PROJECT REPORT

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TITLE

Building Integrated Energy Systems in Smart Energy Efficient Buildings – A State-of-the Art

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ABSTRACT

This report summarises the State-of-the art within Building Integrated Energy Systems (BIES) and related area. The report marks the start of subtask 2.2 “Building Integrated Energy Systems” within the project “Smart Energy Efficient Buildings” (*SmartBuild*). The aim of the *SmartBuild* project is to develop new knowledge, integrated solutions, and technologies that will make it possible to cover our building-related energy needs with substantially less harmful environmental emissions, while still satisfying the whole range of end-user needs such as comfort, aesthetics, costs, operability, reliability and functionality.

Building integrated energy systems are defined as systems in the building envelope or building structure that utilize the available on-site energy resources in a way that minimizes the need for purchased energy and maintains a satisfactory indoor environment.

In this report, the systems have been categorized into *passive* and *active* systems.

Passive systems are characterized by their direct interaction between the building structure and the environment. They do not produce power and do not need any mechanical devices or significant mechanical energy in order to operate. However, it should be noted that systems that originally are passive, might experience enhanced performance if used in conjunction with some mechanical devices.

Active systems are designed to utilize the environment to avoid or meet a significant proportion of the residual demand. These systems either produce power, or they operate in conjunction with some mechanical devices to utilize renewable energy to provide heating and cooling.

KEYWORDS:	ENGLISH	NORWEGIAN
GROUP 1	Energy	Energi
GROUP 2	Building Technology	Byggteknikk
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1. Introduction

1.1 Project background

A large part of the energy loads in buildings is related to protection from the external climate and operation of systems needed to create an optimum indoor environment. Conventionally, envelopes are designed to isolate the building from the exterior environment, through massive thermal insulation, wind and rain proofing, small windows etc. The building envelope and other structural elements are commonly designed and optimised without regard to the mechanical service systems for heating, cooling, ventilation, lighting, water and electricity supply. These systems are often added on after the main decisions about the building design have been reached.

There are many opportunities for exploiting the energies available in the exterior climate, and thus reduce the need for purchased energy. New energy technologies are being developed, some are already applied in buildings: e.g. solar thermal energy, solar electricity, daylighting, and natural ventilation systems. To work in an optimal manner, these systems must be combined with other conventional or advanced technologies to create energy-producing climate-adapted envelopes. The integration between building envelope and the climate-control service systems thus gives new opportunities in exploiting natural energy and reduce demands for purchased energy, and at the same time reduce costs.

1.2 Objectives

The goal of this task is to build the scientific background necessary for the development of smart intelligent interactive building envelopes and building elements that are integrated with the building's heating, cooling and ventilation system, with the overall aim to exploit energy from environment to modulate indoor climate and provide comfort.

1.3 Project workplan

The main activity of this project will comprise system analysis techniques to the many combinations of available technologies that can be applied at the building envelope and within the building structure:

- Solar thermal energy systems (passive/active)
- Solar photovoltaic systems
- Daylighting systems
- Solar shading/glare control systems
- Natural/hybrid ventilation
- Decentralised energy storage at envelope or within building structure
- Decentralised indoor climate systems at envelope or within the building structure

There are many combinations of technologies which can be applied. With an integrated approach they offer a large potential for energy savings, and also investment savings. A system analysis will uncover both opportunities and constraints. Computer simulations of the integrated dynamic performance of the building with advanced technologies will be another important activity. The optimal combinations will of course be climate and building demand dependent. Other factors that also need parallel attention are architectural integration, LCC/LCA, acoustics etc.

The project calls for an interdisciplinary approach, and is well suited for the strategic program. NTNU and SINTEF have already established a multidisciplinary research programme on natural and hybrid ventilation, including 3 PhD studies. Participation in a newly started European COST action, “Glass and interactive envelopes”, will also provide important input to this project. In parallel with this project, NTNU leads a national project entitled “Energy efficient intelligent facades”, supported by the Glass Trade Association of Norway, Hydro Aluminium and the Norwegian Research Council. In addition, a newly started research project entitled “Passive climatisation”, financed by the research council and various industry, will be closely tied to this task. The work will also be co-ordinated with the activities in other relevant Strategic University Programme (SUP)/Strategic Institute Programme (SIP) tasks, e.g. the SIP of the Norwegian Building Research Institute (NBI). This complex project requires the input of experienced researchers, possibly a post-doctoral candidate. The multidisciplinary activities needed for the development of the concepts makes it necessary to involve many NTNU/SINTEF units.

1.4 Deliverables

The outcome of this project will be system analysis based design guidance for energy systems integrated in envelope and building fabric, operating in coherence with mechanical system for indoor climate comfort: heating, cooling, and ventilation, including optimal control system logic. The project will also produce performance data for different climatic regions.

1.5 Benefits

The project will produce guidance and concepts for energy-efficient buildings with integrated technical systems, relevant for technology and product development. The integrated systems that will be the final outcome of the project will have major impacts on the demand for purchased energy in buildings. These systems will give relevant Norwegian industry new opportunities in development of innovative products, which will have an international market. The project will also build new scientific knowledge within the range of multidisciplinary research units involved, covering architecture, building technology, HVAC and energy system engineering.

1.6 The smart build work packages

The SmartBuild work packages are as follows:

WP 1: The Users and the Environment
- 1.1: User Cultures and User Needs
- 1.2: Environmental Friendliness
- 1.3: Indoor Environment
- 1.4: Implementation Strategies

WP 2: The Building
- 2.1: Integrated Design
- 2.2: Building Integrated Energy Systems
- 2.3: Lighting Systems
- 2.4: Building Integrated Photovoltaic Systems

WP 3: Energy Systems
- 3.1: Heating, Cooling, and Ventilation Systems
- 3.2: Heat Pumps
- 3.3: Operation and Automation
- 3.4: Energy Storage

1.7 Definitions

Building integrated energy systems can be defined as follows:

"Building integrated energy systems are systems in the building envelope or fabric that utilizes the available on-site energy resources in a way that minimizes the need for purchased energy and maintains a satisfactory indoor environment."

From the definition, it is clear that building integrated energy systems cover also two other work-packages in the smartbuild project, namely WP 2.3; Lighting Systems and WP 2.4; Building Integrated Photovoltaic Systems.

It is possible to distinguish between *passive* and *active systems*. *Passive systems* are characterized by their direct interaction between the building fabric and the environment. They do not produce power and do not need any mechanical devices or significant mechanical energy in order to operate. However, it should be noted that systems that originally are passive, might experience enhanced performance if used in conjunction with some mechanical devices.

Active systems are designed to utilize the environment to avoid or meet a significant proportion of the residual demand. These systems either produce power, or they operate in conjunction with some mechanical devices to utilize renewable energy to provide heating and cooling.

2. Passive building integrated energy systems

There are many possibilities for direct inter-action between the building fabric and the environment in order to reduce the need for additional energy to achieve the desired comfort and cover the residual demand. It is difficult to categorize the various passive systems because they often combine strategies for power generation, passive cooling, passive heating as well as heat storage, heat recovery or avoidance of the various external and internal heat gains.

This report distinguishes between solar related energy systems, daylight systems, integrated ventilation systems and heat storage systems. However, it should be noted that many integrated energy systems combines the utilisation of solar energy with integrated ventilation and related heat storage in the building fabric or other integrated elements.

2.1 Solar related energy systems

Passive solar energy systems are designed to capture and process solar radiation passively, where eventual storage is bound to the interior elements and the building fabric. Such systems consist of various elements.

2.1.1 Elements for direct solar gain

Elements for direct solar gain consist of internal surfaces or obstruction objects, i.e. furniture receiving solar beam and diffuse radiation. This type of passive system is thus present in all buildings with windows, and is therefore one of the most important means of providing passive solar energy. It has been estimated that correctly dimensioned and oriented window openings can give 5-15% reduction in the heating energy consumption by use of regular, well insulated windows [2]. However, conscious planning is necessary in order to take full advantage of this potential, and to avoid overheating problems in summer.

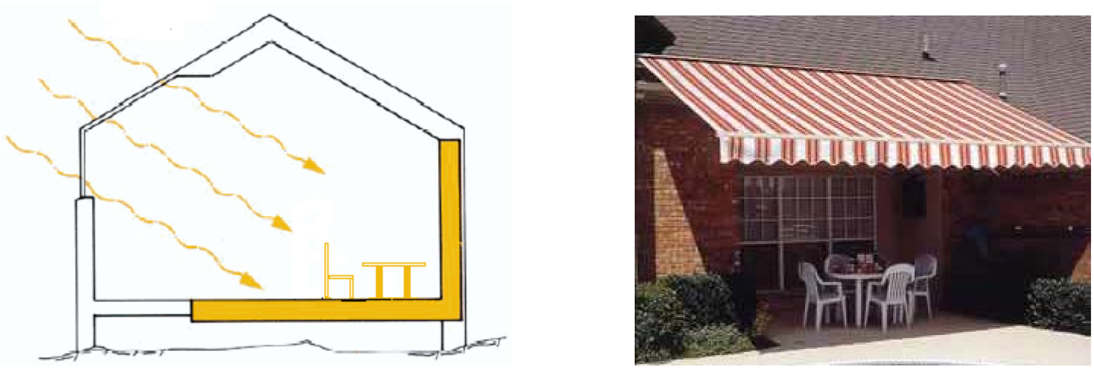

Figure 2-1 Illustration of direct solar gain (left). Shading is often necessary to avoid overheating in summer (right).

2.1.2 Glazed Atria and sunspaces

Glazed Atria

An atrium is a glazed space attached to a large building or placed between two or more such buildings. Atria give attractive environments that can be used for several purposes. Typical use of atria is traffic areas, gardens, cafés or canteens. The use may vary depending on the season.

