Recent developments in the intelligent refurbishment of non-domestic buildings

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Abstract

This paper describes the state-of-the-art in the refurbishment of non-domestic buildings, and describes some of the innovative technologies that are in development and that could improve energy efficiency and reduce building emissions radically. By reducing heat and mass transfer through the envelope, the main energy consuming factors are tackled by reducing envelope air leakage, externally and internally insulating with vacuum and nano-structured technologies, reducing heat gains and losses with low U-value vacuum glazing and power generating windows, and coating external facades with self cleaning and pollution controlling, and energy scavenging materials. As heat gains and losses through the envelope are reduced, the use of energy within the building is tackled by refurbishing with low energy lighting systems. Innovative light fidelity lighting (LiFi) offers lower energy consumption, improved control of lighting, lower cost and quicker payback periods, and large area plasma lighting can both reduce lighting consumption and recover some heat generated in the lighting system for other services. Once heating, cooling and electrical loads are reduced, the plant requirement is reduced. Innovative low energy and renewable technologies can be used to minimise primary energy consumption and CO_2 emissions. Phase change materials (PCMs) store and release latent heat and can moderate internal temperatures in climates where there are medium to large temperature swings between day and night. Windcatchers can ventilate deep plate buildings using natural ventilation and be incorporated with low energy/renewable cooling and dehumidification systems. Biomass CHP systems offer a renewable source of heating and power. Heat pumps driven by low carbon and renewable sources can provide high performance and reliable heating and cooling systems.

Keywords: intelligent buildings, adaptive buildings, passive and active, low-carbon

1. Introduction

Buildings are responsible for about 45% of Europe's total primary energy consumption and carbon dioxide emissions, with non-domestic buildings accounting for about a third of the total (IEA, 2008). The EU is committed to reducing CO_2 emissions relative to the base year of 1990 by 20 per cent by 2020 and by 80% by 2050. As is pointed out in the EC (2001) and

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EC (2005), rational use of energy and integration of renewable energy technologies could substantially improve the energy performance of buildings, reducing the conventional energy demand in new and existing buildings by at least 20% and substantially contributing to reducing energy intensity. The European Directive on Energy Performance of Buildings (EC, 2003) aimed to improve the overall energy efficiency of new buildings and large existing buildings (>1,000m^2). The most recent update of the directive (EU, 2010) calls for cost-optimal solutions for both new buildings and for the renovation of existing buildings. This should be done by the implementation of advanced measures of technologies and materials in the building envelope, HVAC systems and on-site energy generation. A comprehensive overview has to be established, where different combinations of commonly used and innovative measures should be assessed.

Developments in sustainable energy technologies and building management systems have enabled new buildings to meet the European Directive on Energy Performance of Buildings. However, at current replacement rates of less than 1% mean that at least 75% of the current building stock will be in existence in 2050. Xing *et al* (2011) described some of the technologies currently in development. There is a clear need to develop new technologies and strategies in this area to address energy efficiency with appropriate procedures and building techniques, while taking account of the social acceptance by the buildings' users and the return on investment.

Mortimer *et al* (1998) produced carbon dioxide abatement curves that showed the cost effectiveness of various energy efficiency measures ranging from replacement of tungsten filament lamps with compact fluorescent lamps, replacement of gas boilers with condensing boilers, to the installation of loft and cavity wall insulation. It was shown that up to 2.5million tonnes of CO_2 per year could be saved cost effectively (the cost savings (£/tonne C) were greater than or equal the cost of implementation) at a discount rate of 8%. They concluded that for UK commercial sector using electricity supplied by gas fired power stations, the most cost effective measures were:

- Condensing natural gas boilers
- Compact fluorescent lamps
- Low energy computing equipment/accessories
- Thermostatically controlled valves
- Improved air conditioning systems
- Fuel switching

It was shown that replacement of single with double glazing was not cost effective, and that loft and cavity wall insulation had only a low cost effectiveness. However, it was pointed out that replacement glazing was commonly implemented for reasons in addition to cost effectiveness alone, such as the replacement glazing at end of life, the reduction in maintenance costs or the reduction in noise pollution. Loft insulation was found to be relatively ineffective because the majority of non-domestic buildings were flat roofed. Cavity wall insulation was ineffective because the majority of buildings were single wall masonry or concrete construction, or steel framed, glazed curtain walled construction. Measures such as external and internal wall insulation or innovative roof retrofitting options were not considered.

