HI-SMART: HIGHER EDUCATION PACKAGE FOR NEARLY ZERO ENERGY AND SMART BUILDING DESIGN

MODULE #2

CHAPTER 3: INNOVATIVE FACADE SYSTEMS OF NZEB

Co-funded by the Erasmus+ Programme of the European Union

2.3.1 DEVELOPMENT OF NOVEL BUILDING ENVELOPE SYSTEMS

Historically, all around the world, building envelope systems in certain location of our planet were constructed according to basic principles determined by climate conditions, e.g. igloo in Antarctica, traditional wooden house “Dacha” in Russian Siberia, massive wall structures of houses in Middle East, and wooden tents in Amazonia.

The world map is divided into different types of climate zones according Köppen-Geiger classification (Fig. 2.3.1). Each location or region is determined by its certain position on the grid system of longitudes and latitudes, as well as elevation above sea level. Fundament design principles is still dependent by climate conditions and its future changes by global warming.

Nowadays, in the advanced technology era, the new concepts and applications of building envelope systems are becoming more relevant than few years ago. Their continuous development (Fig. 2.3.2) started from the fundamental construction types based on the simple principles and have been transformed to the adaptive and intelligent systems based on the complex principles and controlled by a certain computational system. These systems are considered as the next milestone mainly in building energy saving campaign. Façade engineering progressively arises as a stand-alone master study programme for fostering up new generation of special engineers in advanced façade systems.

Development in façade technology always involved specialization either in local level as a certain simple component (window or detailed glazing system/frame, non-transparent parts, surface properties etc.) or in global level as a whole system composed of several components which co-operate together (shape changing, variable thermal/optical/acoustical properties, etc.). The integration of responsive and auto-reacting materials (PCM – phase change material, DIS – dynamic insulation system or other new revealing systems like SMA – shape memory alloys).

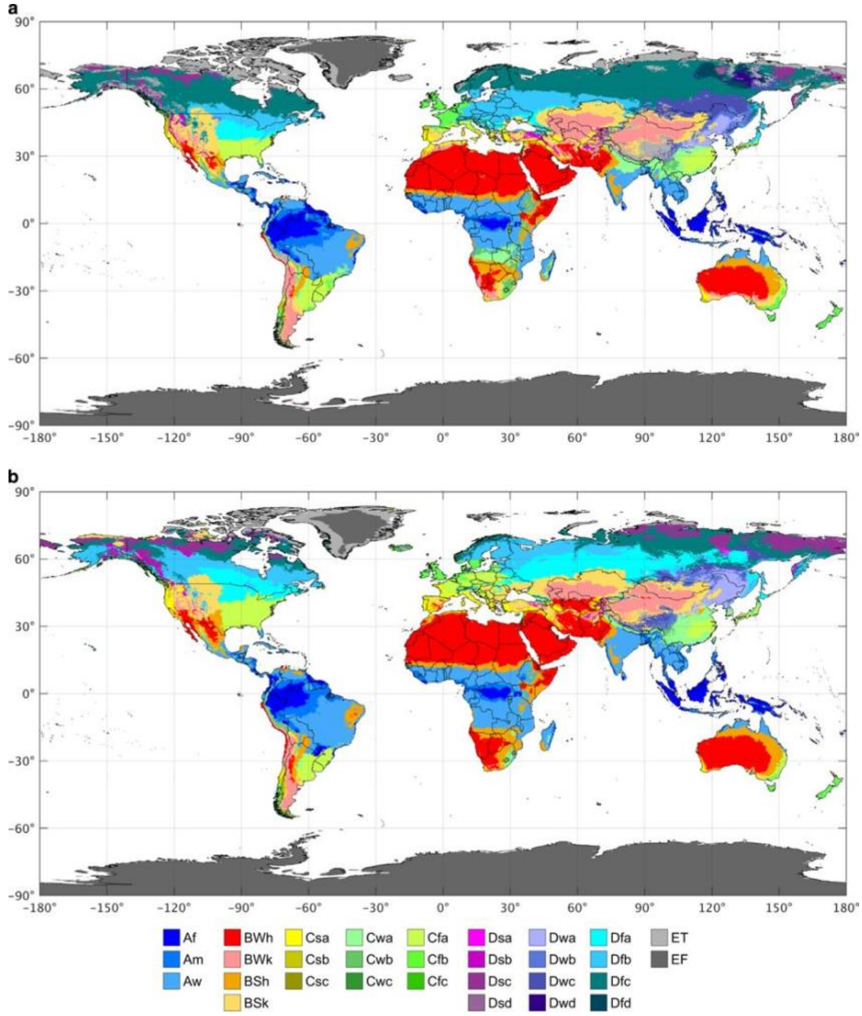

Figure 2.3.1 – Köppen-Geiger classifications: a) present-day map (1980-2016), b) future map (2071-2100). Source: H.E. Beck et al. (2018).

