radiation.

**Disadvantages**

The environmental impacts of lighting are caused by the energy consumption of lighting, the material used to produce lighting equipment, and the disposal of used equipment. Emissions during the production of electricity and also as a result of the burning of fuel in fuel-based lighting (the most wide-spread in developing countries) are responsible for most of the lighting-related greenhouse gas emissions. Hazardous materials (e.g. lead, mercury) used in the lamps and ballasts, if not disposed of properly, can cause harmful impacts on the environment.
Incandescent lamps
- Low efficacies
- High infrared output
- High bulb wall
- High temperature
- Short life
- Voltage sensitive.

Fluorescent lamps
- Large size for the amount of light produced
- Light control more difficult, which results in a diffuse, shadowless environment.

HID
- Need for a ballast to regulate lamp current and voltage as well as a starting aid
- Delay in restarting after a momentary power interruption.

LEDs
- LEDs are currently more expensive per lumen, on an initial capital cost basis, than more conventional lighting technologies (found to be convenient in terms of total cost of ownership including energy and maintenance costs)
- LED performance largely depends on the ambient temperature of the operating environment (overheating of the LED package, eventually could lead to device failure)
- LEDs must be supplied with the correct current. This can involve series resistors or current-regulated power supplies
- Blue LEDs and white LEDs are now capable of exceeding safe limits of the so-called blue-light hazard causing (not respecting eye safety specifications)
- High price
- Low luminous flux / package
- CRI can be low
- Risk of glare due to high output with small lamp size
- Need for thermal management
- Lack of standardisation.

Market penetration and utilisation
The global lighting market is impacted by the macroeconomic situation which is influencing new construction and consequently the number of new lighting installations. Currently there is a global trend to phase out inefficient light sources from the market through legislation and voluntary measures. These regulations will effectively remove incandescent lamps, mercury lamps and certain inefficient fluorescent and HID lamps from the European market. Energy efficiency regulations and greater energy awareness are redefining future lighting products. Furthermore government actions limiting certain energy sources will result in additional demand for energy efficient products such as LEDs.

Lighting still continues to be one of the largest end-uses of electricity. Currently, more than 33 billion lamps operate worldwide, consuming more than 19% of the global electricity consumption. Lighting uses a quite smaller fraction in the European Union (14%). Almost 40% of global lighting electricity is consumed by the commercial/tertiary sector, the industrial and
the residential sectors follow with 25% and 21% respectively, the outdoor sector represents 15% of the total electricity consumption for lighting as illustrated in Figure 4.5 (IEA, 2006).

![Pie chart showing electricity consumption for lighting in Europe distributed on sectors in 2007](image)

**Figure 4.5: Electricity consumption for lighting in Europe distributed on sectors in 2007 [JRC Scientific and Policy Reports 2012]**

A clear distinction needs to be made translating economic forecasts between the luminaire and the lamp markets. The market for luminaire and lighting system control components is predominantly driven by new installations while the lamp market is mainly driven by replacements and it depends almost solely on the number of installed sockets and the lifetime of the technologies in place. With a small volume of new buildings, major energy savings on lighting can only be realized by retrofitting the existing building stock.

With better use of natural lighting and adoption of highly efficient lamp technologies, building’s energy consumption for lighting could be reduced by 40% in 2050 compared with current levels. Incandescent lighting in all regions of the world is progressively replaced with more efficient lighting technologies, including best available fluorescent lighting and SSL. Variable controls and sensors should be added to existing lighting systems via retrofitting programmes. Requirements to lighting power intensity in new buildings should be added to all building codes and comprehensive retrofitting programmes globally. Figure 4.6 shows a forecast by product category for the global lighting market between 2011 and 2020: green traditional products will have a market volume of around 37 billion euros in 2016 that will be reached by a broad application of LEDs that would dramatically decrease energy consumption levels.
Figure 4.6: Global lighting market outlook from 2011 to 2020, by product category (in billion euros): (http://www.statista.com/statistics/216379/global-lighting-market-trend-by-energy-efficient-products/)

The accelerating drop in LED prices have affected long-term forecasts of the size of the lighting market so that it has been calculated that the LED share of general lighting would be 45% in 2016 and almost 70% in 2020 (McKinsey 2012).

Further technological developments on electroluminescent light sources are forecasted. These developments involve improvements in the device efficiency, light output and cost of lumens per package. The application varieties impose a clear demand for the design of controllable LED drivers. At luminaire level, controllers and drivers are becoming indispensable components. As the LED technology continues to evolve, the possibilities for new and more intelligent products or systems based on intelligent controllers and drivers is expected to grow.

**Energy and economic performance**

Electricity uses for artificial lighting play a relevant role in the total energy uses of school buildings, especially in the northern countries, due to the daylighting availability during the winter season. The replacement of old electric lighting systems with new and more efficient technologies are following explored.

The impact of the technology on the performance in school buildings to be renovated was screened in a particular frame work of the project dedicated to technology screening. The whole calculation set can be downloaded from the project website (http://www.school-of-the-future.eu/index.php/project-results/technology-screening). In the following some exemplary outcomes are presented, including energy, environment and economic issues. The results are achieved under very different boundary conditions, in terms of climatic conditions, reference building characteristics, energy prices, primary energy factors and performance and investment costs of the selected technologies.

In this framework the following results provide a general view of the technology application in improving the performance of existing school buildings in each country rather than comparing the technology impact among different countries. According to this assumption the results are presented separately for each country. The selected climatic zones of the participating countries...
are: Denmark (Copenhagen), Germany (Potsdam), Italy (Turin for the north, Terni for the centre and Taranto for the south) and Norway (Oslo).