Georgopoulou *at al* (2006) analysed greenhouse gas emission reduction potential for domestic and non-domestic buildings in Greece. In the non-domestic sector up to 70% of the potential reduction measures came from energy efficient electricity use, including low energy light bulbs, building management systems and ceiling fans. Investigating measures that were cost effective with economic support policies and subsidies, it was shown that win-win measures (measures in which abatement costs are less than or equal to the cost savings at a 6% discount rate) were around 4.5million tonnes of CO_2, representing 88% of the technically feasible carbon abatement measures. This did not include high cost measures such as external insulation, double glazing and solar thermal hot water systems. These additional measures represented about 8% of the technically feasible at a 6% discount rate.

We have divided the retrofit technologies into some general themes. The reduction in energy consumption as one of the major hurdles to cutting carbon dioxide emissions as well as reducing the running costs of buildings, reducing reliance on imported fossil fuels and increasing the security of our energy supply, and so tacking envelope losses is important in reaching a near Zero Energy Building. As heating and cooling loads are reduced, the energy used in operating the building increasingly dominates and so energy efficient and low carbon technologies that reduce energy consumption will be developed. With heating and cooling loads reduced, building services plant and machinery can be reduced and more efficient and low carbon and renewable technologies can be deployed.

2. Innovative and emerging technologies

2.1 Envelope

One of the main methods of improving thermal insulation both to reduce heat losses in cold climates and heat gains in hot climates is the installation of external or internal insulation. (Dylewski and Adamczyk, 2011, Anastaselos *et al*, 2009, Cabeza *et al*, 2011, Ballarini and Corrado, 2012). Many technologies are in development to improve thermal performance such as aerogel (Kamiuto et al 1999, Smith et al 1998), multi-layer insulation (Eames, 2009), gas-filled panels (Haller, 1999) and vacuum insulation (Fricke *et al*, 2008).

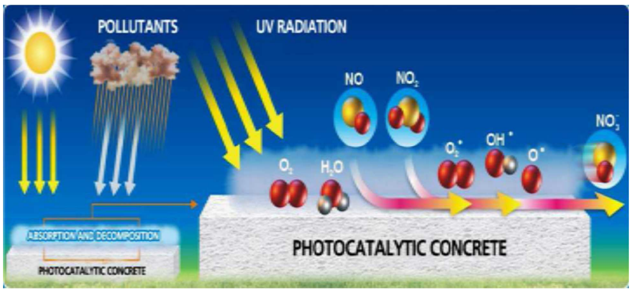
2.1.1 Biocrete Cladding: Biocrete sandwich panel cladding is a high strength highly insulated vacuum paneling system that can reduce heat transfer by up to 70% compared to standard insulation systems. It is produced using recycled paper components (hardboard skins with honeycomb cores with glass grit filling) with recycled glass fibre epoxy skins and multi-foil insulation, giving the equivalent thermal insulation from a 100mm thick panel as would be achieved from a 500mm Rockwool core panel. Aggregates and cementitous materials are highly energy intensive and contribute at least 5% to global carbon dioxide production. Society produces large quantities of waste, much of the waste is reusable, and its conversion has a minimal carbon footprint. The material content of Biocrete can vary depending on local raw material sources, but is mainly made up of waste paper/wood, grit/glass, aluminium and plastics.