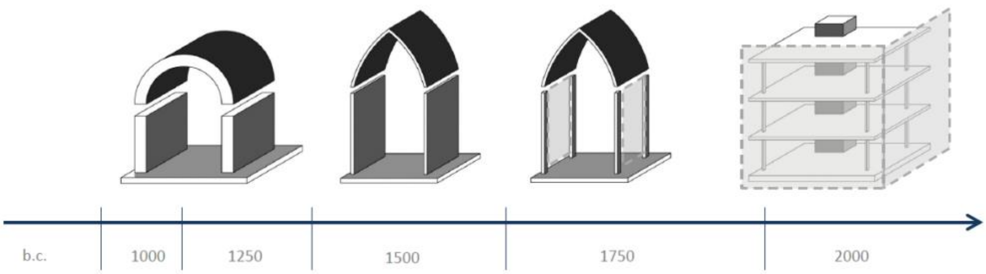

Figure 2.3.2 – The historical evolution of building envelope systems. Source: P. Molter, TU Munich.

The definition of Responsive Building Elements (RBE) is based on active utilization of the transfer and storage of heat/cold energy, natural light, air and water. Their combination with other elements and interconnection with HVAC systems is a logical step for gradually increasing the energy efficiency in building environment with decreasing CO_2 emissions to the atmosphere.

Accordingly, the façade elements are multi-functional parts of an overall building envelope system with various responses on different parts of outside climatic and interior conditions. That means, they provide not only climatic (thermal, sun, wind) protection but as well as control of natural ventilation (especially for double-skin façade), humidity (surface condensation), energy generation (photovoltaic, wind energy etc.) and ultimately, should be aesthetic (Fig. 2.3.3).

Every property of each part of building envelope should be fine-tuning according to boundary conditions and its inertial dynamic changes, where façade system continuously became adaptive.

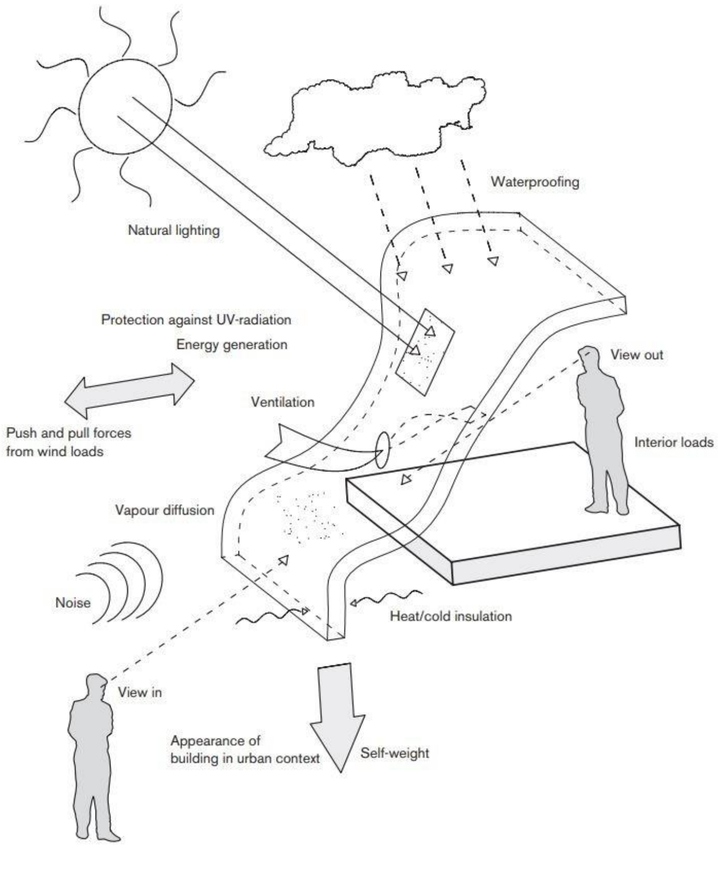

Figure 2.3.3 – Functions of façade. Source: U. Knaack et al. (2007).

The adaptive façade technologies are determined by systematic approach – the definition of higher rank structures within the façade (façade systems) and recognition the lower-rank sub-structures: (components and materials) which made up the higher rank structures (Fig. 2.3.4). This approach also allows to study the sub-structures separately into three main groups:

- **Material**: a material can be in different states of refinements such as raw, extruded or coated. In addition, inseparable materials, such as bi-metals, belong to this category. Polymer, Bi-metal, steel, wood, and phase change material are some of the examples in this category.
- **Component:** a component is an assembly of different elements. It forms a complete constructional or functional unit as part of a façade. For example, we can define as component systems an insulated glass unit but also a window frame including glazing or a sun-shading device.
- **Façade-system:** a façade system is composed of different transparent or opaque structural or technical components. It fulfils all basic technical façade functions such as insulation, rain protection, and windshield. Example of façade systems are: curtain wall; prefabricated module; double skin façade; ventilated façade, etc.