The impact of this single energy measure is calculated based on a reference building configuration. The reference school building has a typical layout that consists of three storeys with classrooms on one side and a corridor on the other, as represented by the pictogram in Figure 4.7.

![Figure 4.7: Pictogram of the reference school building floor](image)

The reference lighting systems consist of traditional T8 fluorescent lamps with only a manual control. The retrofitting technologies taken into account consisted of installing better light-emitting technology, better control systems (occupancy and daylight-dependent dimming) and a possibility for control of the lighting system depending on its location within the room – near the windows or far from the windows – so-called zoning. In the calculations, this complete package is therefore analysed. Often this is done as one package because the marginal cost of including the control and zoning is rather limited when a new lighting system is installed.

The efficient lighting systems considered are new light tubes – T5, fluorescent light lamps. A continuous automatic dimming and 2-zone control instead one such as in the reference case have been analysed. To be noted that several approaches can be followed in this case, which include, as examples, advanced solutions for lamps (e.g. LED) and integrated management of the artificial lighting with BEMS (Building Energy Management Systems). As a consequence, the following results should be considered as a specific case study rather than a general assessment of the technology, which needs more detailed and specific analyses.

Technical and economic parameters relating to lighting measure adopted are summarised in Table 4.2.

<table>
<thead>
<tr>
<th>Country</th>
<th>Treated floor area m²</th>
<th>Max Power W/m²</th>
<th>Min Power W/m²</th>
<th>Max Light Level Lux</th>
<th>Min Light Level Lux</th>
<th>Sensitivity Control Lux above required light level</th>
<th>N° zones controlled</th>
<th>Investment €</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark</td>
<td>3,000</td>
<td>4.0</td>
<td>0.8</td>
<td>216</td>
<td>43</td>
<td>100</td>
<td>2</td>
<td>89,713</td>
</tr>
<tr>
<td>Germany</td>
<td>3,000</td>
<td>4.0</td>
<td>0.8</td>
<td>216</td>
<td>43</td>
<td>100</td>
<td>2</td>
<td>107,254</td>
</tr>
<tr>
<td>Italy</td>
<td>1,453</td>
<td>11.0</td>
<td>0.8</td>
<td>500</td>
<td>43</td>
<td>100</td>
<td>2</td>
<td>14,637</td>
</tr>
<tr>
<td>Norway</td>
<td>3,000</td>
<td>4.0</td>
<td>0.8</td>
<td>216</td>
<td>43</td>
<td>100</td>
<td>2</td>
<td>89,713</td>
</tr>
</tbody>
</table>

Energy savings due to lighting systems application show saved electricity and total primary energy consumption as the economic parameters are planned in comparison with the reference buildings.
Following tables show energy savings (both final and primary saved energy are presented), environmental (CO₂ reduction emissions) and financial (simply payback time and net present value) results for Denmark (Table 4.3), Germany (Table 4.4), Italy (Turin, Terni, Taranto) (Tables 4.5) and Norway (Table 4.6).

The table 4.3 presents the results for the Danish reference school. The measure provides a primary energy saving of 25 kWh/m² per year with a payback time (PBT) of about 10 years. The investment at the end of the life cycle will provide a positive net present value (NPV) of 38€/m². The measure is hence significant in a technical and financial perspective.

Table 4.3: Denmark: Energy and economic results

<table>
<thead>
<tr>
<th>Results</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final energy (electricity)</td>
<td>[kWh/m²]</td>
<td>10.3</td>
</tr>
<tr>
<td>Primary energy (electricity)</td>
<td>[kWh/m²]</td>
<td>25.8</td>
</tr>
<tr>
<td>CO₂ reduction</td>
<td>[kg/m²]</td>
<td>3.5</td>
</tr>
<tr>
<td>Investment/saved energy</td>
<td>[€/(kWh/m²) year]</td>
<td>1.2</td>
</tr>
<tr>
<td>Payback time</td>
<td>[years]</td>
<td>10.3</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>[€/m²]</td>
<td>38.1</td>
</tr>
</tbody>
</table>

The table 4.4 presents the results for the German school. Primary energy savings are close to 10 kWh/m² per year, in this case the high installation cost and the moderate climatic conditions lead to a 30 years payback time, which in turns leads to a negative NPV (-7 €/m²). As expected the investment to saved energy ratio is relevant: 3.6 €/(kWh/m² year).

Table 4.4: Germany: Energy and economic results

<table>
<thead>
<tr>
<th>Results</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final energy (electricity)</td>
<td>[kWh/m²]</td>
<td>4.1</td>
</tr>
<tr>
<td>Primary energy (electricity)</td>
<td>[kWh/m²]</td>
<td>9.8</td>
</tr>
<tr>
<td>CO₂ reduction</td>
<td>[kg/m²]</td>
<td>2.7</td>
</tr>
<tr>
<td>Investment/saved energy</td>
<td>[€/(kWh/m²) year]</td>
<td>3.6</td>
</tr>
<tr>
<td>Payback time</td>
<td>[years]</td>
<td>29.1</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>[€/m²]</td>
<td>-6.8</td>
</tr>
</tbody>
</table>

The results for the Italian reference building are reported in table 4.5. It can be noted that energy indicators are practically the same for Turin and Terni, and slightly lower for Taranto, where the sunny climatic conditions reduce the number of hours in which the artificial lighting has to be switched on. The primary energy is between 8 and 9 kWh/m² per year for the three localities; however, the favourable economic conditions lead to positive NPVs, ranging from 10 to 12 kWh/m² per year with a low investment to saved energy ratio (about 0.5 for the three localities). The limited economic benefit of the measure can also be inferred by the PBT, ranging between 10 and 12 years.
Table 4.5: Italy: Energy and economic results