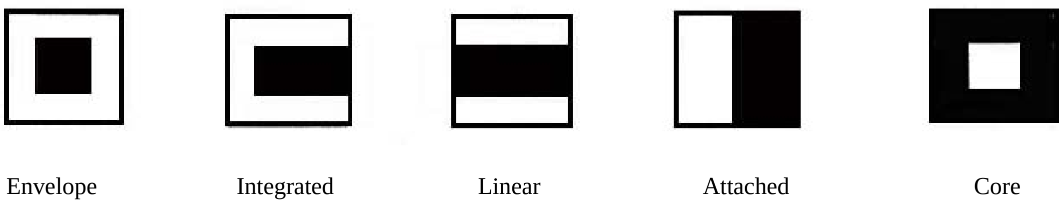

Figure 2-2 Illustration of various types of atria [1].

Energy performance can be improved through use of atria. They will reduce heat loss from the surrounding building spaces that would otherwise be exposed to the exterior environment, at the same time as they provide them with daylight and visual amenity. This improves comfort and reduces the need for artificial lighting systems. Elements within the space, including both the building fabric and furniture, can absorb solar radiation. This heat will be convected into the space and preheat the air within, which then can be used for ventilation. This preheating-effect provides opportunities for use of natural ventilation in buildings with atria.

However, if heating is provided within an atrium in order to maintain comfortable temperatures, this will increase the buildings energy demand significantly. Overheating in summer is another important problem that can cause severe thermal discomfort and/or high cooling loads both in the atrium itself and the surrounding building spaces.

Atrium design is a complex task, and procedures for optimization and planning of operational strategies should thus involve computational modelling combined multidisciplinary expert knowledge.

Glazed sunspaces

A sunspace is defined as a relatively small glazed space attached to a dwelling. They improve the insulation of the external wall, and thereby slightly reduce the heating energy consumption. However, the important advantage is achieved when the solar heat in the sunspace is used to preheat the ventilation air, see Figure 2-4 below (lower right). It has been estimated that this can reduce the energy consumption of the dwelling with 15-25 % [2].

A typical application of such sunspaces is glazed balconies. However, this can provide an attractive area that the occupants desire to use not only in the summer season, but also in early spring and autumn. As a result, they often install heating systems which have severe negative consequences with respect to energy consumption.

2.1.3 Double facades

A double façade is a system involving the addition of a second glazed envelope. A double façade does thus have many properties in common with an atrium or a glazed sunspace. However, the cavity in a double façade does not offer space for occupation.

Double facades can create opportunities for maximising daylight and improving energy performance. The extra skin offers improved insulation, which both can reduce cooling demand in summer and heating demand in winter. Solar shading systems can be integrated in the facade, protecting them from the exterior environment. The solar radiation absorbed by the shading systems will be convected into the air volume of the cavity. Depending on if there is a heating or cooling demand, this preheated air can be ventilated out or used to ventilate the interior space. The effect of thermal buoyancy will create a natural driving force for the ventilation, se Figure 2-3.

A combination of a passive and an active system that has been demonstrated at NTNU, Trondheim is the BP-solar wall, see Figure 3-5 (right) page 28. The wall has integrated photovoltaic (PV) cells in the exterior glazing of the double skin. The ventilation within the cavity provides the necessary cooling needed for the electricity producing PV-cells while the cells themselves can provide shading and aesthetical qualities to the building.

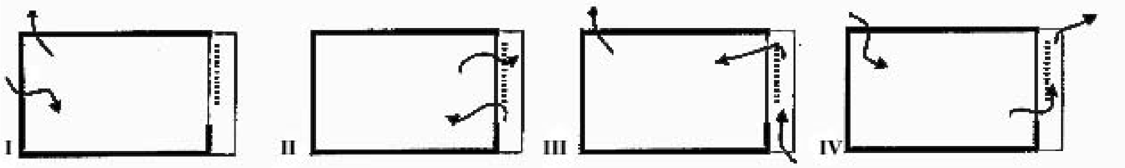

Figure 2-3 Alternative configurations for double façades3. I: Cavity closed. II: Cavity open. III: Cavity serving as supply path. IV: Cavity serving as extract path.

2.1.4 Solar wall systems

A wall facing the sun can function as a solar absorber. With a certain time delay that depends on the heat capacity of the wall, some of the absorbed heat will be conducted through the wall, providing a heat flux into the room, see Figure 2-4, upper left. However, the wall can also be insulated, in which case the heat is taken advantage of through natural ventilation.

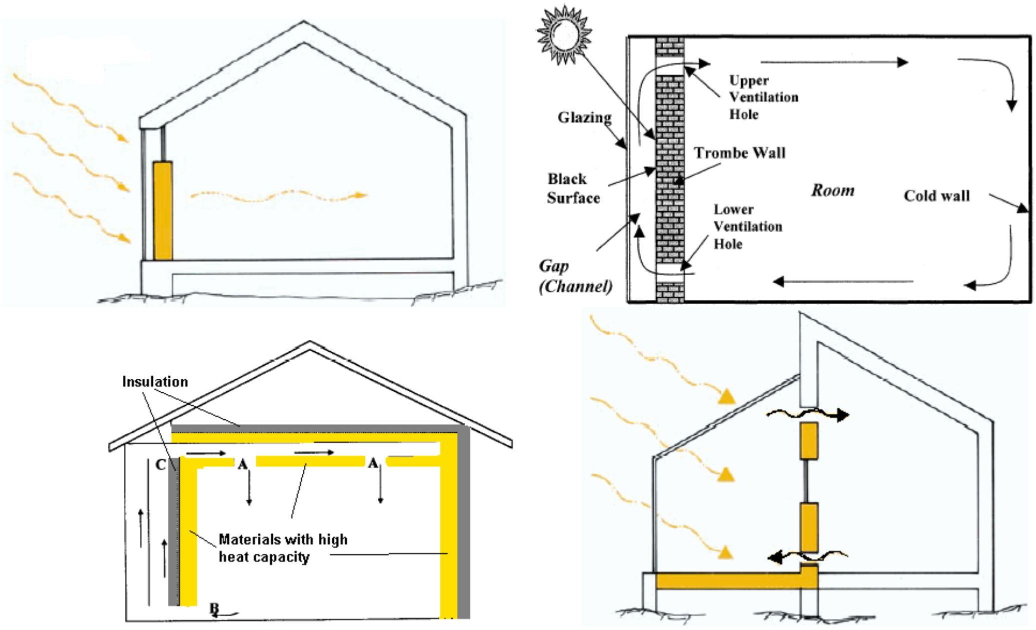

Figure 2-4 The solar wall principle (upper left) and an example of a Trombe Wall (upper right). A similar system based on the same principle proposed by Barra and Constantini (lower left). Solar walls can be combined with double facades, atria or as shown here, a glazed sunspace (lower right).

A Trombe Wall is an example of a solar wall that is placed within a transparent envelope consisting of glass or transparent insulation material (TIM), see Figure 2-4 (upper right). The stored solar heat during daytime can, during evening and night, be used to heat the interior spaces through conduction or ventilation air preheating.

Another example of a solar wall system is the system proposed by Barra and Costantini [4]. It is composed by a thermally insulated wall and a transparent cover system. A thin metal plate, functioning as solar collector, is placed between these two components, giving two parallel and independent vertical ducts, where airflow is induced by natural convection. Air flows by thermosiphoning in the solar duct, removing heat on both sides of the solar collector, through openings C in Figure 2-4 (lower left). It reaches the horizontal ducted ceiling, storing heat in the ceiling structure before being mixed into the room through openings A. Cooler air leaves the room through openings B. Operable panels or dampers are located at the inside face of the openings in order to operate automatic changeover between day and night functions.

2.1.5 Solar thermal collectors

Solar thermal collectors capture incident solar radiation energy and convert it to heat (thermal energy).

Solar thermal collectors can be divided into three categories:

- Low-temperature collectors provide low grade heat, less than 45 ^{0}C, through either metallic or nonmetallic absorbers for applications such as swimming pool heating and low-grade water and space heating.
- Medium-temperature collectors provide medium to high-grade heat (greater than 45 ^{0}C, usually 60-80 ^{0}C), either through glazed flat-plate collectors using air or liquid as the heat transfer medium or through concentrator collectors that concentrate the heat to levels greater than "one sun." These include evacuated tube collectors, and are most commonly used for residential hot water heating.
- High-temperature collectors are parabolic dish or trough collectors primarily used by independent power producers to generate electricity for the electric grid.

Only low or medium temperature collectors can normally be integrated in the building envelope. High-temperature collectors will therefore not be treated further here.

The media most commonly used for absorbing and transferring the heat are air and water[i]. It is thus possible to separate between air and water collectors.

The efficiency is defined as the ratio between the heat deposited in the air or water and the total amount of energy which at the same time hits the collector area in terms of solar radiation.

Air collectors

An air collector can be as simple as a bare sheet of metal, like a metal roof, painted a dull black to absorb as much energy as possible, with air blown underneath in a duct of some type. A second type, called a covered plate collector, uses a cover plate of glass, plastic or fiberglass with air circulated between the cover and the absorber plate. The cover acts as a barrier between the wind and absorber and reduces heat loss from the absorber plate to the outside air due to wind blowing across the surface and taking away some of the heat.
A third type, called a covered, suspended plate, has air circulated both above and below the absorber plate. This provides twice as much surface area for heat transfer from the absorber plate to the air. The top cover reduces convection loss from the wind across the surface, as it does in the covered plate type.

In most collectors, insulation for the back of the collector is necessary to reduce the conduction heat loss through the rear of the collector. A cover also reduces radiation heat loss from the front of the collector.

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[i] In colder climates, some antifreeze product is often mixed with the water.