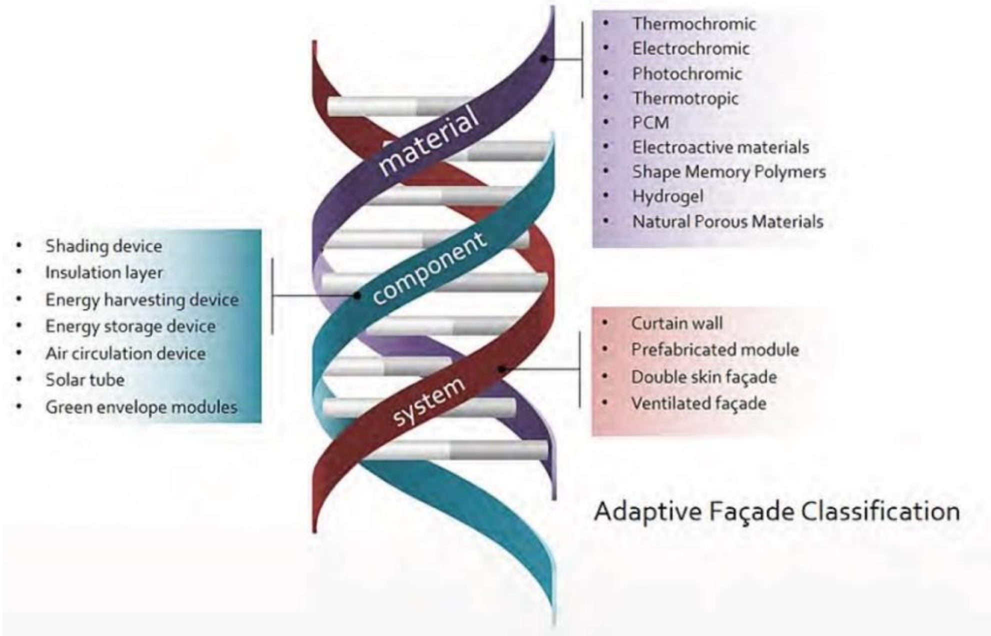

Figure 2.3.4 – The conceptual diagram of systematic approach in adaptive façades. Source: COST TU 1403.

A dynamic/adaptive façade needs to be actuated through an input motion. These inputs will be transferred to the system according to performance requirements. This could be ensured through control of external and internal loads or deformations. Mutual interaction and synchronization between sensors and actuators (extrinsic control) ensures the transfer of information between interior thermal comfort demand and exterior climate conditions. This is part of whole building intelligent management system (Fig. 2.3.5).

Another feasible way of adaptive control is using passive systems (intrinsic control). This means utilization of systems' ability to self-adjust in response to the environmental stimuli like temperature, solar radiation, wind intensity/direction, humidity and so forth, without external energy inputs. PCMs as responsive materials that self-adjust their physical properties as an example of intrinsic control system. It should be noted that this method is limited for manual interventions. In addition, the performance of intrinsic systems significantly depends on dynamic and time-transient changes at different time-scale levels. This is the main reason why responsive materials are so far developed only on prototypical scale, but in combination with extrinsic control, their potential could increase.

Both energy performance and architectural expression of the adaptive façade can be adjusted (and controlled) with spatio-temporal resolution via individually addressed modules. Using selecting approach of the façade performance is ensured by either transmitting, tempering, storing, shifting, redirecting or transforming the energy and mass flow from the outside to inside building or vice versa. However, there are several important factors, which should be taken into account in design of adaptive solar based façade:

- the scope of the implemented adaptive properties that change the energy performance of building,
- advanced material properties integrated in the façade systems and consequently their time-scale responsive mechanism (reactivity of the façade) according to boundary conditions (interior/exterior),
- appropriate selection of the control strategy of the façade.

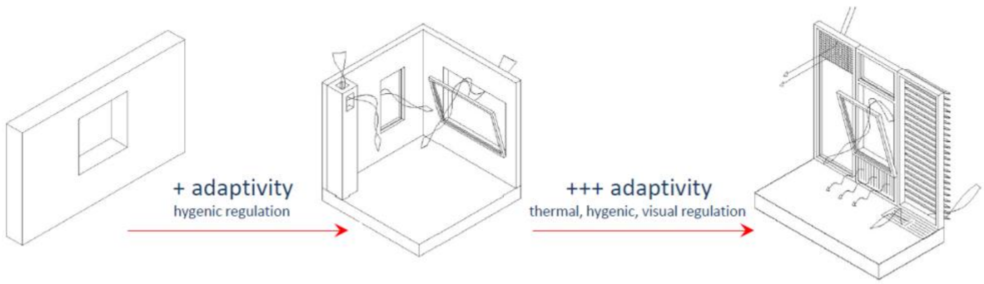

Figure 2.3.5 – The application of self-adaptive functions in facades. Source: U. Knaack et al. (2007).