<table>
<thead>
<tr>
<th>Results</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TURIN</td>
<td></td>
<td></td>
</tr>
<tr>
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<tr>
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</tr>
<tr>
<td>CO₂ reduction</td>
<td>[kg/m²]</td>
<td>1.8</td>
</tr>
<tr>
<td>Investment/saved energy</td>
<td>[€/(kWh/m²) year]</td>
<td>0.5</td>
</tr>
<tr>
<td>Payback time</td>
<td>[years]</td>
<td>12.8</td>
</tr>
<tr>
<td>Net Present Value</td>
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</tr>
<tr>
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<td>[kg/m²]</td>
<td>1.8</td>
</tr>
<tr>
<td>Investment/saved energy</td>
<td>[€/(kWh/m²) year]</td>
<td>0.5</td>
</tr>
<tr>
<td>Payback time</td>
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<tr>
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<td>[€/m²]</td>
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<tr>
<td>CO₂ reduction</td>
<td>[kg/m²]</td>
<td>1.6</td>
</tr>
<tr>
<td>Investment/saved energy</td>
<td>[€/(kWh/m²) year]</td>
<td>0.6</td>
</tr>
<tr>
<td>Payback time</td>
<td>[years]</td>
<td>14.3</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>[€/m²]</td>
<td>9.8</td>
</tr>
</tbody>
</table>

The table 4.6 presents the results for the Norwegian reference school. The measure provides a primary energy saving of 30 kWh/m² per year with a payback time (PBT) of about 27 years and with an investment to saved energy ratio of 1 €/(kWh/m²) per year, which is sufficiently low. The measures is penalised by the low cost of electricity in the country, as inferred by the high PBT (close to 27 years), which causes a negative NPV.

Table 4.6: Norway: Energy and economic results

<table>
<thead>
<tr>
<th>Results</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final energy (electricity)</td>
<td>[kWh/m²]</td>
<td>12.2</td>
</tr>
<tr>
<td>Primary energy (electricity)</td>
<td>[kWh/m²]</td>
<td>30.6</td>
</tr>
<tr>
<td>CO₂ reduction</td>
<td>[kg/m²]</td>
<td>4.2</td>
</tr>
<tr>
<td>Investment/saved energy</td>
<td>[€/(kWh/m²) year]</td>
<td>1.0</td>
</tr>
<tr>
<td>Payback time</td>
<td>[years]</td>
<td>26.7</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>[€/m²]</td>
<td>-3.6</td>
</tr>
</tbody>
</table>

It is important to emphasise that the impact of lighting systems in retrofitting buildings cannot be addressed only in energy and economic terms, since it improves the environmental quality in a critical environment like a classroom with pupils. The right system depends strongly on the required minimal and maximal indoor illuminance rate, and outdoor illuminance levels.
Examples of applications in the School of the Future

The electric lighting was addressed in the School of the Future demonstration buildings, being this energy service relevant especially in the central and Nordic European countries, due to the limited daylighting contribution during the winter season. Different solutions were explored.

Denmark

The lighting systems in the class-rooms were quite efficient and a replacement in all classrooms was not significant in terms of energy savings. However, the municipality was interested in getting experiences with new (LED) lighting systems and therefore it was planned to carry out a test of two different LED systems in two classrooms.

Figure 4.8: The new circular LED lamps in the classrooms and in the east-corridor.

After the retrofit the lamps in the classrooms are controlled by advanced control systems based on presence and daylight sensors. Two classrooms were selected to test advanced solutions. In the two tests classes new white ceilings have been mounted and the electrical wiring changed to allow for the mounting of the new fixtures. Two different types LED fixtures are installed: square and round fixtures. They have daylight control and also the lights at the smart boards are regulated automatically. The black board lighting has also been changed to LED light.

In the corridors, there was a strong need for improved electric lighting and it has therefore been decided to upgrade the lighting levels to that of a classroom in order to provide good quality light for the use of the corridors as extended teaching areas. New LED lamps have been installed in the corridors. They are controlled by daylight sensors divided in three separately controlled rows.

Germany

In most areas, T8 compact fluorescent lamps (CFL) were installed. Newer T5 CFL’s only existed in the gym. The installed power was reduced to the required minimum of the national standards by simply taking out unnecessary lamps. No controls were installed, except for the outdoor lights in the entrance area which are switched on at dusk and switched off at 11 pm. The retrofitting of the lighting system includes a continuous automatic dimming control with the installation of daylight detection controls (staircases) and presence detectors (classrooms and staircases). Old T8 compact fluorescent lamps (CFL) have been replaced with T5 CFLs. Conventional ballasts have been replaced with electronic ballasts.
Norway

During the renovation the lighting system was modernised with T5 low energy lighting fixtures and presence detectors in all classrooms, larger occupied zones and corridors.

Conclusions

Lighting is a large and rapidly growing source of energy demand and greenhouse gas emissions. At the same time, the savings potential of lighting electricity is high even with the current technology, and there are new energy efficient lighting technologies coming on the market. The total lighting-related carbon dioxide emissions were estimated to be about 7% of the total global CO₂ emissions from the consumption of fossil fuels. It is important to search for technological lighting solutions which meet human needs with the lowest impact on the environment during their life cycle. The environmental impacts of lighting include production, operation and disposal of lamps and related materials.