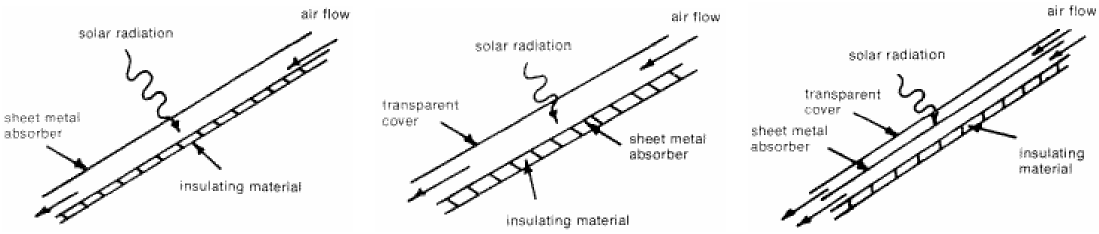


Figure 2-5 Principle sketch of some typical air collectors: A bare-plate type (left), a covered-plate type (middle) and a covered, suspended plate type (right).

Water collectors

These collectors have the same basic components as an air collector: an absorber plate and a transfer medium. The difference is in how the medium is passed over the absorber.

The basic water collector consists of an absorber plate, generally with water tubes attached, a cover, and insulation behind the absorber plate. Heat from the absorber plate is removed by the water circulating in the tubes. The principle is illustrated in Figure 2-6 (left) below.

Another type of water collector has no water tubes. The water simply flows down over the absorber in a sheet or in an open channel if the absorber is corrugated. The type with tubes is generally more efficient, but the open channel type generally costs less.

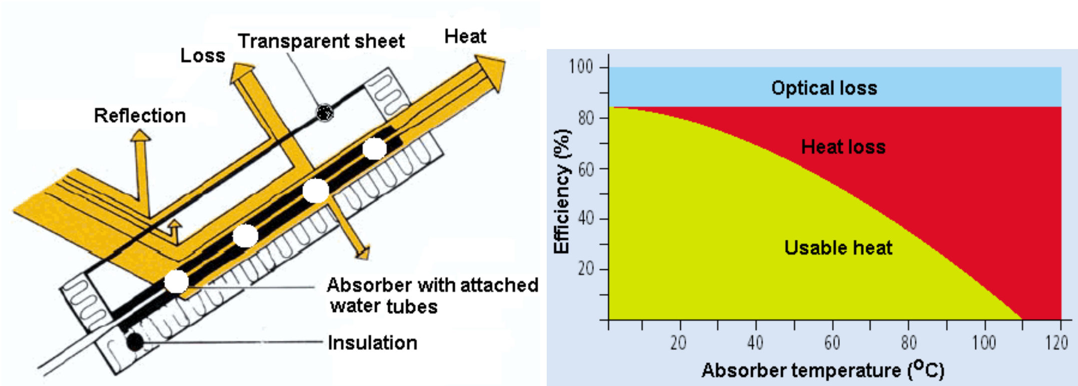


Figure 2-6 Heat flow in a flat plate solar collector with attached water tubes (left). The heat loss increases with the absorber temperature (right) [2].

The heat loss through the transparent sheet will depend on the absorber temperature as illustrated in Figure 2-6 (right). The heat loss also depends on the properties of the (eventual) transparent sheet and the absorber. Selective coatings on the absorber can increase performance significantly. The best option depends on the operational temperature range, and is thus a design issue. When the working temperature of the fluid is particularly low, a collector without transparent sheet can be the best option. Such low grade heat can be used e.g. for swimming-pool or room heating. For hot water heating, however, glazed collectors with selective coatings will normally be advantageous.

Solar thermal collector design is evolving rapidly. In addition to performance, functionality and robustness, aesthetics and integration into the building envelope is getting increased attention. However, the necessary massiveness and complexity of the system is a challenge, and, being exposed to high temperature differences, particular attention should be given to potential problems with leakage.

An example of a modern collector is the one distributed by the norwegian company SolarNor shown in Figure 2-7 below. The collector was developed in cooperation with General Electric Plastics, the Netherlads. It consists of two twin-wall sheets of high temperature resistant and fully recyclable plastics, fixed in an aluminium frame. The solar radiation is converted to heat in the absorber sheet. Pure water is trickling through a channel structure, absorbs the heat which is deposited in the absorber and carries the heat to a heat store. Figure 2-7 (middle and right) also shows two examples of application on a Dwelling (middle) and Klosterenga eco-houses (right) in Oslo.

Figure 2-7 The SolarNor solar thermal collector is composed of a transparent sheet of polycarbonate plastics covering a black double sheet made out of the plastic material noryl. The inner structure is composed of narrow channels filled with small, pourous pellets. Water trickles through a channel structure, absorbs the heat which is deposited in the absorber and carries the heat to a heat store.

The SolarNor collectors used for cooling purposes through the effect of thermal radiation at night has also been studied for typical Oslo climate conditions [5]. The study concluded that except for mid-summer ambient temperature and high relative humidity, the system consisting of 5.3 m^2 of radiator (collector) area and a 280 l reservoir, was able to cover the cooling demand of a typical single-family house.

The air/liquid flow in systems with solar thermal collectors can be driven by natural driving forces, so-called thermosiphoning, driven by the fact that hot air or water is lighter than cold air or water (as long as the water temperature is above 4 ^{0}C). However, due to the relatively high pressure drop in many collectors, they do not perform well unless a pump or a fan enhances the flow through them. In such cases they do not provide a purely passive system.

2.1.6 Movable insulation

The performance of passive solar energy systems is often significantly reduced due to heat loss during hours without or with very limited solar radiation. Movable insulation can therefore increase the performance of such systems significantly.

Movable (operable) insulation is a device such as an insulating shade, shutter, panel, or curtain that reduces heat loss at night and during cloudy periods, and heat gain during the day in warm weather. When used properly, movable insulation can increase or decrease net heat gain, depending on user needs. These insulation devices may either be removed or adjusted to allow heat gain in the day when it is needed.

2.1.7 Roof systems

As roofs are usually insulated to minimise both heat loss and external heat gain it is not possible to take advantage of low nocturnal temperature unless the roof is designed in a certain way. A simple method of achieving radiant cooling is to use a heavy but highly conductive roof exposed to the sky at night, but highly insulated in the day using movable insulation.

The skytherm system

Several buildings in the United States have used the skytherm system [6] in which the roof is made of structural steel deck plates. Plastic bags filled with water are placed above the steel decks and above them are movable insulation panels that are moved by a motor. In Winter the water bags are exposed to the sun in the day and covered by the insulation panels at night. In Summer when cooling is required the water bags are exposed and cooled at night and insulated during the daytime, see Figure 2-8 left and right respectively. As the cooled water bags are in direct contact with the metal deck the ceiling serves as a cooling element over the entire space.

The skyterm system can be a very efficient way of providing both heating and cooling, in particular in warm and hot climates with many hours of sun. A study made by shows that for a 140.55 m^2 one story house in shiraz, Iran, the skytherm system is capable of reducing heating demands by 86% and cooling loads by 52% [7].

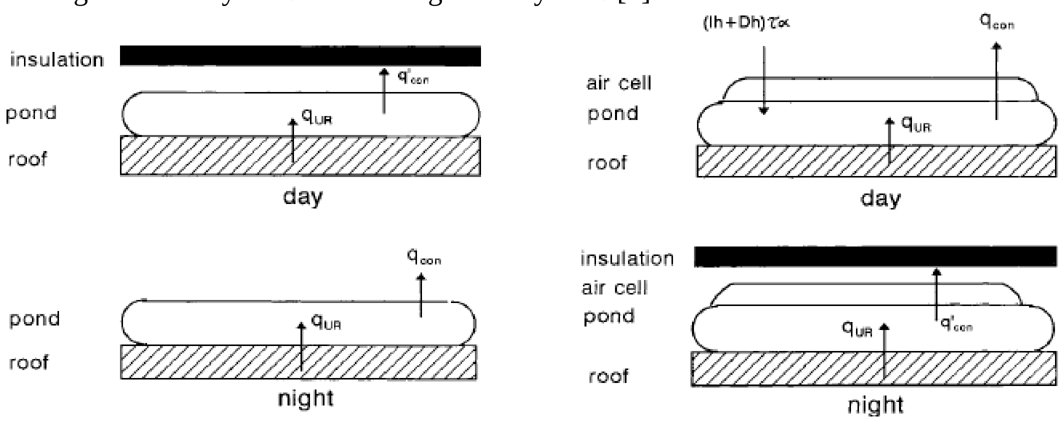


Figure 2-8 The *sky therm* system. Summer operation (left) and winter operation (right).

Roof ponds

In contrast to using indirect and direct evaporative cooling in conjunction with air being introduced into a building it is possible to cool a roof by placing a cooled pond over it. The building is then cooled by conduction across the roof which lowers indoor air and radiant temperatures without increasing the indoor water vapour content.
Givoni, [8] suggests the ceiling temperature in the case of a concrete roof over a well insulated building would be about 2°C above the water temperature. It is concluded that the water temperature of a shaded pond follows approximately the average wet bulb temperature. The suggested maximum wet bulb temperature for applications of this type of evaporative cooling in summer is 22-24°C and the dry bulb temperature not higher than 42-44°C.

2.2 Building integrated lighting systems

The integration of lighting systems in buildings is an obvious objective. Essential aspects related to energy consumption are daylight utilization, efficiency and control. New systems and materials for shading and daylight-redirecting made available to the market enables improved utilization of daylight. Kischkoweit-Lopin [9] have provided a comprehensive overview over various building integrated daylight systems.

In addition to the shading systems shown in [9] , a new application was demonstrated through the British Pavilion, in Expo 92, Seville, Spain [10]. As a response to traditional water fountains, Wiliam Pye designed the 70 m long east facade as a waterfall. The water falling on the glazed surface gives the glass a dynamic translucent quality. The surface evaporation of water limits the maximum glass temperature to around 24^{0}C, and thus provide cooler internal environment. Fine tuning of the high-level jets ensured an even flow of water.

