A REVIEW OF ENERGY EFFICIENT SYSTEMS INTEGRATED INTO BUILDING ENVELOPES

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Abstract
There is an essential need to reduce energy consumption in building sector as it consumes about 40 percent of the world energy and causes environmental problems. About fifty percent of energy in the building sector is used for heating, cooling and air conditioning purposes. Considering building envelopes as particular building elements with many functions which its energetic function is the most important one influencing building energy consumption, enhancing the thermal and energy efficiency of envelopes would decrease energy consumption of the buildings. Building envelopes contain roofs, external walls which are in touch with the outside environment and the floors on the ground. This paper would review a brief history of envelopes evolution and introduce a categorization for the envelopes based on different strategies for enhancing energetic function. A huge literature review on building envelopes has been done to identify different techniques. The result is summarized in five strategies as energy generation, cooling and heating, sun radiation control, and Thermal moderation and adaptive.

Keywords: Building envelope, Classification, Energy efficiency, Energy saving, Technologies

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INTRODUCTION

Envelopes are the first architectural elements, which were created for Protecting human from different environmental conditions as shelters. Then through a long history they evolve into today's architectural structures. Primary envelopes were created using the natural materials in the environment. In fact, the reason behind primary shelters was to moderate the natural environmental harsh conditions and to provide a more proper living space (James Marston Fiteh 1960). As structures evolved more during the history, the role of outside surfaces of buildings for providing a more comfortable indoors became more important (Auer 2011).

Building envelope is defined as all exterior surfaces of buildings that are in direct contact with the outside. It includes mainly exterior walls and openings, roofs and the floor in touch with the ground. Although in some literature texts only façades and roofs are referred as building envelopes (Suresh B. Sadineni⁎ 2011). Building envelopes different properties define how the building would interact with the external environment (Clark W. Gellings 2002). Building envelopes have many functions, the main ones are: enclosing the indoors and create a boundary between the interior and exterior, moderating the weather conditions (temperature, radiation, humidity, air flow), providing light for the interior, providing a visual connection with outside and its views, supplying the fresh air and ventilation, creating the image of building , contributing to the structural stability of the building, symbolization and delivering message to the audience outside. Among these functions, environmental conditioning function which affects thermal comfort is the most essential one that affects the energetic function of building. External surfaces of buildings have the most interaction with the external environment and therefore play an essential role in creating thermal comfort and exchanging energy with the outside natural environment. Hence the major function of theses exterior surfaces of buildings or envelopes is to attenuate the changing environmental conditions even in current architecture, so the building's energy performance and users' comfort is still determined mainly by building envelopes. Among the main functions of building envelopes are sun radiation control, providing natural ventilation and reducing the heat exchange between indoor and outdoor (Auer 2011).

Environmental factors such as temperature, solar radiation, air current and humidity would influence the thermal performance of building envelopes. Considering envelope as the most important element in determining inside thermal comfort and heat transfer between inside and outside, its thermal function is very important in its design (Sozer* 2010). So the most important parameter in the design of sustainable buildings is to achieve optimize solutions for building envelopes (Per Heiselberg* 2009).

THE EVOLUTION OF BUILDING ENVELOPS

During the history till the twentieth century, exterior walls had mostly structural function as bearing walls, although environmental conditioning was also amongst their main functions. Before twentieth century, walls did their environmental function through their material properties and their thickness which affects the thermal resistant and thermal capacity of them (F. Goia 2010). Where the environment was very harsh, the more thickness of the walls helped reaching a better thermal function. Other influencing factors were the number and size of the openings and transparent surfaces in the outside walls. Vernacular architectures which evolved through long time have developed suitable solutions for environmental problems. So they are huge treasures for applying native resources and renewable energies without costs for heating and cooling. Though the thermal comfort in such buildings was not achieved as today's, but they could provide an acceptable indoor condition with the least amount of energy (Coch 1998; Almusaed 2011).