2.1.2 Vacuum insulated panel (VIP): In many instances external insulation is unable to be used because of asthetic or practical reasons, therefore internal insulation can be effective in reducing heat gains and losses across envelopes. Vacuum insulated panels have been developed over a number of years, but have major drawbacks such as the loss of vaccum over time due to damage to the panels or leakage and therefore a loss of insulation performance. Innovative vacuum insulation panels that use nano-scale honeycomb structures to enable large volumes of air to be evaculated but provide machanical strength for the panel. The panels can have thermal conductance of 0.0036W/m.K, for a 25mm thickness VIP panel equivalent to a 165mm polyurethane insulation panel. The core material is a composition of silica and carbon, which produces a low-density, porous nano-structure. These cores are encapsulated under vacuum in a multi-layer metallised film, thus offering a rigid flat insulating panel.

2.1.3 Composite external panel: Composite panels inspired by the aerospace industry have potential for application in the commercial refurbishment sectors. Light-weight, strong and with low thermal transmission properties, composite panels can be embedded with active fibres to alter their performance dynamically, and integrate energy harvesting technologies into the envelopes of buildings.

2.1.4 External surface coating: Titanium dioxide has been used as a photocatalyst for self cleaning surfaces such as windows. It is however not ideal for use with conventional building materials such as brickwork and concrete walls because it can easily lose its photocatalytic capacity. A new photocatalytic coating that incorporates an oxidation catalyst (TiO_2) into an active oxide matrix to destroy organic matter and toxins, to inhibit the growth of algae and mould, inorganic nano-particles to minimise the adhesion of contaminants. The coating material can be used either as a self-cleaning coating on a surface of a building or can be used as a self-cleaning and pollution reducing coating for buildings in high pollution environments (Figure 1). The coating will be environmentally-friendly and long lasting and could be applied by spray, dipping or other simple coating methods at ambient conditions. Application of the coating will reduce the heat loss resulting from rainwater absorption by conventional wall materials. Coatings that selectively absorb and reflect solar irradiation help to reduce solar gain from roofs in the summer and reduce infra-red radiation losses in winter. High performance glazing often uses spectrally selective coatings that perform the same function.

Figure 1. Illustration of photocatalytic concrete



2.1.5. Vacuum tube glazing: To improve the thermal performance of a glazing unit, a novel window technology using glass evacuated tubes and triple glazed evacuated panels has been developed. The vacuum tube glazing consists of two concentric glass tubes. The air is evacuated from the space between the glass tubes to form a vacuum, which eliminates conductive and convective heat loss. To improve the thermal performance of a glazing unit, a novel window technology using glass evacuated tubes has been developed, as shown in Figure 2. Each evacuated tube consists of two glass tubes. The outer tube is made of extremely strong transparent glass that is able to resist a large impact. The inner tube is also made of a glass tube. The air is evacuated from the space between the two glass tubes to form a vacuum, which eliminates conductive and convective heat loss. To maintain the vacuum between the two glass layers, a barium getter is used (the same as in television tubes). During manufacture, this getter is exposed to high temperatures which cause the bottom of the evacuated tube to be coated with a pure layer of barium. The vacuum tubes are enclosed within a frame. The tubes are covered with two sheets of glass with liner lenses to minimise vision distortion. The vacuum tubes can provide a much lower U-value (below 0.7 W/m^{2}K) than conventional glazing. The evacuated triple glazing units use the same technology to maintain a vacuum in flat panels.

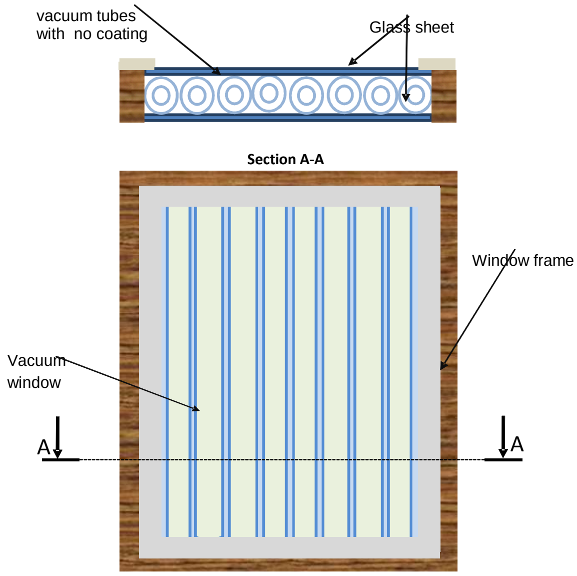


Figure 2. Vacuum tube window

It is expected that the vacuum glazed windows will reduce heat losses through glazing by 50% compared to the systems currently in place and 20% compared to high performance triple glazing.