Figure 2-9 British Pavilion, Expo 92, Seville, Spain (architect Nicolas Grimshaw)(left). The east facing “water-wall” (right). The surface evaporation of water limit the maximum glass temperature to around 24^{0}C, and thus provide cooler internal environment. In addition, the curved shadings on the roof shields it from sun and limits the rise of internal temperature.

Lighting systems are defined as an own work package (WP 2.3) in the SmartBuild project. For further details, see the state-of-the art report on Lighting Systems in Smart Energy Efficient Buildings [11]

2.3 Ventilation related systems

Passive systems related to ventilation are either natural ventilation or dynamic insulation.

2.3.1 Natural ventilation

Natural ventilation has during the last decade experienced a renaissance in Europe. The penalty of electrical energy use of traditional mechanical ventilation and air conditioning is the main reason.

Natural ventilation relies on wind and thermal buoyancy as driving forces for the ventilation air flow. The driving pressures derived from wind and thermal buoyancy are however low compared to those produced by fans in mechanical ventilation systems. This has consequences for the architecture of both the exterior and interior of naturally ventilated building as the building structure by means of its shaping is supposed to exploit the natural driving forces to drive the air through its interiors[12].

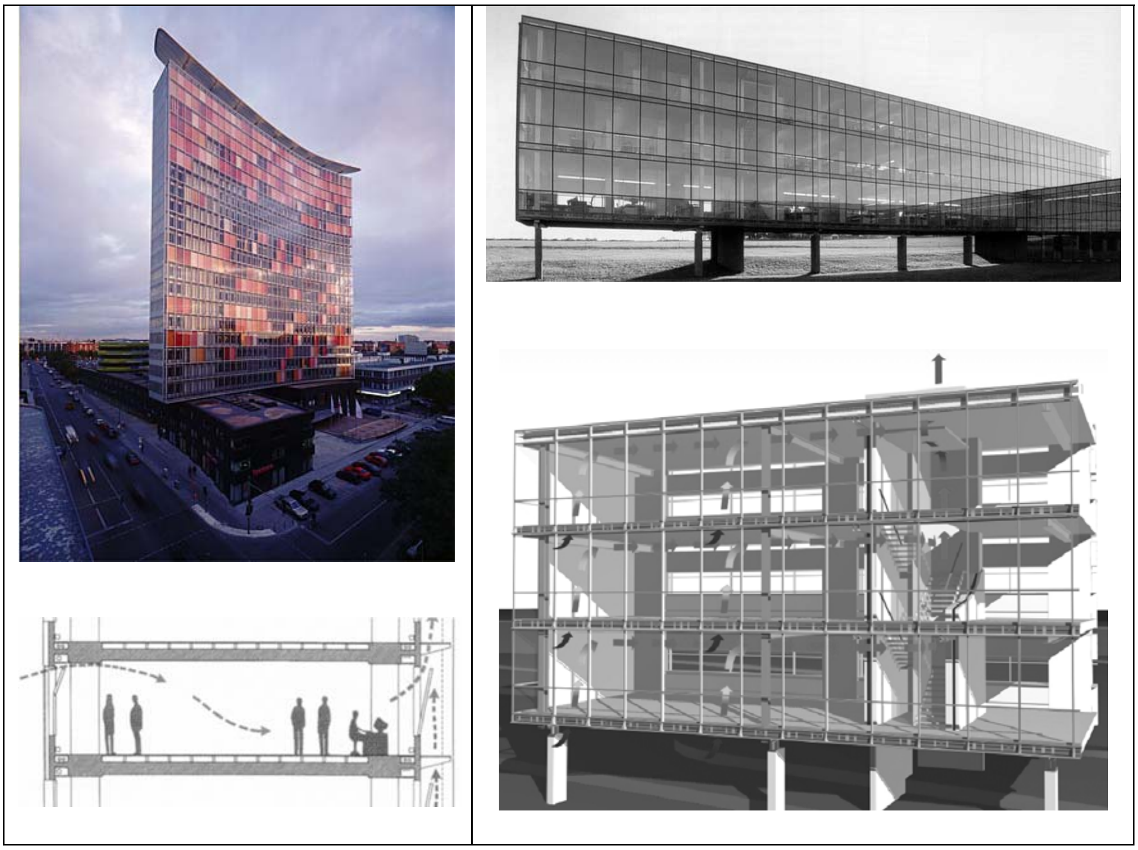


Figure 2-10 The double skin west-facade of the naturally ventilated GSW building, Berlin Germany functions as a solar chimney (left. Photo: Anette Kisling). Ventilation air is sucked in through the east facade and extracted via the cavity in the double skin facade. A wing on the roof protects the outlet and strengthens the wind-induced suction. The elevated, rectangular shaped southern office wing of the Bang & Olufsen headquarters, Struer, Denmark uses natural ventilation (upper right), supported by help fans mounted on top of the staircases to assure comfort when the natural driving forces are insufficient. The princible has been illustrated by Birch & Krogboe A/S (lower right).

In the exterior this may be manifested in the way the building body harness the driving forces to drive air into and out of the building. This can influence the shaping of building volume(s), the reciprocal constellation of volumes and the orientation of the building relative to prevailing wind direction(s) and the sun.

In the interior this may be manifested in the way the interior spaces are organised and shaped to provide low resistance air paths. The pressure losses in the path (from inlet to outlet) should be sufficiently low to compensate for the weaker driving pressures. Thus, the structure of the building, with rooms, corridors, stairs and so on, rather than the ducts familiar from mechanical ventilation, is used as air path. These interior spaces provide a far lower resistance to the airflow than ducts do due to their considerably larger cross sections. In the interiors natural ventilation might be reflected in more open spatial connections. A natural ventilation concept is therefore highly integrated in the building body.

The notion natural ventilated concept can be described through use of three essential aspects [12,13,14]. The first aspect is the *natural force* utilised to drive the ventilation. The driving force can be wind, buoyancy or a combination of both. The second aspect is the *ventilation principle* used to exploit the natural driving forces to ventilate a space. This can be done by single-sided ventilation, cross ventilation, or stack ventilation. The third aspect is the *characteristic ventilation element* used to realise natural ventilation. The most important characteristic elements are wind towers, wind scoops, chimneys, double façades, atria, and embedded ducts. All these elements are covered by the definition of building integrated energy systems.

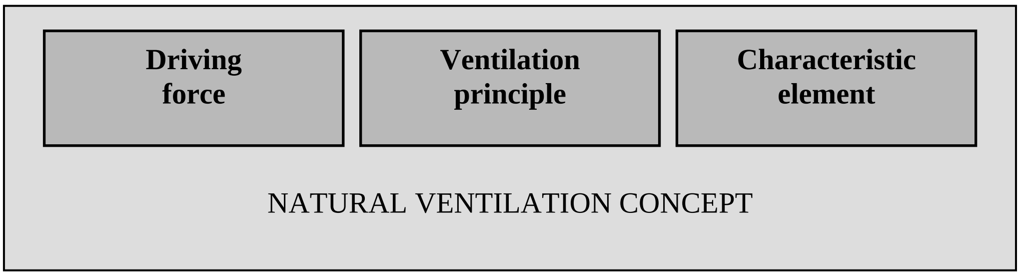


Figure 2-11 The notion natural ventilation concept can be assigned the driving force that is utilised to drive a ventilation principle with the aid of certain characteristic ventilation elements.

However, natural ventilation can be realised without the use of dedicated ventilation elements. The building itself doubles then as a ventilation element, which could be named "*building integrated element*. In this case the building, as a result of its design, is capable of harnessing the natural driving forces and to direct the ventilation air through its spaces without the need for dedicated ventilation elements. In this sense, a building integrated ventilation element is really not an element, but rather the absence of one. As the "ventilation system" and the occupants share the same spaces (rooms, corridors, stairwells et cetera), and windows and doors are utilised as part of the air-paths as well, the most characteristic feature of a building integrated element is that the building appears not to have a ventilation system at all. There are no characteristic natural ventilation elements, nor a mechanical ventilation system present. The main advantage with a building integrated element is that the ventilation system represents no additional use of space in the building. Ductworks, ventilation plants, and related components are avoided.

In addition to avoid extensive use of electric fan power, natural ventilation is an efficient mean of providing thermal comfort in summer (without the need for active conditioning) through the three following mechanisms:

- Direct cooling of indoor air by replacing or diluting it with outdoor air as long as outdoor temperatures are lower than the indoor temperatures.
- Cooling of the building structure, typically at night.
- A direct cooling effect over the human body through convection and evaporation

Many different strategies to realise the natural ventilation concept are possible. The chosen strategies often involve a combination between the three natural ventilation principles through the application of various characteristic elements. Some fundamental strategies are shown in Figure 2-12 below.

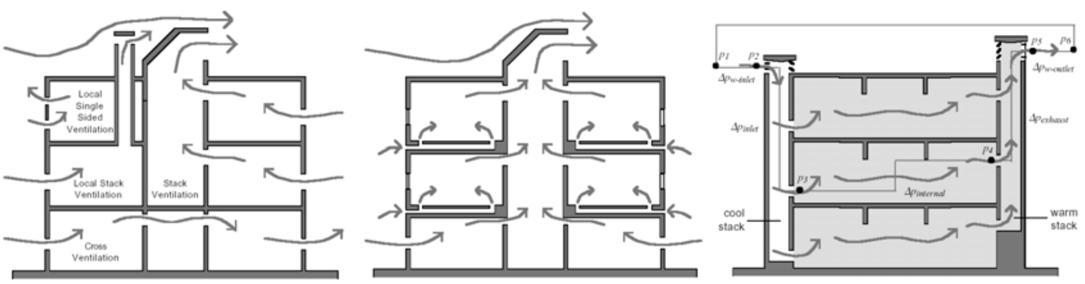


Figure 2-12 Illustration of some fundamental natural ventilation strategies; mixed (left), stack ventilation with sub-slab distribution (middle) and top-down or balanced stack ventilation (right) [15].