Technological achievements of the modern world introduced methods of construction which was eliminated much of the structural function of exterior bearing walls. It provides the possibility of making thinner and lighter walls and thus creating more visual communication between outside and inside through applying large transparent surfaces and glasses. Though this structural achievement caused considerable change in visual and aesthetic aspects of the buildings but it disrupted the basic function of the envelopes for their environmental function. This leads to the application of mechanical facilities for compensating the malfunction of envelopes (Abraham Mwasha 2011). Also using thermal insulation in the envelopes and increasing air seals in their openings consequently created other problems for ventilation and causing condensation. The modern way of living is seeking more thermal comfort for the building occupants that emphasized more on the usage of mechanical devices. The necessity for application of the mechanical facilities to provide essential heating, cooling and ventilation was the main reason to compensate inefficiency of building envelopes function. Mechanical devices used fossil energy and consuming fossil energy for decades which it caused rapid increasing of carbon dioxide in the atmosphere and consequently cause weather warming and environmental pollutions. Also fossil resources are nonrenewable resources and so they are not sustainable solutions for energy provision (Luis Pe´rez-Lombard a 2008; Riccardo Maria Pulselli* 2009). According to this, it seems solving structural and visual problems of the envelopes caused newer problems in their thermal function and finally leads to more broad problems in the environment. For this reason, reducing the consumption of energy and using renewable energy resources became inevitable to save the environment and to solve the energy problems.

Coming to this understanding that building envelopes are responsible for energy consumption in the early twenty-first century, the searches went toward integrating climate-related technologies in the building envelopes. In the nineties in the center of Europe there was a trend toward dynamic buildings with a layered façade (Dynamic means physical-temporal functions, properties and behavior of envelope that can change with time and in boundary conditions). This meant that every function in the envelope would be realized through a special layer (Auer 2011) (Per Heiselberg* 2009). Layering is one of the basic solutions to control closing and opening of the boundaries of the building. Double-skin façade is an example of layering solution that is consisted of two layers of glass with a cavity in between; in the cavity there exist shading and ventilation systems.

Climatic factors which determine the thermal behavior of envelopes include radiation, outside air temperature, air flow and moisture(Loonen 2010). Factors that affect building envelope energy efficiency are solar radiation, ventilation and heat transfer between inside and outside. Since Heat transfer can be through radiation, convection (ventilation), conduction and phase change (humidity and moisture), so different types of envelope systems try to control heat transfer in one or more way to reduce the energy consumption for heating and cooling. Also applying renewable energy resources for different applications is another way to reduce building dependency on fossil energy. The third solution is the combination of the two before, which means different applications can be integrated into building envelopes to control its heat transfer and to provide energy based on renewable resources.

Searching more functional efficiency for building envelopes necessitates integrating environmental functions into them. This procedure (integrated utilities in the envelope), should keep the interaction of building envelope with the environment while mechanical systems work within it. On the other hand integration of facilities would bring optimizing flexibility of the building inside. This means that no installation would be installed on the roof and walls which provides more mobility and flexibility. Increasing the flexibility, make it suitable for multiple functions(Ulrich Knaack 2008).

PROCEDURES

Through literature review on the technologies used in building envelopes to improve their thermal and energetic performance, various techniques were identified and common strategies were extracted based on the way envelope system tries to achieve one main goal. Each strategy has a clear approach to meet a goal which finally all of them would meet the final goals of energy saving and decreasing dependency on centralized fossil energy provision. Then, based on the technique which is applied in every system to achieve the strategic goal, the envelopes categorized in sub-divisions under any strategy.

STRATEGIES

Accordingly, it can be identified five main strategies to increase the envelope efficiency and reduce energy consumption. These strategies include local and decentralized energy generation, providing heating and cooling, radiation control, thermal moderation and adaptive strategies.

Table 1: Main strategies for energy saving

Strategy	Approach
Energy generation	• Creating local energy
Passive heating and cooling	• Decrease energy consumption
Radiation control	• Control receiving energy
Thermal moderation	• Decrease thermal change
Adaptability	• Response to change

Energy generation strategy

Different energy generator systems based on renewable energies can be integrated into building envelopes. These systems can supply the building with needed energy for different building applications and especially for cooling, heating, ventilation and lighting. They are local energy providers and because energy is generated in every building separately it is considered as decentralized energy generation. Decentralized energy generation has many advantages in comparison to centralized energy generation in plants. Centralized energy generation needs more complex technical installations with more costs for delivery and production besides environmental costs. Environmental costs consist of destruction of ecosystems and environmental pollutions.