2.1.6 Heat insulation solar glass (HISG): Windows are vital parts of a building in that they allow daylight into the building, reducing the need for artificial lighting and improving the occupant's health and wellbeing. However, windows are one of the major causes of energy consumption in buildings. Glazing that contains embedded structures are being developed so that light and heat can be selectively admitted to provide the required illumination and heat transfer. Heat will be transmitted and stored so that very little additional

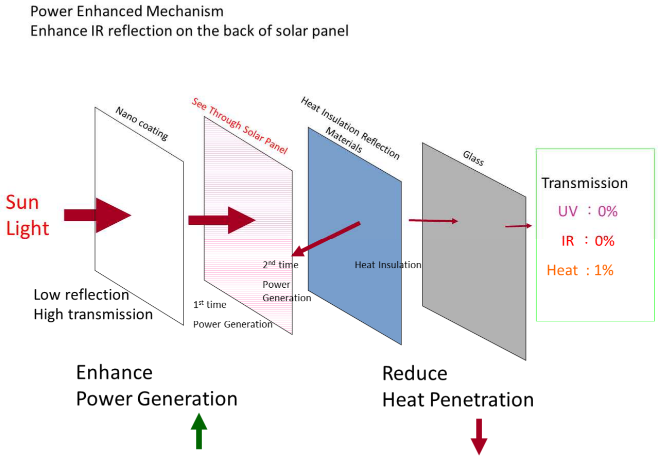


Figure 3. Heat insulation solar glass.

heating or cooling is required. Figure 3 shows a schematic diagram of the working principle behind the heat insulation solar glass. The glazing unit consists of four elements, a low reflection, high transmission glass sheet, a power generation sheet which consists of a transparent layer with embedded nano-crystals and semi-conductor materials which convert solar irradiation into electricity, a third heat insulation layer reflects infrared radiation back to the power generation sheet and increases the power output, but transmits visible light, and a fourth glass layer that interfaces with the interior of the building. The system is a power generator and a heat insulator and can convert up to 10% of the solar irradiation into electricity and reduce air conditioning energy consumption by up to 75%.

2.1.7 Energy scavenging: Standard photovoltaic (PV) systems convert solar irradiation directly into electricity and are now standard features of many public buildings. However, integrating PV systems into facades of existing buildings or old and historic buildings creates both a practical and aesthetic difficulties. Novel energy scavenging technologies are in development for small-scale harvesting in applications such as charging small power devices using movement (walking, running) and thermal gradients (body heat). Scale-up to applications in buildings is not feasible at the moment, but as buildings offer large surface areas exposed to the various climate conditions such as wind, solar and ambient temperature gradients, there are great opportunities for exploiting this vast resource and turn a building from fortresses built to fight against the environment into power generators and active, adaptable structures.

2.2 Energy efficient services

One of the most cost effective methods of reducing energy consumption and carbon emissions is by converting from incandescent lamps to compact fluorescent lamps (CFL) (Houri and Khoury, 2010, Trifunovic *et al* 2009a, Trifunovic *et al* 2009b).

2.2.1 LED/LiFi lighting: Electric lighting in most public buildings is the largest consumer of electricity after heating/cooling systems. Novel lighting systems that can change illumination levels, colour in time and space can create desirable places to live and work as well as cutting electricity use. Modern compact fluorescent lighting (CFL) reduced energy consumption by about 70% compared to a standard incandescent lamp. Modern CFLs, known as T5, can cut electricity consumption by about a half compared to standard CFLs (known as T8 lamps). Light fidelity lighting (LiFi) uses electromagnetic induction to operate and control lighting. The HiFi lamps have no physical connections to the power source and so are more reliable and last longer than CFLs. The system employs dynamic control of lamps using both external and internal light levels, and occupancy sensing to optimise energy usage.