There is significant potential for improving the energy efficiency of old and new lighting installations even with the existing technology by the following measures:

- the choice of lamps: incandescent lamps should be replaced with CFLs, infrared coated tungsten halogen lamps or LEDs, mercury lamps by high-pressure sodium lamps, metal halide amps, or LEDs
- the use of controllable electronic ballasts with low losses
- the lighting design: the use of efficient luminaires and localised task lighting
- the use of daylight: the control of light with manual dimming, presence sensors, and dimming
- the use of high efficiency LED-based lighting systems.

Through professional lighting design, energy efficient and high quality lighting can be reached. Better lighting quality does not necessarily mean higher consumption of energy. While it is important to provide adequate light levels for ensuring optimised visual performance, there are always light levels above which a further increase in the light level does not improve performance. The use of lighting control systems, based on presence detection and the integration of electric light with daylight, can lead to substantial energy savings. New technologies such as LEDs offer high flexibility in the control of light spectra and intensities, which enhance their attractiveness besides their growing luminous efficacy.

Electric lighting is one of the major energy consumers and particularly in school buildings where it strongly affects visual performance and visual comfort by aiming to maintain adequate, appropriate illumination while controlling reflectance and glare.

Improved global building design can also offer significant potential to reduce the demand for lighting in buildings, through building orientation and advanced fenestration technologies such as dynamic windows.

Without a palpable change in lighting quality, a market shift from inefficient incandescent lamps to CFLs would cut global electricity demand for lighting by 18% (IEA 2006). The waste of light can also be readily reduced by the use of time-scheduled switching, occupancy sensors and daylight-responsive dimming technologies, all of which are mature and fully proven techniques with high savings returns. For the near future, solid-state lighting is emerging as a promising lighting technology.
Literature and references

- HIS Technology Lighting & LEDs Team - “Top Lighting and LEDs Trends for 2015”
- IEA Transition to Sustainable Buildings Strategies and Opportunities to 2050
- JRC Scientific and Policy Reports 2012
- Prof. Majoros, András, Budapest University of Technology and Economics Faculty of Architecture, Department of Building Energetics and Services: Artificial Lighting – www.egt.bme.hu
PHOTOVOLTAIC SYSTEM

Introduction

Photovoltaics (PV) is a renewable energy technology that converts solar radiation directly and instantaneously into electricity. The technology went through an impressive market penetration during the past years owing to favourable financial incentive mechanisms and the easy integration in existing buildings. Even though the technology is well established, it is still important to portray its potential within the framework of the FP7 EU Project School of the Future, for several reasons: PV technologies alternative to existing ones are still developing, promising higher efficiencies and lower costs; building integration is gaining interest for the architectural integration; electricity trends show a constant increase in the non-residential sector.

Costs have dramatically decreased in the past years and, even though the financial mechanism are coming to an end in most European countries, the technology deserves attention due to the growing number of energy supply systems that utilises electricity as an energy source, e.g. heat pumps.

School buildings present general favourable conditions for the PV installation. They are limited in height (generally few floors), but larger in footprint surface; this implies, in general, the presence of a relevant roof surface, suitable for the installation of PV plant. The technology potentialities need to be assessed according to the solar radiation availability through the year or the building operation period, as well as the installation costs and eventual subsidy schemes.

Brief technology description

PV gets its name from the process of converting light (photons) to electricity (voltage), which is called the PV effect. Photovoltaic cells are made of at least two layers of semiconducting material (sandwiched together in the cell). The first layer has a positive charge; the second layer has a negative one. When sunlight strikes the cell, the semiconducting material absorbs photons from the light. This process frees electrons from the negative layer to move to the positive layer, see Figure 5.1. The continuous flow of electrons constitutes an electric current, which can be captured in a circuit connecting the two layers. The cell does not “use up” its electrons and loose power. It is just a converter, changing one kind of energy (sunlight) into another (flowing electrons).

![Figure 5.1: Principle of electricity generation by PV cells (Apec Virtual Center for Environmental Technology Exchange: Photovoltaic Generation Technologies)](image-url)
The most common solar cell material is crystalline silicon. PV cells could be made of silicon in a single crystal state (high-purity silicon/high efficiency), polycrystalline silicon (less efficient/less expensive), amorphous silicon (not crystalline structure/high economic advantages) - see Figure 5.2. Lifetime of conventional PV technologies is at least 20 years.

Figure 5.2: Typical mono, polycrystalline and amorphous silicon cell (Pak Agro Tech: Types of Solar Standard Panels)

Second-generation solar cells are called thin-film solar cells because they are made from amorphous silicon or non-silicon materials such as cadmium telluride (CdTe), copper indium diselenide (CIS), gallium arsenide (GaAs) and amorphous silicon. Thin-film solar cells use layers of semiconductor materials only a few micrometres thick. Because of their flexibility, thin-film solar cells are found to be ideal for building-integrated PV products such as rooftop shingles and tiles, building facades, or glazing for skylights. Life span of such products ranges between 12 and 20 years according to the specific technology.

Third-generation solar cells are made from a variety of new materials including: solar inks printed on aluminium foils with conventional printing press technologies, solar dyes and conductive plastics. Organic photovoltaic (OPV) cells are low-cost, use easy process techniques, and are light-weight alternatives to inorganic photovoltaic cells. Low power conversion efficiency is a key factor that currently hinders their commercialisation. Almost all organic photovoltaic cells have a planar layered structure, where the organic active layer(s) is (are) sandwiched between two different electrodes. One of them must be transparent. A transparent conductive oxide (TCO) is used, usually indium tin oxide (ITO). The other electrode is often aluminium. A structure and a sample of the technology are shown in Figure 5.3. Multi-junction solar cells or tandem cells are solar cells containing several p-n junctions. This is the new frontier, but it is still far from being marketable and one of the main issue is the lifetime of the product; it is claimed that for vert low cost PV systems and 5 years lifetime might be acceptable, even if for most application the target is a lifetime equivalent to that of conventional PV (at least 20 years).