At present, almost all of the systems for energy generation in the buildings depend on solar energy. These techniques can be used to achieve zero energy buildings. Thus, these systems reduce dependency on non-renewable energy sources and reduce building energy consumption costs. Typical examples include solar systems integrated in building envelopes as solar collectors, PV systems and solar ponds. However, heat pumps and wind turbines can also be integrated into building envelopes, as energy provides not based on other energy sources (H. Lunda 2011).

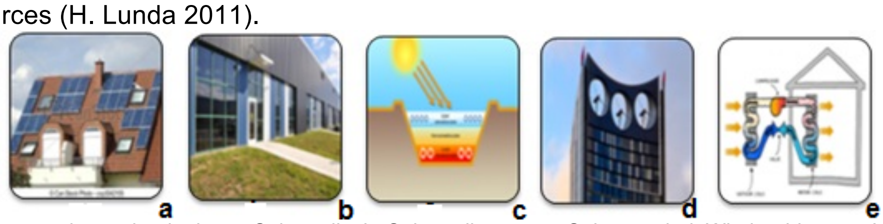

Figure 1: Energy generation technologies a. Solar cells, b. Solar collectors, c. Solar pond, d. Wind turbines, e. Heat pump

Building-integrated solar systems (BISS)

Solar systems can provide different functions which include heating, ventilation and electricity production. They are systems that operate based on solar energy. Solar systems can be divided into two main categories as opaque and transparent. Opaque systems absorb and reflect sunlight and thereby provide energy and heat. If the system generates electricity (photovoltaic cells) or heat from sun by the use of mechanical and electrical systems, it would be called active (Fuschillo 1975; Christoph Maurer 2012). For solar systems to be economically viable, they must integrate into envelopes - including roofs and facades. And integration is possible only when the design of the solar system is included in architectural design. These systems are classified in sub-categories according to their form and function and are dependent on sun.

Different Types of photovoltaic systems integrated into the building (BIPV) and solar heating systems integrated into the building (BIST) have mechanical parts. The two systems can be opaque or transparent and translucent. Solar cells generate electricity using solar energy and can be integrated into envelope as building materials. Solar collectors absorb solar energy to generate heat, they can be also integrated into envelopes and not attached to them and so become a part of the building envelope. Being opaque or transparent, give more choice and flexibility to use them in the windows or as walls and roofs. Using TBISS(*Transparent building-integrated solar systems)* proved 30 percent saving in energy consumption of the building(Christoph Maurer 2012). So solar cells and collectors can be envelope’s parts which generate energy for the building applications. This combination can bring more efficiency for the envelopes and more optimization for energy consumption) Archibald 2003; Maria Cristina Munari Probst 2007; Guillermo Quesada 2012(. Solar collectors have different types which can be categorized in two main categories as concentrated and non concentrated collectors. Solar collectors that can be integrated into envelopes are mostly non concentrated collectors. They provide heating for different usage as space heating and providing warm water) Archibald 2003; Maria Cristina Munari Probst 2007; MariaCristina Munari Probst * 2007(.

Finally solar cells and collectors can be combined as a new hybrid system with both applications. In this way, they can be more efficient because there would be more area of the envelope for the systems and more cell/collectors can be used in the envelopes (v. V. Tyagi 2012). Also it would make more flexibility and provide more area for other techniques and strategies to provide more efficiency in energy consumption and saving.

Solar ponds

Solar ponds can be located on the roof to collect sun energy and create heat for different usage. Solar pond heat generation mechanism is based on layers of different salt water to prevent convection. Three layers of water with different salt contents existed in the solar pond. The degree of salt water is different in different layers and as the lowest layer at the bottom of the pond has the most salt density, so the temperature rises significantly in the bottom of the pond and pipes are located there to collect the heat (V. Velmurugana 2008). Also the bottom of the pond had dark color to absorb more radiation. The lower layer of the pond is the heat storage of the system. The system can be covered at night to decrease energy loss.