2.2.2 Plasma lighting technology: The plasma lighting technology is complimentary to LED/LiFi systems for large area lighting. It is designed as a chain of modules going from the plug to the bulb. A power module outputs a direct voltage above 3 kV in order to supply a magnetron. This second component outputs microwaves at 2.45 GHz. The bulb, which is filled with a rare gas, is coupled to the magnetron so that a discharge appears at the electromagnetic resonance. Then the substance contained inside the bulb evaporates and heats up by induction, and as a result, a flux of light is produced. After a short warm-up, the light becomes very similar to the sunlight, as showed by spectral measurements.

The plasma lighting system reduces the environment footprint of buildings in two respects, i) The high luminous efficiency reduces electricity consumption, ii) the design principle makes it suitable for intelligent heat management systems because most of the heat emission can be collected at its source.

This technology has a great potential in the illumination of large volumes or large areas. It is particularly well suited for shopping centres, stadiums, halls, atriums, exhibition halls, television studios and theatres.

2.3 HVAC

By reducing heat gains and losses the energy consumption of artificial heating and cooling systems can be reduced and low-zero carbon technologies can be employed. State of the art in low impact heating and cooling encompasses solar thermal heating for water and space heating in cold climates and solar thermal cooling in hot climates (Hirugnanasambandam et al, 2010, Casino *et al*, 2011), heat pumps for space heating and reversed heat pumps for cooling (Badescu, 2003) and Biomass boilers (Kalina, 2010). Combined heat and power (CHP) systems provide electricity from combustion fuel sources ranging from the small scale such as sterling engines and diesel engines to large scale systems such as gas turbine generators. The waste heat is utilised for space and water heating and/or cooling. (Mago and Smith, 2012, Thomas, 2008).

2.3.1 PCM in ventilated façade/solar collector: Phase change materials (PCMs) melt and freeze at a constant temperature and absorb or release latent heat in the process. Heat transfer processes across the building elements can be modified by storing and releasing the heat. PCMs can be used passively in a building element such as plasterboard or ceiling tiles, or actively as part of a ventilation system. PCMs are expensive materials and so passive installations have a limited use because they rely on natural convection and conduction to transfer the heat. The energy density of PCMs can be improved greatly by the use of forced convection as part of a ventilation system. However, natural ventilation systems do not use active ventilation. An alternative would be to create ventilated facades in which air flows either through natural means or by fans and blowers. PCMs integrated with ventilated facades could be much more effective than either passive or standard active systems. PCMs can have a single phase transition temperature, a range of temperatures or can have phase change induced chemically, electrically or acoustically. This could allow buildings to store and release heat in a controlled manner in response to outside conditions or internal requirements. Solar PV and solar thermal collectors could be integrated with the ventilated façade the extract electricity and heat.

3.3.2 PCM COOL-PHASE: The COOL-PHASE system uses the concept of a ‘Thermal Battery’ to capture and store heat. Thermal Batteries use materials that melt and freeze around room temperatures and are known as phase change materials (PCMs). In summer, air is passed through a heat exchanger solidifying the PCMs at night when the air is cool, storing energy. As temperatures rise through the day, warm air is passed through PCMs causing them to melt, absorbing heat from the air. Phase change materials (PCMs) melt and freeze at constant temperatures and absorb or release latent heat in the process. This concept is taken advantage of in the COOL-PHASE system to freeze (charge) the PCMs and transfer heat from the PCMs to the air at unoccupied periods when temperatures are low and then melt (discharge) the PCMs and transfer heat form the air to the PCMs and so reduce the swings in temperature in buildings. The only energy input is from fans that circulate the air. The COOL-PHASE system is illustrated in Figure 4.

2.3.3 Windcatchers/PV for natural ventilation: Where possible, passive systems are preferable for the provision of fresh air and thermal comfort. Novel passive solutions are being developed, including solar chimneys with photocatalytic coating for heating and self-cleaning incoming air during heating seasons or for natural ventilation and passive cooling in cooing seasons. A windcatcher integrated into a lightpipe to provide daylight and natural ventilation for buildings and a wind catcher integrated with indirect evaporative cooling. The indirect evaporative cooling system produces the cooling effect through the evaporation process while the wind catcher assists air flow in and out of the evaporative.