Figure 5.3: Organic PV cell structure (Solar Server: Solar Report 2007)
PV systems are made up of several photovoltaic solar cells (about 40 cells) connected together to form larger units called modules which, in turn, can be connected to form even larger units called arrays that are connected to produce more power. The number of arrays depends on the plant power (Figure 5.4).

![Figure 5.4: PV systems: Kildeskovshallen - Gentofte Denmark (Aagesen Vickie, Cenergia)](image)

The flat-plate PV arrays can be mounted at a fixed tilt angle facing south or on a tracking device to point toward the sun (movement along one or two axes). Concentrated PV (CPV) Systems use plastic lenses or mirrors to concentrate sunlight onto a very small surface of high efficiency PV material (thus reducing cell costs), and increasing the efficiency of the cells. CPV systems require sophisticated tracking devices in order to ensure accurate beam radiation focusing.

Photovoltaic plants can be categorised in:

**Stand-alone (or off-grid)** plants operate independently of the electric utility grid. PV panels do not store energy and can generate electricity only during daylight hours. Storage batteries are required to ensure a continuous electricity supply.

**Grid-Tied** solar systems are wired parallel to the utility grid lines. Whenever the wattage generated by the PV panels is surplus to household requirements, the grid-tie inverter sends the surplus to the utility grid. This is good for just taking down the electric bill, or for selling back extra energy to the company (net metering). Some Grid-tied systems also use batteries. This method is used to provide backup power for a home during power outages on the utility grid.

The electricity generated by photovoltaic panels is direct current. This means that it is necessary to install an inverter that change the direct current (DC) produced by solar panels into the useable alternating current (AC) needed to run a building. Inverters play a crucial role in any solar energy system. There are a few different options when using solar inverters. An off-grid inverter changes the current from the batteries into useable current. Grid-tied inverters are inverters that connect to the utility grid (see Figure 5.5).

A good inverter needs to be able to deliver clean energy without overheating or shutting down. When selecting a solar inverter for your system you'll need to take into account how much power you're looking to generate, the size of the building, energy use changes through time and the type of solar panels used in the system. Also, inverters have to match the voltage of energy system.
Cable management is one of the most important aspects of the safety and longevity of every photovoltaic (PV) system. Since the equipment is installed outdoors the electrical conductors must be rated for sunlight resistance and be supported and secured properly. Solar cables are designed to be UV resistant and weather resistant. It can be used within a large temperature range and are generally laid outside. Care shall be taken to provide sufficient mechanical protection for exposed cables (Figure 5.6).

**Photovoltaic system performance**

The performance of photovoltaic systems depends on the performance of its individual components (arrays, cells, inverters) and on the orientation and tilt of the PV panels.

PV module performance is measured with peak Watt ratings (maximum power of a PV module under laboratory conditions), or at a nominal operating cell temperature (more realistic), or considering the whole day rather than "peak" sunshine hours. Typical efficiencies are shown in Table 5.1.

Orientation and tilt are probably the most important factors affecting solar PV system efficiency. Typically, fixed PV arrays should be tilted toward the sun’s “average” elevation (equal to the latitude of the array’s location) maximising annual energy production.

### Table 5.1: Typical efficiencies for PV systems

<table>
<thead>
<tr>
<th>Cell material</th>
<th>Module efficiency</th>
<th>Surface area required for 1 kWp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monocrystalline</td>
<td>15-17%</td>
<td>7 m²</td>
</tr>
<tr>
<td>Polycrystalline</td>
<td>12-14%</td>
<td>8 m²</td>
</tr>
<tr>
<td>Thin Film</td>
<td>10-11%</td>
<td>10 m²</td>
</tr>
</tbody>
</table>

**Photovoltaic building integration**

A building integrated photovoltaic (BIPV) system consists of integrating PV modules into the building envelope, merging architecture and energy needs. By simultaneously serving as building envelope material and power generator BIPV systems can provide savings in materials and electricity costs. In this way, the incremental cost of photovoltaics is reduced and its life-cycle cost is improved.

BIPV is able to fulfil several functions:

- Weather protection
• Heat insulation
• Sun protection
• Noise protection
• Control of daylight.

BIPV can be applied to:

• Roofs (flat and pitched roofs): a way to integrate PV is to use PV shingles or PV tiles.
• Exterior walls: PV modules can be added to existing walls or be an integral part of the building facade also constituting a ventilated facade.
• Semi-transparent facades providing a filtered vision to the outside.
• Skylights: PV elements provide both electricity and light to the building.
• Shading systems: PV modules of different shapes can be used as shading elements (horizontal or vertical, fixed or mobile) above windows or as part of an overhead glazing structure. PV shading systems may also use one-way trackers to tilt the PV array for maximum power while providing a variable degree of shading.

The BIPV system design must optimise some aspects such as:

• Minimising the effects of shading over the PV array
• Optimising the orientation of PV panels
• Checking the effects of temperature on PV cells’ efficiency and on comfort parameters (PV conversion efficiencies are reduced at increased operating temperatures)
• Ensuring compliance with requirements to thermal insulation, waterproofing, air tightness, sound insulation, fire resistance
• Safety design
• Predicting maintenance operations.