With an increased ability to respond to specific environmental stimuli as needed, adaptable building envelopes present an attractive method for potentially mitigating the effects of undesirable outdoor environmental variables on indoor comfort. This depends upon the building envelope engaging in a continuous negotiation between indoor and outdoor conditions, permitting desirable energy exchange between the environments and rejecting any unwanted transfer. With more responsive building envelope elements, the ability to filter desirable environmental attributes improves, which leads to reducing the dependence on energy from mechanical systems (Fig. 2.3.6).

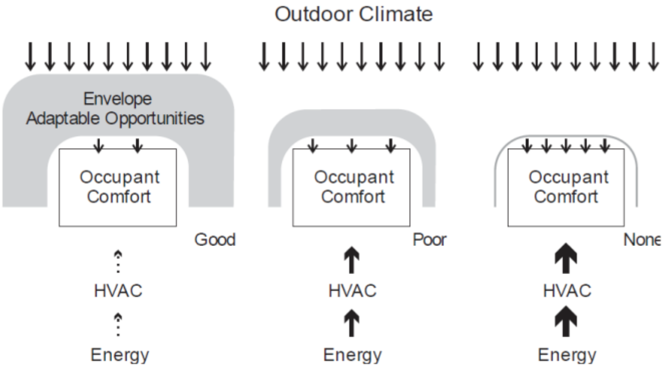

Figure 2.3.6 – Adaptive opportunities and energy usage. Source: J. Erickson (2013).

The historical evolution of façade systems has currently started with an exponential growing interest around the world (Fig. 2.3.7). The first step for successful achieving building energy goals has to be done by changing philosophy of designing architectural constructions. Thereupon, it is necessary to devise some new type of building envelope construction which could be not only providing low *U-value* but also could produce and store energy from renewable sources. Interconnections between utilizing of renewable energy sources and laws of building physics have to be assessed from complex point of view.

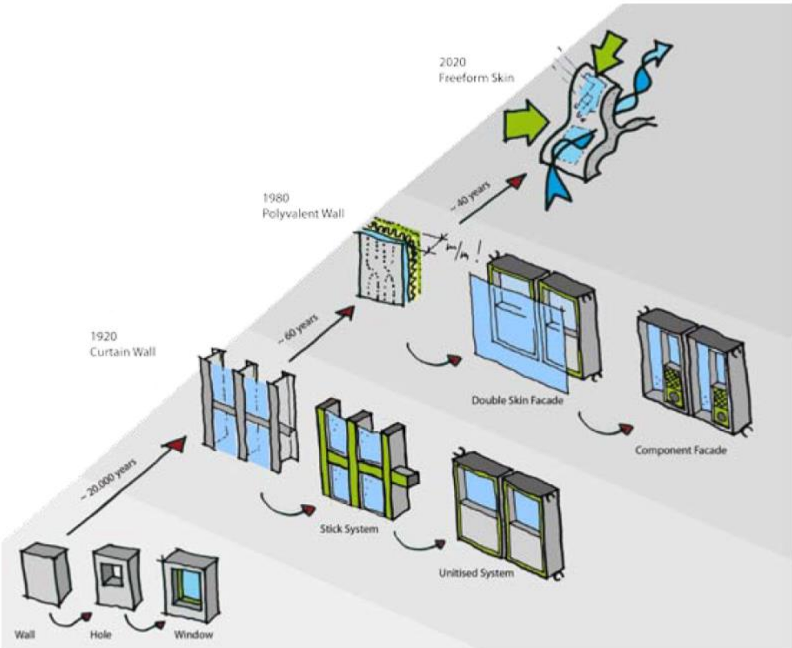

Figure 2.3.7 – Façade systems development. Source: H. Strauß (2013).

2.3.2 SOLAR BUILDING ENVELOPE SYSTEMS

One of the key criteria for increasing energy efficiency of buildings is utilization of building envelope for distribution, conversion and storage of energy especially from renewable sources. Energy form the Sun (Solar energy) is one of the best types of renewable source, mainly for its clean, unlimited and infinite nature. Basically, almost every type of energy on Earth represents another form of solar energy, e.g. burning fossil fuels is essentially releasing the energy stored in ancient plants which were buried underground for millions of years and created by activity of Sun. Additionally, the effect of solar radiation is closely linked to wind power, tidal energy, geothermal energy and other kinds of renewable energy.

Greenhouse effect – since short-wave radiation penetrates through glass, the space behind the glass layer can heat up by absorbing the solar radiation. Thereafter, short-wave radiation is then transformed into long-wave radiation for which glass layer proves impermeable (Fig. 2.3.8).

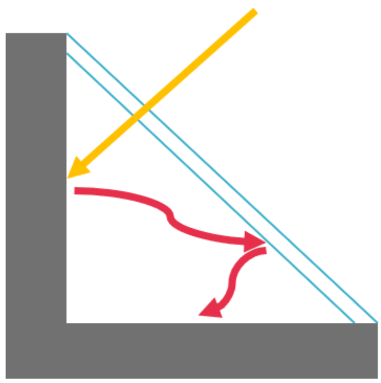

Figure 2.3.8 – The Greenhouse effect

Each hour solar energy received on the Earth provides as much energy as the whole world needs for one year. Accordingly, several solar façade systems have been developed. The opaque solar facades absorb and reflect the incident solar radiation but cannot transfer directly solar heat gain into the building. When such opaque solar facades transform the incident sunlight into electricity for immediate use or for transmitting the thermal energy into the building using electrical or mechanical equipment (pumps, fans, valves, control equipment), then they are called opaque and active solar facades.