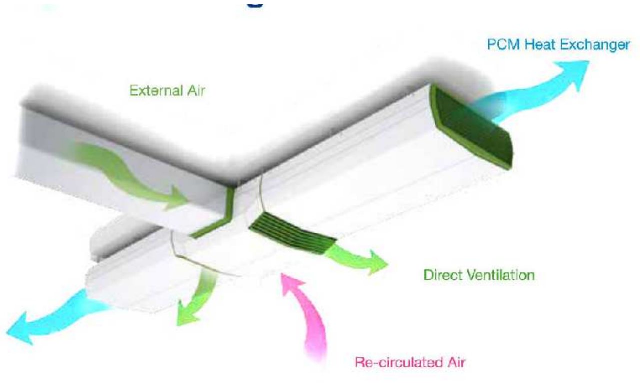


Figure 4. COOL-PHASE system

2.3.4 Inter-seasonal storage: By storing solar energy when it is most abundant but least needed and using it when it is needed, inter-seasonal storage could enable buildings that have large winter heating loads to store the required heat in summer and use it in winter. High energy density chemi-sorption technologies using novel large surface area nano-structured materials will be developed to store renewable heat efficiently and within building structures, such as foundations and highly insulated storage tanks.

2.3.5 Biomass CHP system: Biomass CHP systems using Organic Rankine Cycles (ORC) to provide heating to buildings and electricity from a novel expander based on a scroll compressor, developed for air conditioning in hybrid electric vehicles. The majority of micro-scale expanders employed recently in small-scale ORC applications suffer from problems including excessive working fluid leakage, thermal losses and low isentropic efficiency, The Sanden scroll compressor SHS-33B4150 developed for the Mercedes S400 electric hybrid cars employs DC brushless motors allowing low supply and exhaust pressure with no clearance volume effect. It is enclosed in a semi-hermetic housing and so reduces the risks of refrigerant leakage.

2.3.6 Hybrid heat pump/solar thermal air conditioning

Electrically driven heat pumps are considered a renewable energy source if the coefficient of performance (COP) is above 3 (three times the heat output to the electricity input). They are becoming common for space heating in many domestic dwellings in places such as Sweden, France, Germany and Finland. High solar irradiation tends to be in syncronisation with cooling loads in hot and humid climates, so cooling may be achieved through solar powered refrigeration systems. However, because of low performance in comparison with standard refrigeration systems they require large solar collector arrays and space for the plant and machinery. A hybrid PV heat pump/solar thermal air conditioning system that utilises solar irradiation for operating the heat pump and the heat powered refrigeration system. It would be a totally renewable cooling system and could be used year round to provide water heating in summer and winter.

2.3.7 Salt tower system

The psychrometric energy tower is based on the interaction between water and air to provide water evaporating to make cold water. Fig 5 illustrates the salt tower system. This technology achieves a high cooling performance. The Psychrometric energy tower uses salty water, which interacts with air to condense water vapour held in the air into water. This produces warm water to improve heat pump heating performance. Moreover, this method prevents frost formation and so the heat pump can operate continuously even in the harsh winter season. The system provides a very efficient and compact regeneration process with a very little thermal energy or electricity input. The thermal COP is above 3 and the electric COP is above 10. The thermal energy could be powered by solar thermal heat, waste heat or rejected heat from the heat pump condenser.