Figure 5.8: BIPV on a tilted roof (Arch. A. Scognamiglio)
Hybrid PV solar thermal (PVT) systems are capturing and utilising the solar thermal resource developed through the heating of the modules and can be useful in cold climates for pre-heating of the incoming ventilation air rate. Some examples are presented in Figure 5.8.

Evaluation - advantages and disadvantages

PV need to be considered as an integral part of the energy saving strategy during the building design process. There should be a good match between the building’s energy demand pattern and the energy available from the PV array.

Silicon and silver are the predominant raw materials for a major segment of crystalline silicon PV. From a resource perspective, silicon and silver availability is not an issue at all due to their high concentrations in specific minerals which are typically mined as target-products.

Environmentally, PV have the significant advantages of producing no pollutant emissions in use and, by replacing grid-generated electricity with solar energy used mainly on site, of reducing CO$_2$, NO$_x$ (nitrogen oxides) and SO$_x$ (SO$_2$ and SO$_3$) emissions. Energy is, of course,
required for their production, but the energy payback period (the time required for the PV installation to produce as much energy as is required for its production) is in the order of 5 to 7 years.

Advantages

- Unlimited resource of solar energy
- Available in all regions of the world
- Modularity: from milliwatts in consumer products to gigawatts in utility-scale power stations
- No air emissions, no waste production during operation
- Virtually no maintenance
- Proven technical lifetime of 30 years: manufacturers generally guarantee module outputs of 80% of the nominal power for 20 – 25 years
- PV can be applied practically on all building envelope elements (roofs and facades, with difference in the energy production efficiency).

Disadvantages

- For some of the current PV technologies, the availability of material may become an important topic.
- A shortage of a critical material of a given PV technology may cap its long-term growth potential.
- An even more severe disadvantage would be caused by an increase of its price and production cost.
- Integration on existing buildings can be an issue for the system efficiency and the architectural impact, but not all existing buildings have the best orientation and sloping of roofs to an optimal placing of the PV system: so the PV integration should be carefully evaluated each time under specific conditions.

Market penetration and utilisation

The world’s cumulative PV capacity reached the 100 GW installed electrical power mark, saving each year more than 53 million tons of CO₂. During 2013, global solar installations rose to 8.5 GW up by 20% from 7.1 GW in the first quarter of the year.

Under a business-as-usual scenario, the global annual market could reach 48 GW in 2017, and in a policy-driven scenario it could be as high as 84 GW in 2017 (EPIA forecast). Europe was found to be a leader in PV development for almost a decade as a result of a few countries being supported by ambitious political commitments. The European PV market, mainly characterised by small roof-mounted installations, is dominated by: Germany, Italy, France and UK. The continent’s annual capacity has progressed from 1 GW in 2003 to 13.6 GW in 2010 up to 22.4 GW in 2011 decreasing to 17.2 in 2012. The cumulative capacity is presented in Figure 5.11.
The impressive results in PV European markets depend on different policy drivers and public support programmes for renewable energy as well as national electricity markets. Until now, the European solar market has been largely policy-driven and in many countries, growth has depended on financial support from the government.

An essential driver for spreading PV technology is feed-in tariffs, which is a monetary reward to the customer producing PV electricity, and the rate is usually higher than the standard rate per kWh that the customer would pay for electricity. The use of feed-in tariffs and the rapid decrease in the cost of PV systems has increased the profitability of investments. These schemes take advantage of net metering, which in turn calls for bi-directional electricity meters. According to this scheme, the owners of PV systems can “store” excess generated electricity in the grid and then consume it later at zero cost.

PV module prices have decreased by 80% and the costs of electricity generated by PV modules have dropped to less than 0.05 €/kWh. Figure 5.12 shows how the technology will become even more cost-effective and competitive across the continent in the different market segments by 2020. The graph shows the cost evolution for different segments, with an associated average size of the installed power: utility (with ground mounted plants sized in Megawatt); industrial (hundreds of kilowatt rooftop mounted); commercial (hundred kilowatt roof top mounted); residential, with few kilowatt mounted on the building roof.

PV system prices are expected to fall from up to 2.31 €/W in 2012 in the residential segment to as low as 1.30 €/W in 2022.
In this context, some barriers hampering European PV installations exist and can be grouped into four main categories:

- Barriers of permitting procedures are often the most severe obstacles to be tackled by a PV system developer.
- Barriers related to grid connection rules and technical standards criteria defined by grid operators and electricity market regulators characterised by a lack of clarity, transparency and uniformity in rules and standards.
- Barriers in grid connection procedures involved with both the initial grid connection permit and the final grid connection phases: they are lengthy; they involve an exaggerated number of different authorities and are characterised by high cost when the costs of grid upgrades is transferred to the PV developer.
- Barriers related to grid capacity issues occur when the development of the grid infrastructure is not properly planned.

**Energy and economic performance**

As previously outline: the improvement of the system performances, the easiness of installation and the financial incentives were among the main reasons of the high market penetration of the technology, which is seen today as one of the first measure to undertake in energy renovation of buildings.

The impact of the technology on the performance in school buildings to be renovated was screened in a particular frame work of the project dedicated to technology screening The whole calculation set can be downloaded from the project website ([http://www.school-of-the-future.eu/index.php/project-results/technology-screening](http://www.school-of-the-future.eu/index.php/project-results/technology-screening)). In the following some exemplary outcomes are presented, including energy, environment and economic issues. The results are achieved under very different boundary conditions, in terms of climatic conditions, reference building characteristics, energy prices, primary energy factors and performance and investment costs of the selected technologies.