- **building-integrated solar thermal (BIST)** system for facades can be conceived as the application of solar collection equipment to the facade of a building so that the equipment performs the function of an envelope while it simultaneously collects solar energy for heating purposes (Fig. 2.3.9).

- **building integrated photovoltaic (BIPV)** system as photovoltaic cells which can be integrated into the building envelope as part of the building structure, and therefore can replace conventional building materials, rather than being installed afterwards. BIPV can be naturally blended into the design of the building, creating a harmonious architecture. Also, as an added benefit, air flow behind the solar cell reduces their temperature which improves their efficiency and durability (Fig. 2.3.10).
- **building integrated photovoltaic thermal (BIPV/T)** system combines the functions of a building integrated photovoltaic system with those of a building-integrated solar thermal system. This combination seeks to achieve a most efficient use of a solar energy-collecting surface in terms of both an optimal electrical conversion and air/water heating (Fig. 2.3.11).
- **thermal storage wall** combines the functions of solar collector and storage into a single unit. Heat is transferred from the wall to the room air and to the air between glazing and wall, by radiation and natural convection. Reducing indoor air temperature swings is one of its principal functions (Fig. 2.3.12).
- **solar chimney** is a structure that consists mainly of one heat-absorbing glazed surface, and it is constructed on the wall facing the direction of the sun. When solar energy heats the chimney and the air within it, it produces an updraft of air in the chimney. The natural aspiration created at the chimney's base can be used to ventilate the building (Fig. 2.3.13).

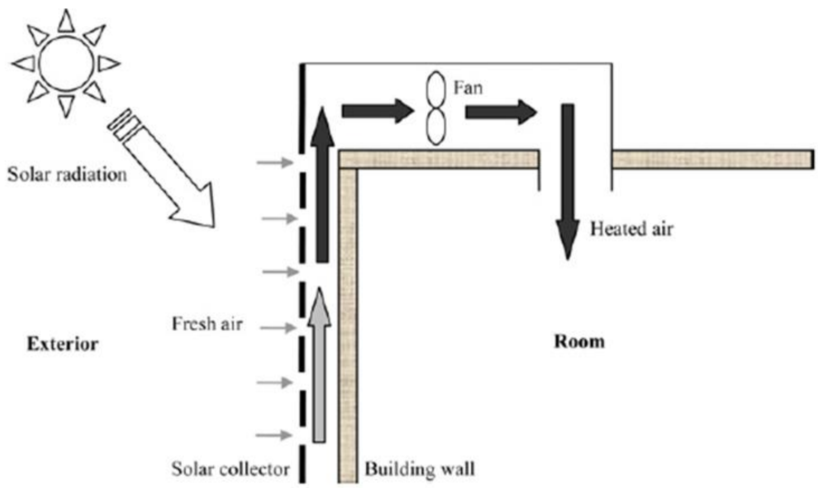

Figure 2.3.9 – Schematic diagram of building-integrated solar thermal system. Source: G. Quesada et al. (2012).

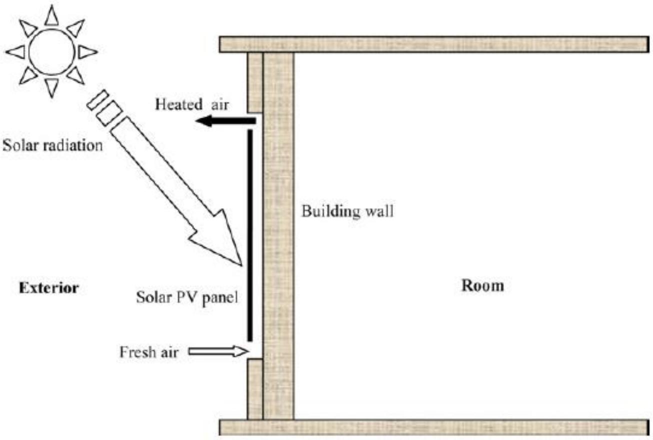

Figure 2.3.10 – Schematic diagram of building integrated photovoltaic system. Source: G. Quesada et al. (2012).