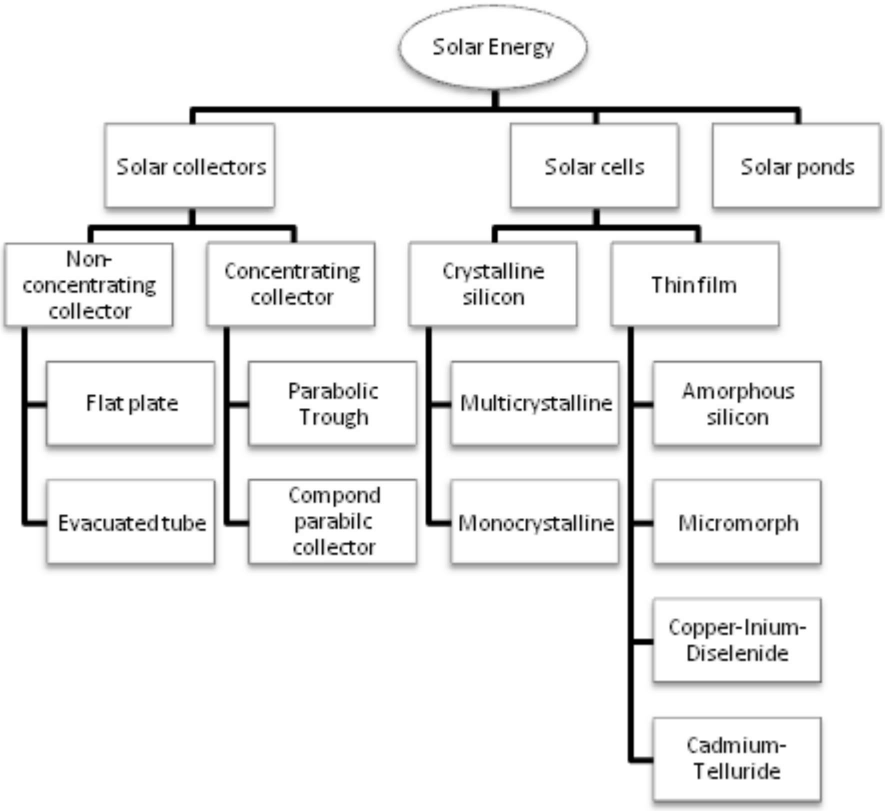

Figure2: Energy generative technologies which can be integrated into envelopes, based on solar energy.

Building integrated wind turbines (BIWT)

Wind is a renewable source of energy. Wind turbines can be used in high rise buildings and the regions benefit winds in most occasions with appropriate speed. Winds turbines can be integrated into envelopes in different scales depend on the scale of the buildings. Wind turbines can be used in two scales, one large scale especially in high rise or large buildings and micro scale which can be used in any building. Micro turbines can be installed and integrated into envelopes for residences and low rise buildings. High rise buildings can benefit more of wind energy because of the more air currents in high levels from the ground. And they can have larger wind turbines integrated into them (A.D. Peacock 2008; Tim Sharpea 2010; Mohannad Bayoumi 2013; Jeongsu Park 2015).

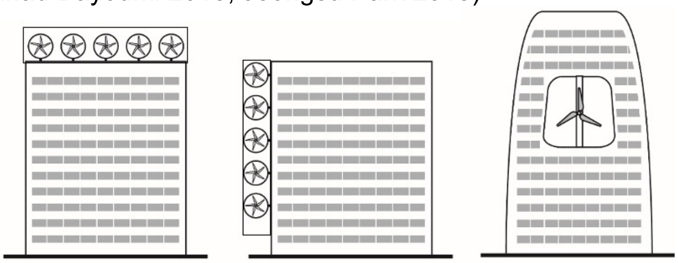

Figure 3: Wind turbines integrated into envelopes in large and small scales.

Heat Pumps

Heat pumps are devices which can transfer heat from underground to the buildings and do reversely as well. But for the pumping heat to the buildings, they can be considered as an energy generator (C.P.Underwood 2017). Heat pumps can be integrated into lower levels of the building envelope which touch the ground.

Passive heating and cooling strategy

These systems use natural resources in a passive way to provide heating, cooling or ventilation needs of the buildings, partially or sometimes completely. Thus, these systems help saving energy. These Systems are mostly based on solar energy. Solar systems integrated into envelopes include, solar trombe walls, solar greenhouse, attached sunrooms, chimneys, roof ponds, evaporated cooling walls and ventilated walls and roofs.