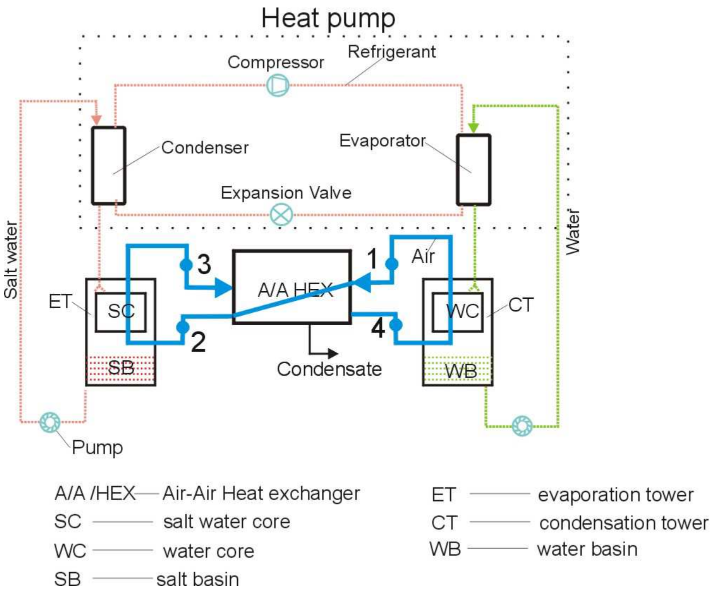


Figure 5. Salt tower heat pump system

2.3.8 Psychrometric energy core (PEC): a novel fibre membrane heat and mass exchanger is in development, in which sensible and latent heat in ventilation systems can be recovered. In one embodiment, a liquid desiccant (liquid that easily absorbs water) soaks a membrane and enhances moisture and heat transfer. In another embodiment water is used to provide indirect evaporative cooling. In hot and dry climates, the vast majority of energy required is for cooling in summer. The PEC can act as a heat recovery exchanger, a cooler and a dehumidifier. The heart of the PEC is the impermeable fibre membrane heat exchanger. The membrane comprises a large number of cellulous fibres compressed into a thin layer (0.1-0.5mm) which allows heat to be conducted from hot to cold sides. The heat exchanger can be dry, in which case it acts as simple air to air heat exchanger but with the addition of moisture transfer from high to low concentrations. The heat exchanger can be wetted with water and can act as a direct or indirect evaporative cooler. The heat exchanger can also be wetted with liquid desiccant (liquid that readily absorbs water) and can act as a dehumidifier. The membrane allows moisture to transfer between the streams but prevents air and desiccant molecules from diffusing across the membrane. Cold and humid air flows in one direction and warm dry air flows in the opposite direction. Heat is transferred from the hot side to the cold side, reducing the temperature of the outlet air and increasing humidity while the inlet air temperature increases and humidity decreases. The moisture content difference between humid and dry streams causes water vapour on the humid side to condense. Moisture migrates to the dry side where it evaporates, increasing humidity.

3. Conclusions

By reducing heat and mass transfer through the envelope, the main energy consuming factors are tackled by reducing envelope air leakage, externally and internally insulating with vacuum and nano-structured technologies, reducing heat gains and losses with low U-value vacuum glazing and power generating windows, and coating external facades with self cleaning and pollution controlling, and energy scavenging materials. As heat gains and losses through the envelope are reduced, the use of energy within the building is tackled by refurbishing with low energy lighting systems. Innovative light fidelity lighting (LiFi) offers lower energy consumption, improved control of lighting, lower cost and quicker payback periods, and large area plasma lighting can both reduce lighting consumption and recover some heat generated in the lighting system for other services. Once heating, cooling and electrical loads are reduced, the plant requirement is reduced. Innovative low energy and renewable technologies can be used to minimise primary energy consumption and CO_2 emissions. Phase change materials (PCMs) store and release latent heat and can moderate internal temperatures in climates where there are medium to large temperature swings between day and night. Windcatchers can ventilate deep plate buildings using natural ventilation and be incorporated with low energy/renewable cooling and dehumidification systems. Biomass CHP systems offer a renewable source of heating and power. Heat pumps driven by low carbon and renewable sources can provide high performance and reliable heating and cooling systems. This hierarchical approach is targeted primarily at reducing the mass and energy flows in buildings that do not directly contribute to the business of the owners and occupants, whether that is administrative and management services in office buildings, teaching and learning in educational buildings or productive output in factories and industrial complexes. The cost of providing heating and cooling to overcome inadequacies in design and construction is wasted and could be invested in technologies described in this paper.

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