![PV System Prices Evolution (€/W)](image-url)
In this framework the following results provide a general view of the technology application in improving the performance of existing school buildings in each country rather than comparing the technology impact among different countries. According to this assumption the results are presented separately for each country. The selected climatic zones of the participating countries are: Denmark (Copenhagen), Germany (Potsdam), Italy (Turin for the north, Terni for the centre and Taranto for the south) and Norway (Oslo).

The impact of this single energy measure is calculated based on a reference building configuration. The reference school building has a typical layout that consists of three storeys with classrooms on one side and a corridor on the other, as represented by the pictogram in Figure 5.13.

The data relating to PV dimensions and efficiency for all the countries are summarised in Table 5.2. Column 3 shows the installed PV panel surface. In column 4 “kilowatt peak” stands for the output power achieved by a solar module under full solar radiation (optimal conditions); the peak power is not the same as the power under actual radiation conditions: this will be approximately 15-20% lower due to the amount of solar radiation; the temperature of the module (output decreases as the temperature rises); the voltage at which the load is drawing power from the module; the Wp value in column 5 shows power output per unit area; column 6 refers to the investment costs of PV installation.

Table 5.2: PV polycrystalline cells characteristics

<table>
<thead>
<tr>
<th>Country</th>
<th>Treated floor area m²</th>
<th>PV Surface m²</th>
<th>Max effect kWpeak</th>
<th>Wp W/m²</th>
<th>Investment Cost €</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark</td>
<td>3,000</td>
<td>120</td>
<td>12.9</td>
<td>134</td>
<td>29,600</td>
</tr>
<tr>
<td>Germany</td>
<td>3,000</td>
<td>120</td>
<td>14.5</td>
<td>134</td>
<td>24,600</td>
</tr>
<tr>
<td>Italy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turin</td>
<td>1,453</td>
<td>85</td>
<td>9.11</td>
<td>134</td>
<td>20,000</td>
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<tr>
<td>Terni</td>
<td>1,453</td>
<td>70</td>
<td>7.50</td>
<td>134</td>
<td>16,500</td>
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<tr>
<td>Taranto</td>
<td>1,453</td>
<td>50</td>
<td>5.36</td>
<td>134</td>
<td>11,800</td>
</tr>
<tr>
<td>Norway</td>
<td>3,000</td>
<td>120</td>
<td>12.9</td>
<td>134</td>
<td>41,640</td>
</tr>
</tbody>
</table>

Following tables show energy savings (both final and primary saved energy are presented), environmental (CO₂ reduction emissions) and financial (simply payback time and net present value) results for Denmark (Table 5.3), Germany (Table 5.4), Italy (Turin, Terni, Taranto) (Table 5.5) and Norway (Table 5.6).

The results show a unique trend for the schools in Denmark, Germany and Italy: the measure provides cost effective energy savings, which are a function of the climatic conditions and, in particular, the solar irradiation. Primary energy savings range between 12 and 28 kWh/m²·year. Also the financial analysis present positive results, payback times are shorter than 8 years in all the cases and the net present values range between 20 and 80 €/m².
## Table 5.3: Denmark: Energy and economic results

<table>
<thead>
<tr>
<th>Results</th>
<th>Unit</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Final energy (electricity)</td>
<td>[kWh/m²]</td>
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<td>[kWh/m²]</td>
<td>12.1</td>
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<tr>
<td>CO₂ reduction</td>
<td>[kg/m²]</td>
<td>1.7</td>
</tr>
<tr>
<td>Investment/saved energy</td>
<td>[€/(kWh/m²) year]</td>
<td>0.82</td>
</tr>
<tr>
<td>Payback time</td>
<td>[years]</td>
<td>7.3</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>[€/m²]</td>
<td>21.9</td>
</tr>
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</table>

## Table 5.4: Germany: Energy and economic results

<table>
<thead>
<tr>
<th>Results</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final energy (electricity)</td>
<td>[kWh/m²]</td>
<td>7.7</td>
</tr>
<tr>
<td>Primary energy (electricity)</td>
<td>[kWh/m²]</td>
<td>18.4</td>
</tr>
<tr>
<td>CO₂ reduction</td>
<td>[kg/m²]</td>
<td>5.1</td>
</tr>
<tr>
<td>Investment/saved energy</td>
<td>[€/(kWh/m²) year]</td>
<td>0.45</td>
</tr>
<tr>
<td>Payback time</td>
<td>[years]</td>
<td>5.4</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>[€/m²]</td>
<td>27.8</td>
</tr>
</tbody>
</table>