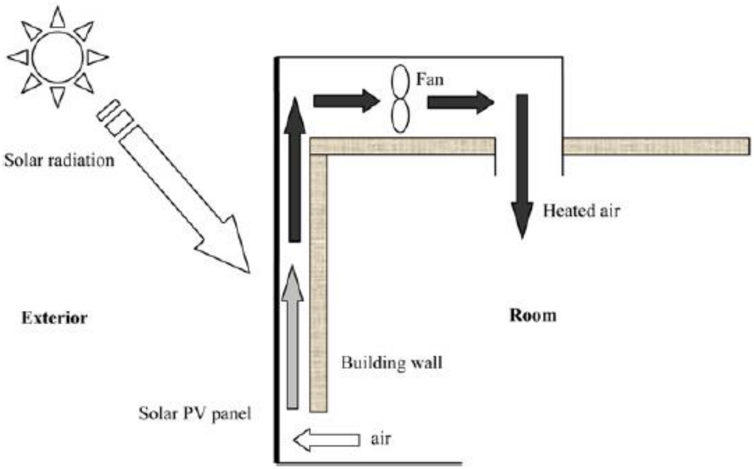

Figure 2.3.11 – Schematic diagram of building-integrated photovoltaic thermal system. Source: G. Quesada et al. (2012).

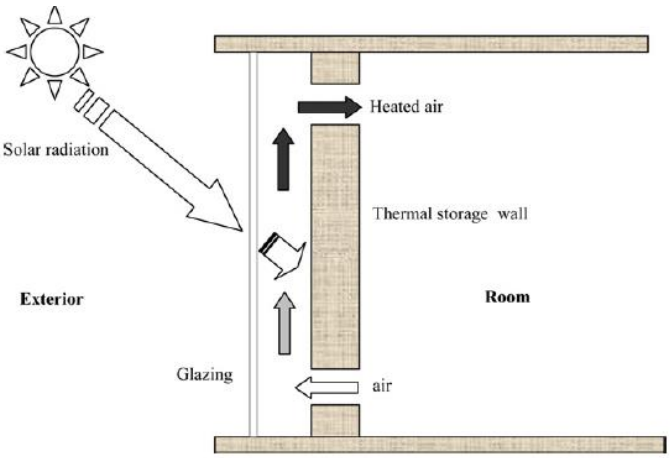

Figure 2.3.12 – Schematic diagram of thermal storage wall. Source: G. Quesada et al. (2012.

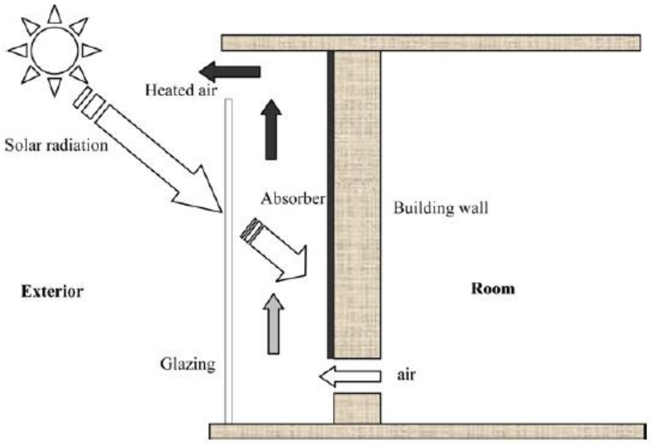

Figure 2.3.13 – Schematic diagram of solar chimney. Source: G. Quesada et al. (2012).

Nowadays, photovoltaic (PV) system is one of the most promising and rapidly growing renewable energy devices for solar radiation conversation to the electrical energy. There are two groups of PV systems according to their degree of technological integration with building: Building Added or Attached Photovoltaic (BaPV) systems and Building Integrated Photovoltaic (BiPV systems) (Fig. 5). BaPV systems represent the first traditional PV systems which have no other function and no thermal energy transfer within the building envelope. On the other hand, BiPV system is a functional and architectural part of building envelope and changes its thermal resistance and optical properties. Classical building materials are substituted by active solar PV components and are perceived as a local power generator and building materials in all. Various commercially available approaches to BiPVs and of various categories of BiPVs can be divided into different building constructions (modules, foils, tiles, glazing etc.).

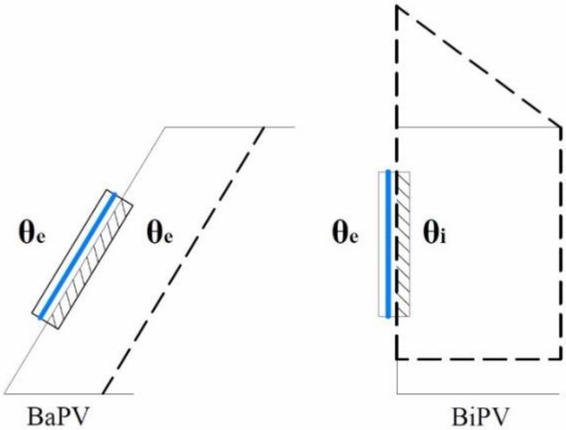

Figure 2.3.14 – Basic schemes of BaPV and BiPV systems.

The overall façade's surface area within the building envelope strongly depends on architecture of a building and has a potential for harvesting and utilization of short-wave solar radiation. It was reported that about ¾ of the BiPV area potential is attributed to roof areas and about ¼ to façade areas, and approximately 15 % ~ 20 % of the electricity production potential can be attributed to façade areas (International Energy Agency - IEA). Defaix et al. estimated the BiPV potential is 951 GWp in the 27 countries within the EU and can provide 840 TWh of electricity, which is approximately 22 % of the expected total electricity demand of the 27 countries within the EU in 2030.