Passive heating
Tromb wall uses solar energy to heat a trapped air and through convection distribute the heat or provide indoor ventilation. If any fan is not used, to create more convections then the system is passive (S.A.M. Burek a). Trombe wall is an exterior southern wall with a layered structure. The inner layer is a masonry or concrete wall with covered with a dark color or metal. The outer layer is a transparent material like glass and there is a cavity between inner and outer layer for air to be heated and move. Massive internal wall absorbs sun light passed through transparent layer and gets warm. It causes the air in the cavity to become warm and move upwards and this creates convection current. Heat generated in the air gap traps due to the greenhouse effect) Gan 1998(. Greenhouse connect to the southern facade of the building can contribute to heating in the winter. Greenhouse heating system is also connected to building envelope on the exterior southern wall (Lavinia Chiara Tagliabue 2012). However, thermal insulation is required at night for the proper functioning of the greenhouse. Gravel beds of pebble function as a thermal mass to store heat at the floor of the greenhouse) Wei Chen 2004(. Solar rooms are rooms attached to external walls which all of or some of its walls and roof are glass. They are like greenhouses, except that they are living spaces.

Passive cooling
Solar chimney is a vertical shaft which utilizes solar heat to create air current and provide cooling. Solar chimneys use stack ventilation to create ventilation (Sompop Punyasompun a 2009; M. Maerefat* 2010).Evaporative wall cooling system consists of a three-layer wall with two air cavities that use the sun heat, evaporative cooling and a fan to create air flow and so provide cooling (H.-Y. Chana 2012). Other evaporative cooling techniques consist of spraying water on the walls and roofs. Ponds and pools on the roof are other passive cooling techniques for warm seasons (Artemisia Spanaki 2011).

Ventilation of building envelope would decrease cooling load of the buildings. It is especially important in warm climates for reducing energy consumption in the summers. Ventilation of building envelope reduce heat transfer into buildings through creating shade and air current (Henry C. Spindler a 2009). Ventilated envelopes have a two layered structure with an air cavity between them for ventilation(A. Gagliano∗ 2012). Self-ventilated façades includes an external wall, insulation, air cavity, structure for attaching the outer layer and the façade covering layer(F. Patania 2010). Self-ventilated roofs are like traditional pitched roofs. They have two layers with a at least 20 degree roof pitch. Ventilated roof can stop heat transfer into building to 50 percent in the summers (A. Gagliano∗ 2012).

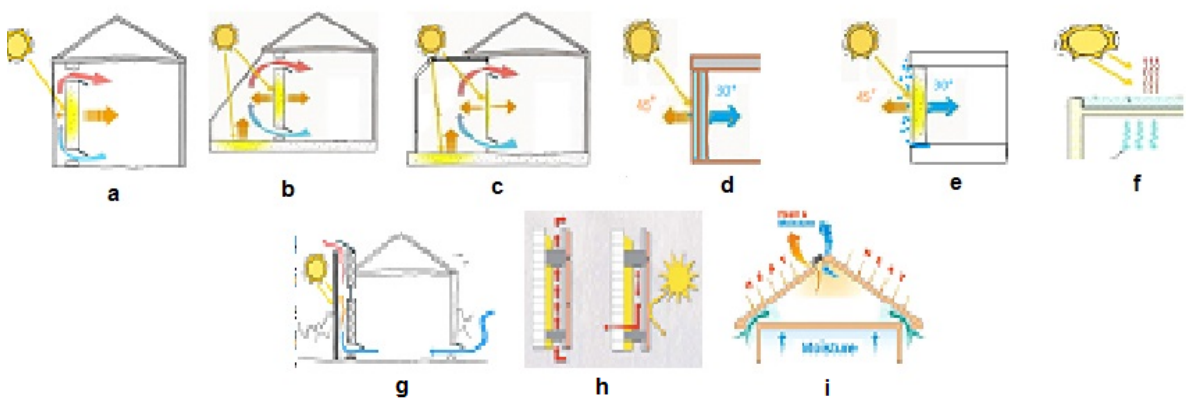

Figure 4: Passive heating a. trombe wall, b. greenhouse, c. solar room, Passive cooling d. evaporative wall, e. sprayed water envelope, f. roof pond, g. solar chimney, h. ventilated wall, i. ventilated roof

Radiation control strategy
Layering is one of the basic solutions to control sun radiation. Some simple architectural layering solutions include the installation of louvers and different types of canopies (GRUBER 2011).