Natural ventilation, in particular when the cross-ventilation principle is applied, can be extremely efficient compared to regular mechanical ventilation. Achieving the same airflow rates with a regular mechanical ventilation system would require powerful fans with negative consequences related to energy consumption, noise and unwanted preheating of the ventilation air.

Passive downdraught evaporative cooling (PDEC)
Through evaporative cooling, the ambient air can potentially be cooled down to the dew point temperature simply by saturating it with moisture. This type of cooling is thus particularly efficient in relatively dry climates.

Passive downdraught evaporative cooling is an ancient Middle Eastern and Eastern Asian natural ventilation strategy that adds evaporative cooling to the supply stack of a top-down balanced stack ventilation system. In the more recent developments of this approach, water is injected high into the supply air stream as a fine spray cooling the air stream via evaporation and simultaneously increasing the supply air density, thereby increasing the buoyancy induced pressure differences that drive the airflow, see Figure 2-13 (left) below [15].

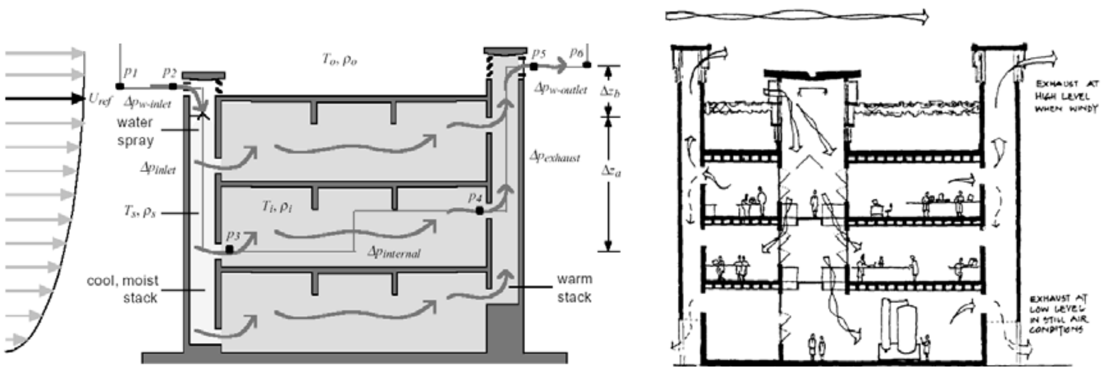


Figure 2-13 Principle diagram (left) illustrating passive downdraught evaporative cooling (PDEC). Water is injected high into the supply air stream as a fine spray cooling the air stream via evaporation and simultaneously increasing the supply air density, thereby increasing the buoyancy induced pressure differences that drive the airflow [15]. The Torrent Research Centre in Ahmedabad, India successfully demonstrates the application of PDEC. As can be seen from the cross section through the building (right), laboratories and offices ae arranged on three levels either side of an open concourse which alloows evaporatively cooled air to be introduced at each level, and exhausted via perimeter stacks.

One of the most important demonstrations of PDEC in India has been made through the design of a new laboratory building in the Torrent Research Centra in Ahmedabad, see Figure 2-13 (right) above.

Monitoring has shown that the building uses 64% less energy than the equivalent conventionally air conditioned building without sacrificing comfort conditions for the occupants. The additional capital cost of 4% over the air conditioned equivalent was paid back in the first year by these energy savings [16].

Another well documented example of application is from a building complex Negev Highlands of southern Israel, where a the peak cooling output of a prototype downdraft cooling tower was measured to 100 kW [17]. In that case a fan was used to enhance the airflow, but wind capture studies were later carried out in order to reduce or eliminate the need of a mechanical fan.

Note however that evaporative cooling carries a risk for condensation on surfaces that are cooler than the wet bulb temperature. Care should thus be made, in particuar if combined with systems like TermoDeck and chilled ceilings.

Control and operation of natural ventilation

Three distinct control regimes should be considered in the operation of natural ventilation systems [15]:

1. control of ventilation rates and air distribution to maintain acceptable indoor air quality (IAQ)
2. control of ventilation rates and air distribution for direct cooling when appropriate
3. control of ventilation rates and air distribution for night cooling

The minimal ventilation to maintain acceptable IAQ is reasonably controlled automatically as personal detection of air quality conditions is generally too subtle to be considered. This is achieved at a coarse level through building configuration and proper design of the topology of the natural ventilation system and at a fine level through proper sizing of the components used in this system, as well as the regulation of key component openings [18]. Pressure responsive self-regulating vents achieve this passively, and thus tend to gradually replace conventional trickle ventilators [15].

Control of ventilation for direct cooling may best be left to building occupants as occupants control appears to be strongly related to productivity [18]. Nevertheless, there are some obvious pitfalls with occupants control including problems of windows left open unintentionally and the need to limit daytime ventilation when night cooling operation is active [15]. Thus, operable windows with mechanical over-rides may have to be used in practice.

It is interesting to note that in a free-floating naturally ventilated building, control might not be as important as in fast responding air conditioned buildings [19,20]. By controlling the cooling effect of night ventilation Liem and Passen [20] found that there was no difference between different predictive control strategies. Five control strategies were compared by modeling their effect on a given building. It was found that the effect of some form of control is required because it improves the performance of the system. It was shown that temperatures can be maintained below certain values for 100–200 h more in a building with some predictive control than in a night ventilated buildings without any control. However, the precise mode of control did not significantly affect the performance.

By using simple controls based on external temperature, radiation and internal gains, Kolokotroni et. al. [19] found that it is possible to improve the performance of the building, so that periods of uncomfortable conditions are limited. On the other hand, it was found that one important aspect to be addressed in developing control strategies for naturally ventilated buildings is to ensure that building occupants have the freedom to alter the conditions, and perceive an almost instantaneous change in the direction of the requested conditions without affecting the performance of the overall system. Without this flexibility, user's satisfaction can be low due to the `big brother knows best' approach used in more traditional BMS control strategies and are not usually acceptable by the users in a more free-floating building.

2.3.2 Dynamic insulation

Dynamic insulation is a form of a "Breathing Wall" construction which allows the movement of air and moisture through the external walls of a building. It provides a method for reducing building envelope heat losses. However, it has been claimed that energy saving produced by dynamic insulation alone is small relative to that obtained in conjunction with conventional air heat recovery methods [21].

Nevertheless, it has been shown that a properly designed dynamically-insulated room can provide thermal comfort with energy savings given that the room is air-tight and provided with controllable heat input [22].

Another advantage with dynamic insulation is that moisture can be prevented to get into the wall from the interior [21] given that the wall operates in contra-flux mode. However, this can be difficult to assure due to altering internal and external conditions, in particular if the building envelope is not completely airtight.

Further, dynamically-insulated rooms might pose problems of local thermal discomfort when the interior surface temperature is well below the room air temperature [22].

AIS-Utvikling AS is a Norwegian company that has developed a new solar heating concept using an air based solar thermal collector with dynamic insulation. Measurements undertaken at the Norwegian Building Research institute indicates an energy saving potential of around 350 kWh/m^2 for this concept [2]. The encouraging results have been verified through a pilot study project in Ørakerveien, Oslo, where 20m^2 of solar thermal collectors provides heat to two domestic dwellings.

2.4 Heat storage systems

2.4.1 Thermal mass

Utilising the thermal capacitance of a heavy weight building can significantly reduce a buildings cooling demand in the warm season. In order to ensure efficient operation, a holistic strategy should be implemented, assuring proper integration with the ventilation and control system.

Exposed thermal mass in both ceilings and floors is desirable. As for natural ventilation systems, suspended ceilings should thus be avoided. The non-presence of suspended ceilings can also be advantageous for natural ventilation systems and the possibilities for highly placed windows and taller floor-to-ceiling height, and thus larger volume (buffer). Due to advances in building simulation technologies, such combined systems can easily be optimised.

In the cold season, excess heat caused by internal gains from people, lighting systems and equipment can be absorbed in the thermal mass during daytime to be released during night time, and thus reduce the need for space heating at night.

Construction elements with high thermal mass can also be used to absorb solar energy. Many possibilities exist for taking advantage of this absorbed heat. Again, a holistic strategy and optimisation is essential in order to achieve the full benefits of this potential.

In order to reduce peak heating loads, a high capacitance building can be preheated at night when the energy demand is low, reducing the peak demand in the morning hours. However, high thermal capacitance buildings' ability to store heat can also increase the required power output from the heating system during start-up.

2.4.2 Phase change materials

Negano et al. claims that using the thermal energy storage of phase change material (PCM) which has a melting point from 15 to 25 °C is to be one of the most effective strategies related to night cooling [23]. PCMs have also attracted much interest in passive and active solar systems, in which case they are designed with a higher melting point, typically around 50-60 ^{0}C.

Sarl [24] list the following advantages related to use of PCMs : (1) they have high latent heat storage capacity (2) they melt and solidify at a nearly constant temperature (3) a small volume is required for a latent heat storage system, thereby the heat losses from the system maintains in a reasonable level during the charging and discharging of heat.

However, phase change materials normally have very low heat conductivity, thus internal heat transfer enhancement techniques such as fins can be advantageous. Internal heat transfer enhancement is essential, especially in a solidification process where the main heat transfer mode is conduction [25].

PCMs have been a main topic in research for the last 25 years, but although the information is quantitatively enormous, it is also spread widely in the literature, and difficult to find. A general review of the history of thermal energy storage with solid–liquid phase change has recently been carried out by Zalba et. al. [26]. The review focus on materials, heat transfer and applications and lists 150 materials used in research as PCMs, and about 45 commercially available PCMs.

PCMs are usually hydrated salts (such as Glauber's salt), paraffins, non-paraffins and fatty acids [27]. Figure 2-14 below presents an overview from Abhat [28].