It should be considered that a major part of incident solar radiation on the PV surface does not contribute to electricity generation (approximately 80 – 95 %), depending on the type of PV semiconductor material and capsulation construction within the overall PV module. Solar radiation represents a solar spectrum of different wavelengths of electromagnetic radiation and PV conversation is basically wavelength-depended in its certain range. The rest of the solar spectrum is transformed to thermal energy after receiving on PV cell (Fig. 2.3.15).

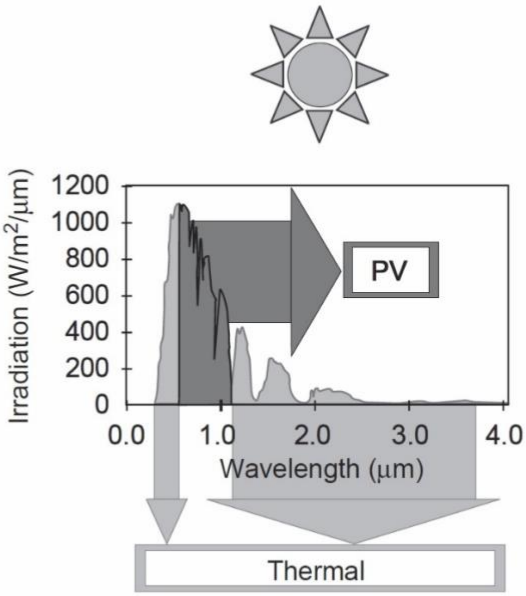

Figure 2.3.15 – Splitting the solar spectrum for PV and thermal energy. Source: A.G. Imenes, D.R. Mills (2004).

The converted part of the solar radiation into heat energy plays a significant role in PV efficiency η_{pv} (heating up of the PV cells) since it affects not only the electricity current and voltage characteristics but also the overall lifetime (temperature-induced degradation) of PV module. Typically, the electric power output of PV system decreases around 0.5 % per one-degree Celsius rise in PV cell temperature. This temperature effect is quite higher in BiPV system in comparison with classical BaPV system, mainly due to its insufficient cooling possibilities after the direct integration into a building envelope (thermal stress problem).

2.3.3 BIPV FACADE SYSTEMS

PV materials in BiPV systems replace traditional building materials in design of building envelopes. Moreover, they become a functional part of envelopes and must meet some requirements (thermal, acoustic, fire-safety, aerodynamic and hydrodynamic, requirements for natural lights). From architectural point of view, BiPV systems cannot be perceived only as “building integration”, but also as “architectural integration” with the consideration of overall aesthetic aspects. There are various categories of commercially available types of BiPVs (modules, foils, tiles, glazing, etc.) together with different semiconductors PV materials. Accordingly, the evaluation of the different BiPV products was performed from several aspects. BiPV systems provide several possibilities for innovative architectural design in different parts of building envelope and can be integrated in facades, roofs, shading systems, semi-transparent elements in window system, roof membranes etc. (Fig. 2.3.16). BiPV module is assembled from different layers (Fig. 2.3.17).

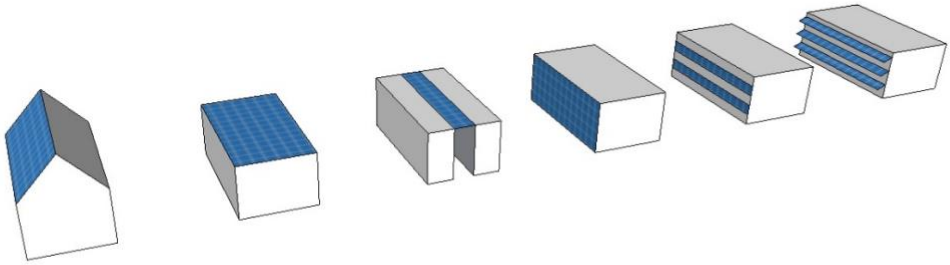

Figure 2.3.16 – BiPV integration systems in different parts of building.