## Table 5.5: Italy - Turin: Energy and economic results

<table>
<thead>
<tr>
<th>Results</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TURIN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final energy (electricity)</td>
<td>[kWh/m²]</td>
<td>13.1</td>
</tr>
<tr>
<td>Primary energy (electricity)</td>
<td>[kWh/m²]</td>
<td>28.6</td>
</tr>
<tr>
<td>CO₂ reduction</td>
<td>[kg/m²]</td>
<td>5.7</td>
</tr>
<tr>
<td>Investment/saved energy</td>
<td>[€/(kWh/m²) year]</td>
<td>0.23</td>
</tr>
<tr>
<td>Payback time</td>
<td>[years]</td>
<td>4.2</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>[€/m²]</td>
<td>78.7</td>
</tr>
<tr>
<td>TERNI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final energy (electricity)</td>
<td>[kWh/m²]</td>
<td>11.5</td>
</tr>
<tr>
<td>Primary energy (electricity)</td>
<td>[kWh/m²]</td>
<td>25.1</td>
</tr>
<tr>
<td>CO₂ reduction</td>
<td>[kg/m²]</td>
<td>5.0</td>
</tr>
<tr>
<td>Investment/saved energy</td>
<td>[€/(kWh/m²) year]</td>
<td>0.22</td>
</tr>
<tr>
<td>Payback time</td>
<td>[years]</td>
<td>4.0</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>[€/m²]</td>
<td>69.9</td>
</tr>
<tr>
<td>TARANTO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final energy (electricity)</td>
<td>[kWh/m²]</td>
<td>10.1</td>
</tr>
<tr>
<td>Primary energy (electricity)</td>
<td>[kWh/m²]</td>
<td>22.0</td>
</tr>
<tr>
<td>CO₂ reduction</td>
<td>[kg/m²]</td>
<td>4.4</td>
</tr>
<tr>
<td>Investment/saved energy</td>
<td>[€/(kWh/m²) year]</td>
<td>0.18</td>
</tr>
<tr>
<td>Payback time</td>
<td>[years]</td>
<td>3.2</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>[€/m²]</td>
<td>62.9</td>
</tr>
</tbody>
</table>
Table 5.6 shows the final results for the Norwegian reference school. To be noted that the energy results are in line with those achieved for the Danish school, however different costs figure make the measure less efficient. The payback time is higher than 30 years with a consequent negative net present value.

Table 5.6: Norway: Energy and economic results

<table>
<thead>
<tr>
<th>Results</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final energy (electricity)</td>
<td>[kWh/m²]</td>
<td>4.8</td>
</tr>
<tr>
<td>Primary energy (electricity)</td>
<td>[kWh/m²]</td>
<td>12.1</td>
</tr>
<tr>
<td>CO₂ reduction</td>
<td>[kg/m²]</td>
<td>1.7</td>
</tr>
<tr>
<td>Investment/saved energy</td>
<td>[€/(kWh/m²) year]</td>
<td>1.15</td>
</tr>
<tr>
<td>Payback time</td>
<td>[years]</td>
<td>31.4</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>[€/m²]</td>
<td>-3.5</td>
</tr>
</tbody>
</table>

Examples of applications in the School of the Future

PV has an interesting potential for school applications; in fact the electricity production takes place during the daytime building operation, making the produced energy available when needed. Conversely, schools are generally closed during summer, i.e. the season with the highest solar radiation availability. This renewable energy can appropriately compensate for the electricity used for the auxiliaries of the heating system and the mechanical ventilation system, as well as the electric lighting systems during some period of the day and of the year. The PV technology finds a wide application in school buildings, often supported by favourable financial mechanisms related to the electricity to be used on site or sold to the grid. As a consequence of these advantages, the technology was adopted in three of the demo buildings of the School of the Future.

Denmark

The Hedegaards School in Ballerup, Denmark takes advantage of the tilted light boxes for a 152 m² PV array, with a total installed power of 22.5 kWp. In Figure 5.14 the photo shows the PV panels installed on the south-oriented pitch of the skylight, i.e. meaning that the vertical skylights face north. The expected annual production is 22.5 MWh.
Italy

A similar solution is adopted for the Plauto School in Cesena, Italy, where a 64.7 kWp monocrystalline PV plant is installed on the roof. The plant does not have an optimised orientation, but it takes advantage of the actual tilt of the pitched roof to minimise the initial investment for structural works. Panels are mounted on the east and south pitches.

The expected annual production is 72.3 MWh. It should be noted that the average electric end use of the building is about 70 MWh, and therefore it is estimated that the school will be electricity neutral. A view of the south-oriented arrays is presented in Figure 5.15.

![Figure 5.15: PV panels at Plauto School in Cesena, Italy](image)

Germany

A photovoltaic system was mounted on the roof of the main building at the Solitude-Gymnasium School in Stuttgart. Being a roof flat, the solution shown in Figure 5.16 was adopted to install as much as possible pv area on the roof. Due to static restrictions, only part of the roof was used, a restraint that limited the size of the plant. It consists of 30 modules, east-west orientated and with a tilt angle of 10 degrees. Each module has a power of 250 kWp. The total power of the system is 7.5 kWp. More details about the demonstration buildings is available on the website of the School of the Future (www.school-of-the-future.eu).
Conclusions

The PV development and market went through significant changes during the past years, affected by economical, technological and geographical factors. The boost of PV in Europe in 2011 was mainly due to the large number of installations in Italy (9.3 GW) and Germany, progressing the market growth of the previous years. This trend decreased in 2012 in Europe (17 GW compared with 23 GW the previous year). At the same time, the PV development outside Europe had a strong development in countries such as China, USA, Australia and Japan, ensuring that a positive trend was maintained at the global level. This trend seems to be confirmed in 2013; Asia being the new market, focal areas being countries such as Thailand, Korea, Taiwan and especially India.

The technology development is now addressing to new advanced materials and production technologies, in a comprehensive life cycle assessment visions. Efforts are, moreover, addressed to specific applications, as: PV seen as self-consumption (in remote and grid-connected sites) and large-scale PV installations (up to 250 MW) connected to existing grids to "export" electricity or to be used otherwise.

The sharp drop in prices of PV technology, new building efficiency regulations and systems of incentives at the level of individual states and at EU level has led to keen competition.

The future of PV will depend on several factors such as the development of the technology, the decrease of the costs, the transformation of existing grids, the price of electricity, but also on political decisions.
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