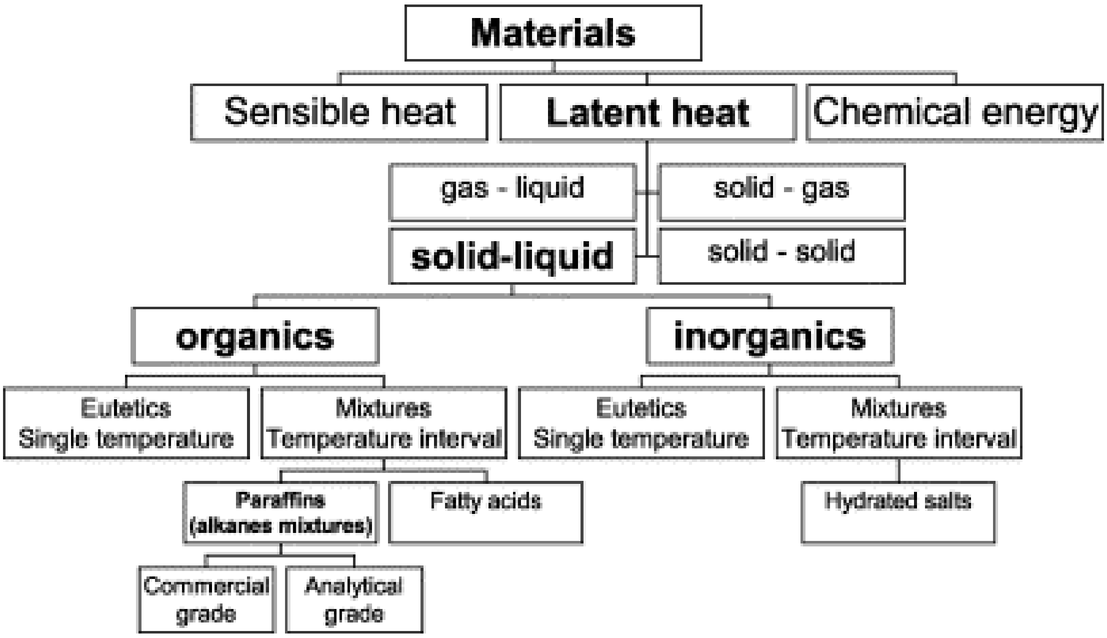


Figure 2-14 Classification of the substances used for thermal energy storage [28]. PCMs are materials capable of storing latent heat through change between the solid and liquid phase.

The utilization of PCMs has improved significantly over the last 25 years and available information has been given to a great number of them. Nevertheless, most PCMs cannot meet the apparent criteria of low cost, availability and simplicity of operation combined with harmless applicability [29]. Most organic PCMs are paraffins or waxes. Generally, inorganic PCMs are cheaper than organic PCMs, but unfortunately, reliable data and information for these inorganic PCMs with regard to the life span, stability, toxicity and corrosion is often unavailable [23]. Applications with paraffin wax have therefore traditionally been the most frequently tested. For example, Turnpenny et al. [30] constructed and tested of a novel latent heat storage (LHS) unit incorporating heat pipes embedded in a paraffin wax PCM for use with night ventilation. Their results indicate that the combination of the prototype system and night cooling provides a rate of heat storage adequate to prevent a room from overheating in normal UK summer conditions, and that the system offers substantial benefits over alternative systems such as chilled beams and air conditioning.

However, one very important subject in applications like the use of PCMs in buildings is that of safety. Fire regulations have limited the application of paraffin wax PCM in real buildings. At present, various inorganic PCM's therefore seems to get increasing attention for building applications. Nagano et al [23] evaluated the potential of $Mn(NO_3)_2 \cdot 6H_2O$ (manganese (II) nitrate hexahydrate) as a new PCM. It was concluded that the thermal properties gave it high potential as a safe and well performing PCM for thermal energy storage in cooling systems.

The mixtures of inorganic salt hydrates, water and nucleating and stabilizing agents are the most commonly used eutectic PCM for cool storage application [31]. But since these eutectic mixtures are to some extent difficult to prepare and manage, other PCMs whose raw materials are easily available in tropical countries are being considered. Salient implication on fatty acids as PCMs has been cited in previous studies [32,33].

Several innovative methods to infuse PCMs into building materials has been demonstrated [34,35,36]. Further, Manz et al. [37] presented and investigated an external wall system for solar space heating and daylighting composed of transparent insulation material (TIM) and translucent phase change material (PCM), see Figure 2-15 below. Both the visual and thermal performance was evaluated through measurements and simulations. Results were promising, but it was reported that backscattering of solar radiation in the solid state reduced the heat and light gains, resulting in reduced system performance.

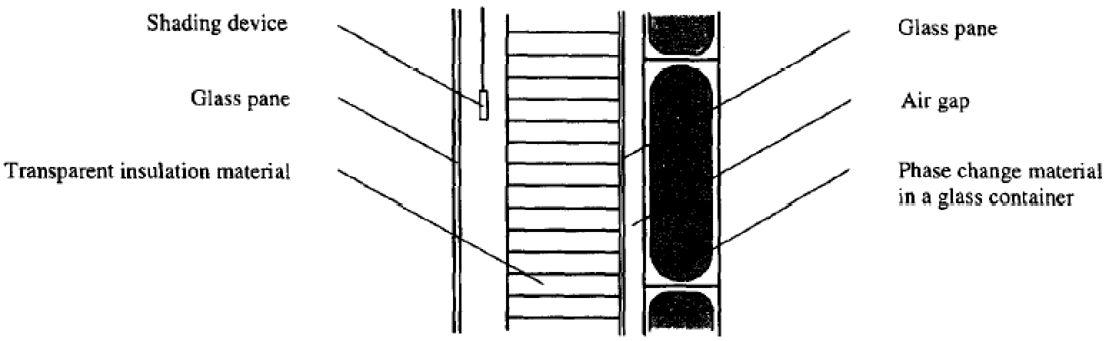


Figure 2-15 Prototype of a transparent insulation material (TIM) – Phase Change Material (PCM) external wall system for solar space heating and daylighting [37].

Even though many applications of phase change materials in buildings have been presented in the literature, few if any focus on the aesthetical aspects. Importantly, clever application of PCMs should potentially provide many visual possibilities in addition to the thermal advantages.

2.4.3 Ground coupled systems

Embedded ducts utilise the thermal mass in the duct walls and the surrounding ground for passive heating and cooling. However, it should be noted that embedded ducts can only be defined as building integrated energy system if part of the building basement.

In wintertime, when outdoor temperatures are low, the intake duct contributes to preheat the ventilation air due to the relatively warmer ground. On hot summer days, the embedded duct provides a cooling effect due to sensible cooling.

The cooling effect explains why embedded ducts have been used for thousands of years in hot arid regions, particularly in countries around the Persian Gulf [38] often in configuration with a wind tower. In these traditional ducts the air is cooled down due to sensible, and often also evaporative cooling. The effects are illustrated in Figure 2-16.

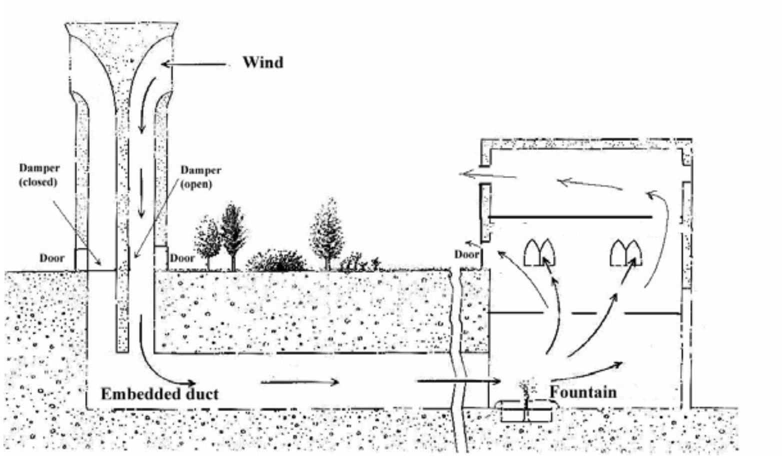


Figure 2-16 Illustration of a traditional embedded duct and its related cooling effects. When the walls are colder than the ventilation air temperature (due to the colder ground temperature), air is being cooled. This is known as sensible cooling. In addition, when trees, shrubs and grass in the ground over the embedded duct are watered, water seeps through the soil and keeps the inside surface of the tunnel walls damp, providing also evaporative cooling. A fountain at the air inlet to the building further increases this effect.

A more recent example is the embedded air intake duct in the hybrid ventilated Medå School in Grong, Norway, providing about 130 kWh of passive cooling pr. day during hot days, with a maximum cooling power of about 12-14 kW during peak hours [14]. During the coldest winter-months the system provides about 1000 kWh per month of heating energy. The surface area of the duct is about 180 m^2. However, it should be noted that the heat transfer with the duct walls, and hence the cooling performance, is significantly enhanced by a supply fan installed at the duct entrance

3. Active building integrated energy systems

Although they cannot be defined as passive, many energy systems are designed to utilize the environment to avoid or meet a significant proportion of the residual demand. These systems either produce power, or they operate in conjunction with some mechanical devices to utilize renewable energy to provide heating and cooling.

Here it has been chosen to separate between solar cooling systems, systems related to ventilation, heat storage and utilization of low grade energy and finally systems related to power generation.

3.1 Solar cooling systems

Solar cooling systems often contains several components that can not be defined as fully building integrated, e.g. pumps, heat exchangers and desiccant wheels. However, part of the system can often be integrated in the building envelope or fabric, e.g. air solar collectors and desiccant beds. These systems can therefore be classified as active building integrated energy systems.