Double Skin Façade (DSF)
Double skin facades consist of two glass layers with an air gap in between. Glasses can be single or double glazed. Cavity can be connected to air conditioning system or earth to air exchanging system. double skin facades can be categorized according to different criteria such as glass layers and cavity being openable or sealed or the geometry type of cavity or the type of ventilation and shading in the cavity or the flexibility of being opaque through external louvers)Marco Perino and DENER 2006; Poirazis 2006; Francesco Goia 2010(.

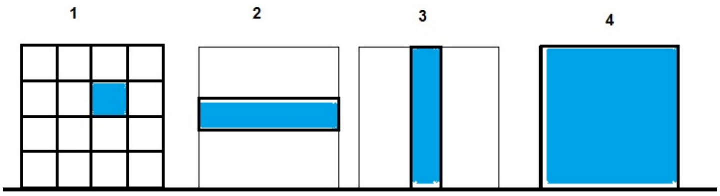

Figure 5: Different types of double skin facades: 1- Box window, 2- Corridor facade, 3-Shaft box facade, 4- Multi story façade. These types are derived base on the part of façade which has shared ventilation.

Green envelopes
Greenery can be used as building materials for the walls and roofs or be added to building envelope structures. Using greenery in building envelopes would improve energy performance of the buildings(Jon LAURENZ 2005). The position of the envelope part affects the application of greenery. Generally green envelopes consist of green walls and green roofs.
Green walls
Green roof has vegetation on the roof that is a layer system. Each layer has its own function. Green roofs are generally considered in two types based on the depth of layers. extensive green roofs have thinner layers with low height plants as grass and intensive green roofs with deep layers and higher plants even trees which can be called roof garden in some cases. Intensive green roofs have better thermal function in comparison to extensive ones. (Julià Coma 2014). Green roofs can improve efficiency of roof thermal function through creating shadow, increasing thermal resistance, evapo-transpiration and increasing thermal mass of the roof (Liu 2003). Green roofs reduce the thermal load of the building both in cold and warm seasons. Green roof helps building passive cooling (intrinsic function) in the warm times.

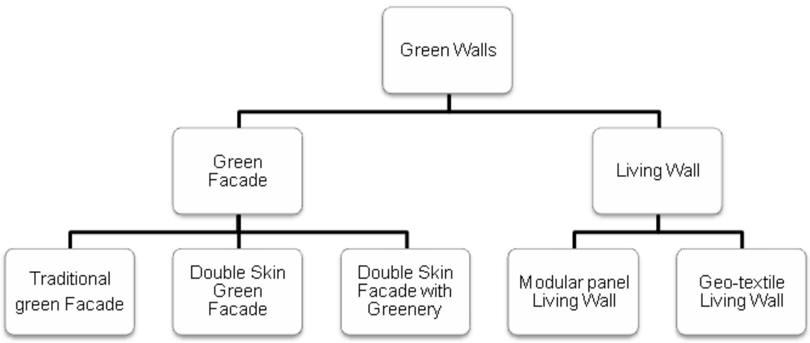

Figure 6. Classification of green walls

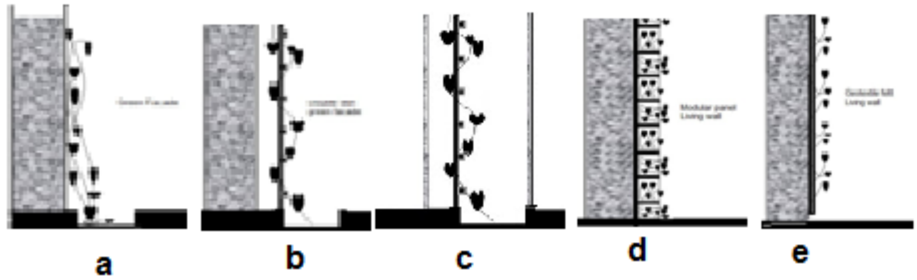

Figure 7: Different types of green walls: a. Traditional green façade, b. Double skin green façade, c. Double skin façade with greenery, d. Modular panel living wall, e. Geo-textile living wall

Green roofs
Green roof has vegetation on the roof that is a layer system. Each layer has its own function. Green roofs are generally considered in two types based on the depth of layers. extensive green roofs have thinner layers with low height plants as grass and intensive green roofs with deep layers and higher plants even trees which can be called roof garden in some cases. Intensive green roofs have better thermal function in comparison to extensive ones. (Julià Coma 2014). Green roofs can improve efficiency of roof thermal function through creating shadow, increasing thermal resistance, evapo-transpiration and increasing thermal mass of the roof (Liu 2003). Green roofs reduce the thermal load of the building both in cold and warm seasons. Green roof helps building passive cooling (intrinsic function) in the warm times.

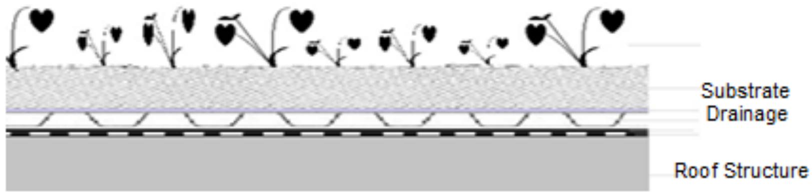

Figure 8: Layering structure of the green roof includes substrate, filter, drainage, roof resistance and water proof which are placed over roof structure.

Thermal moderation strategy
Techniques that are used to moderate heat transfer through envelopes are achieved by material properties and is a passive strategy which means there is no need to supply energy for their function.

Thermal storage
One of the techniques is using thermal storage materials to store heat because of their high heat capacity or high latent heat. Thermal energy storage (TES) systems make benefit from material properties of the building envelopes to save energy and reduce energy consumption. These materials can store large thermal energy in them and release thermal energy in gradually to the environment. So they can delay heat transfer through envelope materials and store heat for the cold hours of night inside the envelope.

Phase change materials (PCM) have great heat capacity and they use the latent heat in the narrow range of temperature (low temperature changes), making them almost like a heat reservoir with fixed temperature. Increasing the temperature causes the material to change state from solid to liquid, and for the fact that this transition is endothermic, so heat is absorbed. When the temperature decreases they change their state from liquid to solid and so is exothermic and will release heat. So the temperature of material remains almost unchanged. Therefore, it is an efficient way to save energy for heating and cooling purposes using phase change materials in floors, roofs and external walls (envelope materials). This passive technique is called latent heat thermal energy storage system (LHTES). Passive here means not using of mechanical installations. Other techniques include using water walls and roof ponds to use water high thermal capacity for moderating the heat transfer through envelope (N. Soaresa 2013) (Hoy-Yen Chan * 2010; Artemisia Spanaki 2011).

Dynamic Insulation
In this technique ventilated air is passed through insulated materials and exchange heat to moderate the insulation temperature (Perino 2008).

Earth coupling system
Earth coupling is a system that uses the ground as a great thermal mass for moderating the temperature of air or water. It is consisted of underground pipes which can be connected to the ventilation system of the buildings for heat recovery or getting cool. So in the winter it can help pre warming for ventilation and in the summers, it is used for pre cooling of the air. The pipes go deep into ground because the ground surface are more fluctuating with outside air temperature (R. Parameshwarana 2012; Hepbasli 2013).

Air or water curtains
These natural curtains play as a layer to separate indoor and outdoor. Air curtains can be used in the envelope openings to outside environment. It creates an air flow to separate the inner and outside environment like an invisible door. So heat transfer would reduce. Applying water curtains would increase humidity and evaporative cooling.