Desiccant cooling

An example of a partly integrated solar cooling system is the solar desiccant enhanced radiative cooling (SDERC) system presented by Lu and Yan [39]. Figure 3-1 illustrates the major operating mechanisms. The desiccant bed encapsulated within glazed roof and side walls consists of selica gel particles that are heated and dried at daytime under sunny conditions. During night time or on a cloudy day, cold humid air, the air passes through the desiccant bed and is dehumidified; i.e. the moisture contained in the air is adsorbed by the silica gel particles. The resulting hot, dry air passes through and transfers heat to a metal duct. If at night, heat is radiated from the outside metal surface into the dark sky to achieve a radiative cooling effect. Finally, the air is evaporatively cooled and conducted into the conditioned space. In particular when the desiccant bed was placed on the roof, Lu and Yan concluded that the system was very energy-saving, with magnificent coefficients of performance (COP). The payback time for the system in Taiwan was estimated to one year when comparing with a regular air conditioning system.

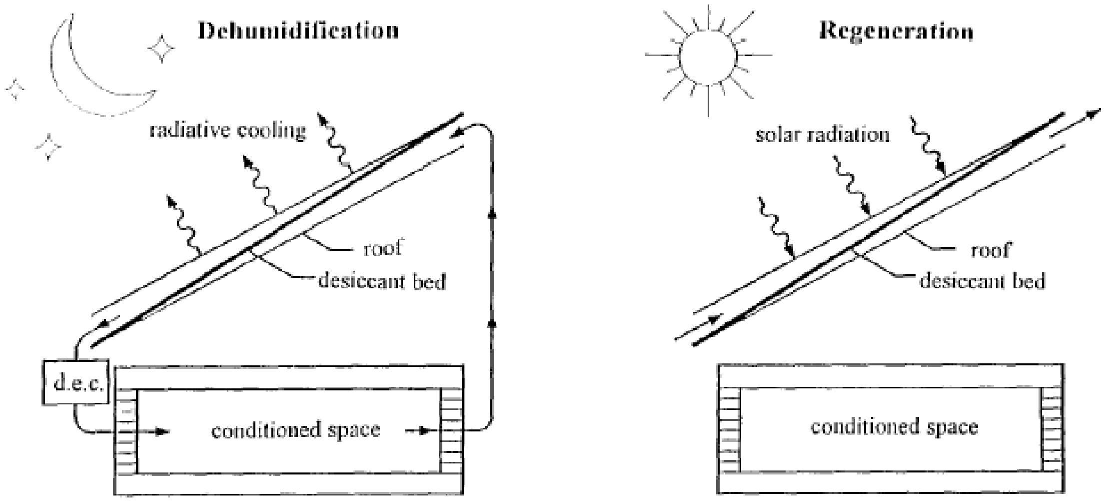


Figure 3-1 The principle operation modes of a solar desiccant enhanced radiative cooling system [39]. Note that d.e.c. stands for direct evaporative cooling.

Another option is combining regular components in a desiccant cooling system with a solar thermal collector, the collector serving as the primary source of energy for the process. An example of two possible combinations has been proposed and evaluated by Henning et. al. [40], se Figure 3-2 below. They concluded that such simple system configurations, with the solar collector as the only heat source for the cooling cycle, are promising concepts in cases where the users accept that the indoor climate does not fulfil standard comfort criteria for a few hours during the cooling season. However, Henning et. al. also evaluated various combinations with buffer storages and auxiliary heater able to satisfy fixed indoor conditions. It was concluded that such combined systems are feasible both from an energetic as well as from an economic point of view. However, it should be noted that the performance of solar assisted desiccant cooling systems is very climate dependent

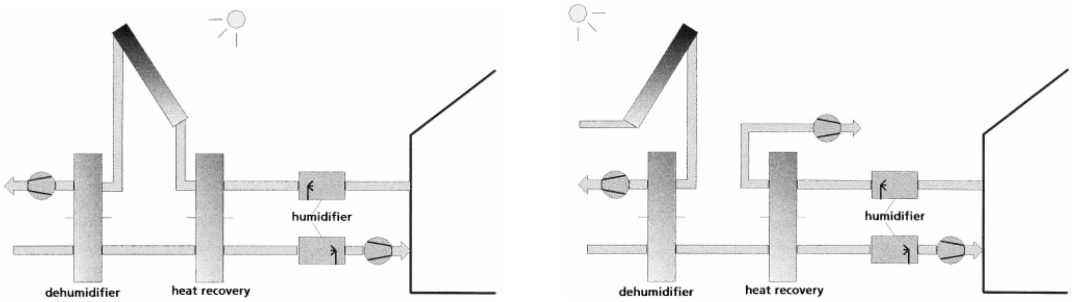


Figure 3-2 Desiccant cooling system with solar air collector as only heat source. System integrated mode (left) and ambient air mode (right).

3.2 Systems related to ventilation, heat storage and utilization of low grade energy

This group of systems covers systems for slab cooling, integrated rock (pebble) beds and chilled ceilings.

3.2.1 Slab cooling

This technique utilizes the thermal capacity of the building structure to store a large amount of energy leading to a small variation of the structure's temperature. In this way, day-time heat gains are absorbed by the structure and stored until they can be purged with night cooling. At the moment, most Fabric Energy Storage systems (FES) utilize floor and ceiling slabs. The basic principle of FES is to bring air or water into contact with the slabs in the building envelope. The FES systems provide flexibility to work with other technologies like natural and mechanical cooling, evaporative cooling etc.[43]

Air slab cooling techniques include [41]:

1. The FES slab (Trade name Termodeck). This is a prefabricated rectangular concrete block with typical dimensions of 4 m length by 1.2 m width by 0.3 m depth. The interconnection of the hollow core slabs establishes the air paths, through which cooled or heated air is discharged via ceiling diffusers to the indoor spaces.

2. The plenum-and-slab system, which provides air through hollow core floor slabs, interconnected between a number of large air plenums. Operating experience indicated that this system is only suitable for floor slabs at the ground floor.

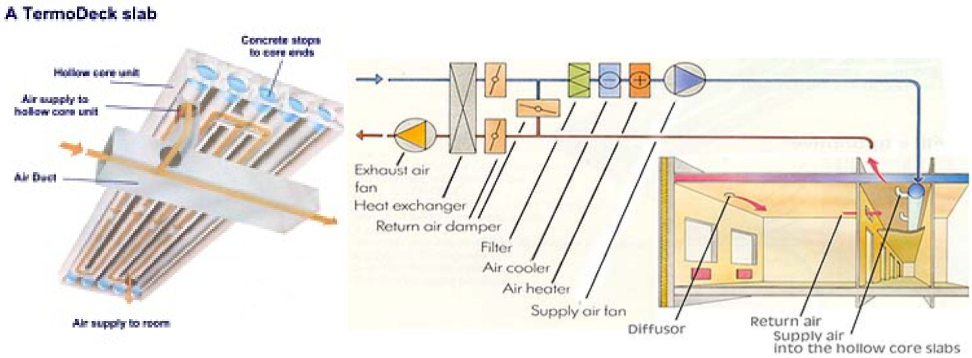
3. The hollow-core screed, which produces cross air paths between a layer of hollow-core screed and a solid concrete slab. The advantage of this system is that it can be retrofitted into an existing building and consists of square grids of semicircles, 37.5 mm in radius, covered with 75 mm thick screed. The narrow air channel design of this method may present difficulties in maintenance.

In general, the above methods provide low capital and operating cost but their potential depends on the level of overnight ambient air temperature and provides sensible cooling only. In the case that water is used to cool the slab, the pipe-work can be in a layer of screed of about 75 mm thick or a layer of solid concrete slab exposed to the conditioned space. A heat exchanger, a chiller or any other apparatus can cool the circulating water but water leakage of the embedded piping and replacement of the embedded pipe-work due to corrosion and erosion problems are serious drawbacks of the method.

The TermoDeck system seems to be one of the best performing and most popular FES systems, and will therefore be treated somewhat more in detail here.

TermoDeck

Termodeck is a fabric energy storage system developed in Scandinavia by two Swedish engineers Mr.Loa Andersson and Mr E.Isfalt in the 1970s. The system uses the slab as both a structural component and also a means of ducting ventilation through the building through oval or round shaped ducts (hollow-cores) within the concrete structure. With the TermoDeck systems the slab temperature is very close to the room temperature, thus assisting comfort and making it suitable for displacement ventilation as well as mixed flow ventilation. In Summer the supply air fans at night bring in the cool air into the hollow slabs to cool the building and the warm outside air is cooled in the daytime.



A good and well studied example of successful application of the TermoDeck system is the Elizabeth Fry Building (John Miller and Partners). The building uses mechanical ventilation with heating and no mechanical cooling at all. Mixed flow ventilation is used throughout the building except the Lecture Theatre where displacement ventilation is used. The building has created much interest and is being closely monitored for energy consumption and occupant satisfaction by the PROBE[i] team. The slab temperature is kept at 22°C with a dead band of 1/2°C for heating and 1.5°C for cooling. TermoDeck's inventor Loa Anderson predicted with computer modelling that at an external peak of 29°C the peak internal temperature should not rise above 26°C with a daily average room temperature around 22°C.

Figure 3-3 The main entrance of the Elisabeth Fry building (left). An IT resource room is located directly above the main entrance, and follows the gentle curve of the elevation (right). Note the row of annular soffit diffusers connecting directly to the exposed TermoDeck slabs.

[i] Professional Organization of Building Examiners, an independent organisation monitoring buildings after occupation.

The PROBE team conclude that of 12 recently constructed buildings in the UK the Elisabeth Fry building had the highest occupant comfort scores and are also recorded the highest comfort scores recorded by the independent survey specialists Building Use Studies. Typical energy consumption for heating and ventilation for the UK is around 200 kWh/m2./y. The gas energy consumption in the Elisabeth Fry building was in 1997 only 33kWh/$m^{2.}$ y, while the total electric energy consumption was 61 kWh/$m^{2.}$ y.