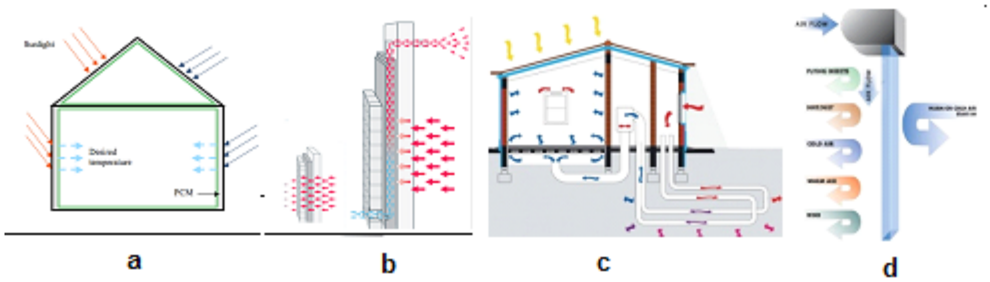

Figure 9: a. Thermal storage materials for the envelope, b. Dynamic insulation, c. Earth to air exchanger, d. Air curtain

Adaptive strategy
The Static nature of the current buildings caused they cannot change according to environmental changes. Passive methods based on the intrinsic properties of materials and other strategies could not bring thermal comfort for residents without using mechanical systems. Thermal performance of the envelopes affects its energy efficiency. Improving thermal performance of the building means adjustment and control of heat exchange with the outside in a way that meets the thermal needs of the residents. Mechanical systems as active systems consume energy and subsequently cause environmental costs. In fact, the main justification for moving toward adaptive buildings is the need for more dynamic buildings so that they can change according to different conditions.

The responsiveness and reaction to environmental changes can happen in two ways. One can be through intrinsic properties of the system material or elements as in smart systems and the other in intelligent systems which need information processing. Intelligent systems collect information from the environment and process the information to make the most suitable response. Smart systems have more narrow range of responses in comparison to intelligent systems and there is limited control over their function, though they do not need energy to react in most of the case. Intelligent systems need energy for their processing performance and for their reactions toward changes (G. Wood * 2007). A combination of both systems can lead to more energy efficiency and saving (Rahul V. Ralegaonkar a 2010).

Responsive building envelopes contain regulating functions which can change them in a dynamic way according to environmental changes to provide residents' comfort conditions and save energy consumption in the building (Bridget Ogwezi1* 2011). Envelope would react to residence needs an environment changes to regulate temperature, light, ventilation and moisture indoor for providing more comfortable space. Intelligent building envelopes has many advantages such as optimization and energy saving, automatic control of complex systems, maintenance, more precise and more predictable function and ultimately users' greater control over building heating, cooling and ventilation performance (Elkadi* 2000; Øyvind Aschehoug 2005; Carlos Ernesto Ochoa 2008; Carlos

Ernesto Ochoa * 2009) (Kathy Velikov 2013) Building envelope adaptability can be categorized in three categories according to functional properties and the scope of changes. First is flexible adaptability that happens in two dimensions of planes. Second is transformable adaptability which is in three dimensional space and the third is responsive adaptability which happens in four dimensions and it is dependent on the time (Pozzer 2007) .

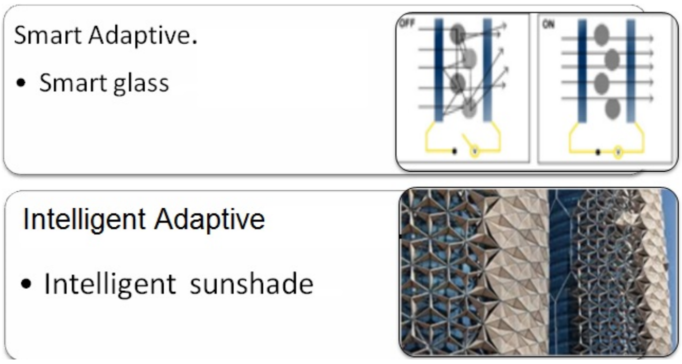

Figure 10: Adaptive strategy has two main categories as smart and intelligent.

CONCLUSIONS

A brief history of the building envelopes has been introduced through history. The design of the building envelope and the utilization of appropriate technologies can affect its energy efficiency. Various systems have been attached and integrated into building envelopes to improve thermal and energy performance of the buildings. These systems implemented a variety of different technologies. This paper summarizes the whole technologies in a new classification based on the strategies they applied to enhance energy function of the envelopes. Then techniques and technologies related to every strategy is introduced. These strategies include energy generation, providing heat and cool, radiation control, thermal moderation and adaptive strategy.

Evolution of the envelopes shows a distinct path toward integration of different thermal and energetic functions into envelopes. Also new technologies are developing to simulate the adaptive behavior of living systems in the building envelopes.

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