The TermoDeck system has since been installed in hot climates such as Saudi Arabia where the slab tends to be kept at a temperature of 19°C. The manufacturers claim that the cooling plant capacity and associated equipment is substantially reduced and the Elizabeth Fry research appears to confirm significantly reduced cooling loads and running costs.

In Norway, the TermoDeck system was installed in some buildings in the early 80’s. The thermal performance was reported to be good. However, various problems were identified42:

- Smell and dust from the un-treated concrete ducts.
- The connections between the ducts were not tight, resulting airflow at unwanted places and reduced performance.
- The ventilation systems were often under-sized, resulting in insufficient ventilation airflow to maintain comfort.

Most of the TermoDeck systems delivered in this period have therefore been rebuilt in order to increase the airflow rates and avoid the problem with concrete dust. The ducts within the concrete structure have therefore been abandoned, and replaced by regular HVAC duct systems. Since the 1990, there have been installed few, if any, ThermoDeck systems in Norway [42].

The TermoDeck-system may be used with mixed flow or displacement ventilation, night cooling, free cooling, desiccant cooling, packaged equipment cooling, DX equipment, chilled water equipment and so is versatile.

3.2.2 Integrated rock beds

Rock beds (or pebble beds) storage units of solar air heating systems can be night-cooled during summer to store “cold” for use the following day. This can be accomplished by passing outside air during the night when the temperature and humidity is low, through an optional evaporative cooler, through the pebble bed and to the exhaust. During the day, the building can be cooled by passing room air through the pebble bed [43].

If the pebble beds are situated within the building fabric, e.g. in a cavity between a transparent insulative wall (TIW) and the inner wall, the system can be defined as building integrated.

A number of applications using pebble beds for solar energy storage are given in [44].

3.2.3 Chilled ceilings

Chilled ceilings are surfaces within the ceiling which are cooled by chilled water circulation for the removal of heat gains, leaving ventilation and humidity control to the air-distribution system [43]. They can provide a cooling system able to efficiently utilize low-grade energy.

An essential feature of these systems is that the entering chilled water temperature should be above the room dew-point by at least 1.5 °C to allow for control tolerance, in order to avoid condensation from forming on the cooling surfaces. Typically, chilled ceiling systems have a flow water temperature of 14–15 °C and a temperature increase across the exchange device of 2–3 °C [45].

The cooling surfaces may take any number of forms and are classified into radiant panels, convective panels and chilled beams.

In the case of radiant and convective panels, the cooling surface covers large areas of the ceiling. The radiant panels depend mainly on radiation heat transfer between their surface and the conditioned space, and can be of a metal or concrete slap type. The radiant panels can be embedded within the false ceiling or be accommodated in shallow ceiling voids, see Figure 3-4 (left). Chilled beams work in a similar manner to convective panels. In this case, the finned coils are located into a unit, which can also supply ventilation air, see Figure 3-4 (right).

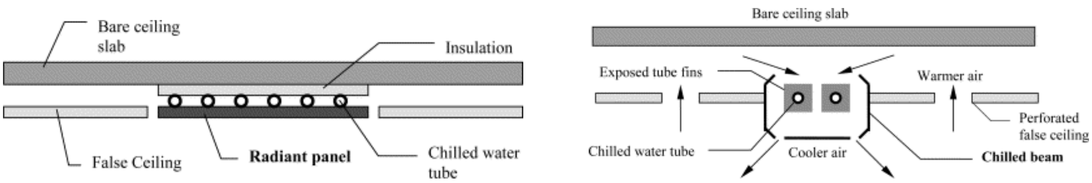


Figure 3-4 Radiant panel embedded within the false ceiling (left) and chilled beam (right) [43].

3.3 Power generation systems

Power generation systems are either building integrated photovoltaics (BIPV) or building integrated wind turbines.

3.3.1 Building Integrated Photovoltaics (BIPV)

The photovoltaic (PV) effect is based on the transfer of the energy of light quanta to the electronic subsystem of a semiconductor and the collection of this energy within a short time - before it is converted into heat. The photovoltaic effect can be achieved by using many different semiconductor materials, the most commonly used is silicon.

The efficiency for conversion of light into electricity depends on the cell material. The conversion efficiency of modules of amorphous silicon cells varies from 5-10 %. Modules of poly-crystalline silicon have a conversion efficiency of about 10-15%, while modules of mono-crystalline silicon cells have an efficiency of 15-20%.

The building facades are important for the architectural expression of a building, and are often designed to express the company's profile. Facade integrated PV modules can add exciting and elegant features to the building envelope while supplying clean electricity to the building.

BIPV may be an integral part of many types of building integrated energy systems. For example, PV integrated into a transparent façade element may be used as a shading element, as part of a thermal solar collector for water heating or as a thermal solar collector for preheating ventilation air, e.g. when used in conjunction with a double facade, se Figure 3-5 (right).

Figure 3-5 PV-modues integrated into the roof construction of two storey undetached houses at Hamar, Norway (left) and into the combined thermal/PV “BP-double skin facade”, NTNU, Gløshaugen (right).

In addition, research is being done to develop PV-powered “smart” windows that can change colour and light transmissivity according to the need for reducing solar gains, and thereby lowering the cooling needs. The research in this area is focused on two different technologies; one is *photovoltaic-powered electrochromic devices*, the other is *photoelectrochromic cells*.

Building Integrated Photovoltaic Systems is defined as an own work package (WP 2.4) in the SmartBuild project. For further details, see the state-of-the art report on Building Integrated Photovoltaics in Smart Energy Efficient Buildings [46].

3.3.2 Building integrated wind turbines

Ducted wind turbines

When the wind blows at right angles to the face of a tall building stagnation will occur at about two-thirds of the total height. Below this level, a rolling vortex is formed; above it, the air rises to pass over the roof. If the roof is flat, the airstream will separate from the upwind edge, possibly reattaching some distance downstream. A ducted wind turbine is designed to draw air from the high-pressure region in the upwind face of the building and exhaust it into the low-pressure region above the flat roof. The device will operate efficiently over a 60% range of wind directions47. It forms a robust and unobtrusive alternative to conventional wind turbine designs, and is particularly suitable for integration into a larger structure such as a building. Another possible application is in remote rural areas, for battery charging or other low-power applications The power output depends on various parameters. These devices are very much in the research and development stage at this moment. Some prototypes have been successfully implemented, e.g. on the lighthouse-building in Glasgow, see Figure 3-6 Ducted wind turbines on the Lighthouse Building in Glasgow (left).The power output from each of the 0.6 m diameter turbines is estimated to approximately 200 kWh/year.

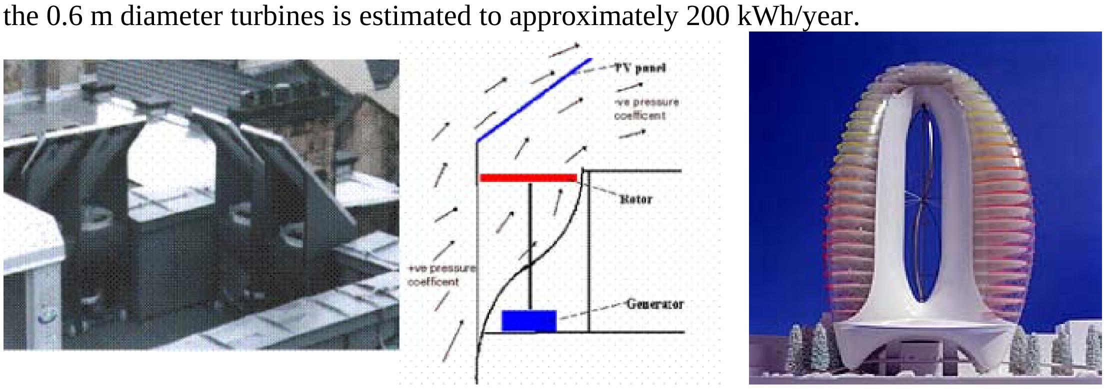


Figure 3-6 Ducted wind turbines on the Lighthouse Building in Glasgow (left). Proposal for an office building with integrated helical wind turbine (right).

Helical wind turbines

Vertical axis wind turbines are able to operate at lower wind speeds and are less stressed mechanically by turbulence than horizontal versions. They are therefore more adapted to be mounted on buildings, and there are several versions available on the market. However, they are still undergoing development. When it is fully appreciated that these machines are reliable, silent, low-maintenance, easy to install, competitive on price and aesthetically appealing, it is not unlikely that they may be widely applied [48]. A proposal for building integration, presented by Future Systems[i], is shown in Figure 3-6 (right) above.

4. Various relevant literature and internet sites

As already noted the topic of *Building Integrated Energy Systems* is fairly broad and therefore there is quite a bit of literature available. In an attempt at creating some structure, the literature has been organized in four sub-sections: books, reports, papers, and internet. Further it has been classified as:

- [A] Recent publication and high relevancy to *BIES* and *SmartBuild*
- [B] Publication with background information or more than 10 years old

Also, where an electronic version of the document is available this is indicated by [pdf].

Since subtask 2.2 does overlap somewhat with both subtasks 2.3 and 2.4 one will probably also find an overlap of literature on both *PV* and *Daylighting* – however for en extensive list of literature for these topics one should refer to the respective state-of-the-art reports.

Books

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Wigginton, M. and J. Harris (2002). *Intelligent Skins*. Architectural Press, Oxford, UK. [A]

Schittich, Christian (2001). *Building Skins. Concepts - Layers - Materials.* Birkhauser - Publishers for Architecture, Basel, Switzerland [A]

Levermore, G. J. (2000). *Building Energy Management Systems. Applications to Low-Energy HVAC and Natural Ventilation Control*. E&FN Spoon, London, UK. [B]

Smith, Peter F. (2003). *Sustainability at the Cutting Edge. Emerging technologies for low energy buildings*. Architectural Press, Oxford, UK. [B]

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