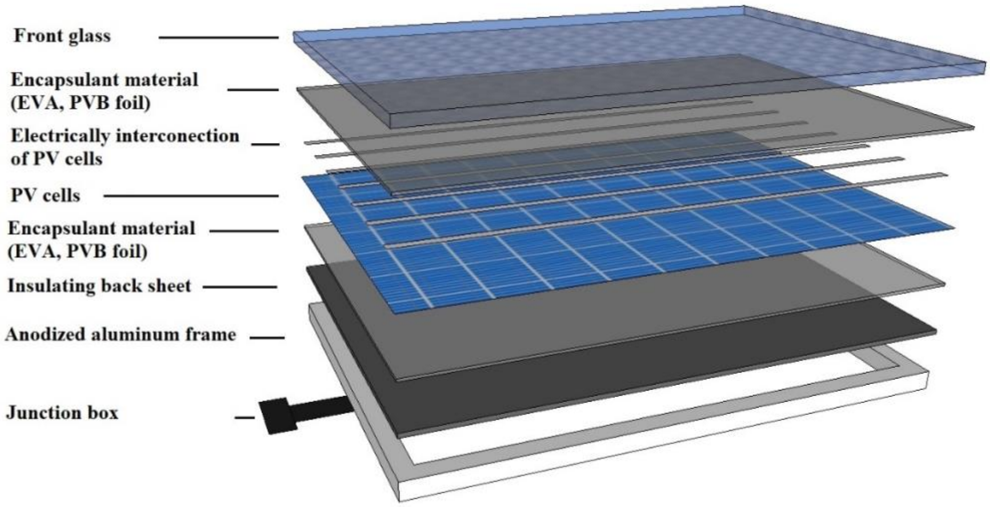

Figure 2.3.17 – Basic structure of PV module.

Different BiPV systems can be classified into several sub-systems according to treatments of heat energy (BiPV/T systems). These systems are based on the principle where PV panels are cooled and directly use the excess heat energy for further applications. Many studies on BiPV/T systems were performed with focusing on different ways of sensible using of heat energy.

There are several types according to the basic scheme of BiPV/T categorization (Fig. 18), where the controlling of PV operating temperature is by either natural or forced air circulation around the rear surface of PV module, liquid hydraulic cooling, thermoelectric cooling, thermosyphon, heat sink system, heat pipe, integration of PCM layer and other special cooling methods.

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These presented cooling techniques could be classified into two main groups, active and passive cooling, where their main distinction is in integration of certain driving system. However, the waste heat during the process of decreasing PV operating temperature should be additionally used in feasible way for partially meeting the building energy load. The BiPV façade integration (in case of ventilated double-skin façade) works as the heat energy supplier by the exterior PV modules where the outside air is pre-heated in the façade cavity and simultaneously the interior heat losses is recovered by the heated cavity air. The next generation of BiPV systems that not only produce the electricity are called building integrated photovoltaic/thermal BiPV/T systems, which used above-mentioned PV cooling principles. In these cases, the PV modules and the thermal unit are coupled together and simultaneously convert solar radiation into electric and thermal energy. The BiPV/T system provides higher energy output in comparison with standard BiPV system but requires additional investment cost for the thermal unit.

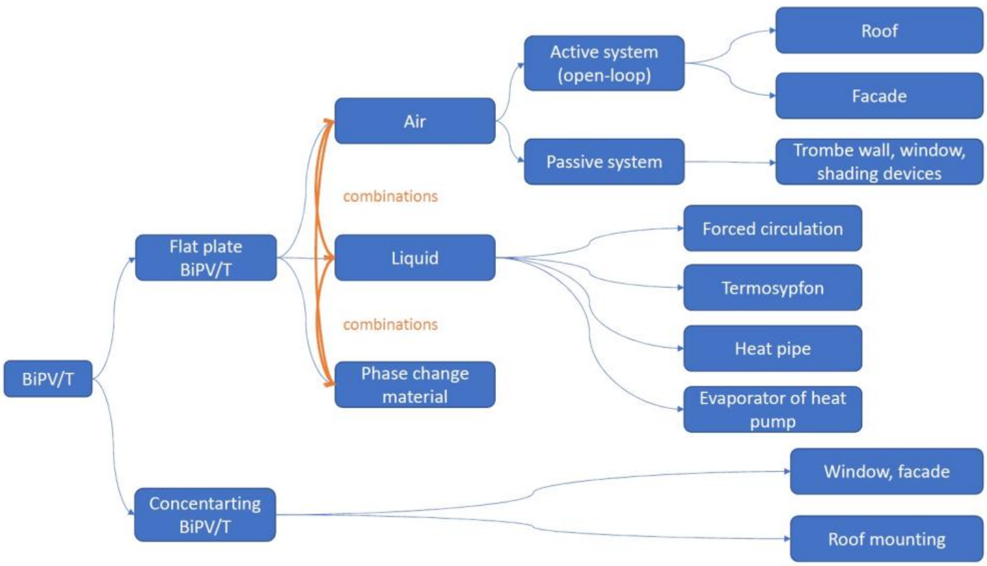

Figure 2.3.18 – Categorization of BiPV/T systems.

PV modules can be integrated in building façade either partially (substitution of exterior layer, e.g. claddings) or fully (lightweight façade element) (Fig. 2.3.20). In case of BiPV façade system, it cannot be considered only PV module as one façade element, but also as a whole system with cables, connectors and profiles. In naturally ventilated BiPV façade system the rear ventilation in façade cavity eliminates the problem of the PV module overheating. Thermal energy from PV is removed by four physical processes: radiation exchange with exterior (sky, surrounding surfaces), outside convection, radiation exchange with solid surfaces inside the cavity and convection with airflow movement in the cavity (Fig. 2.3.19).

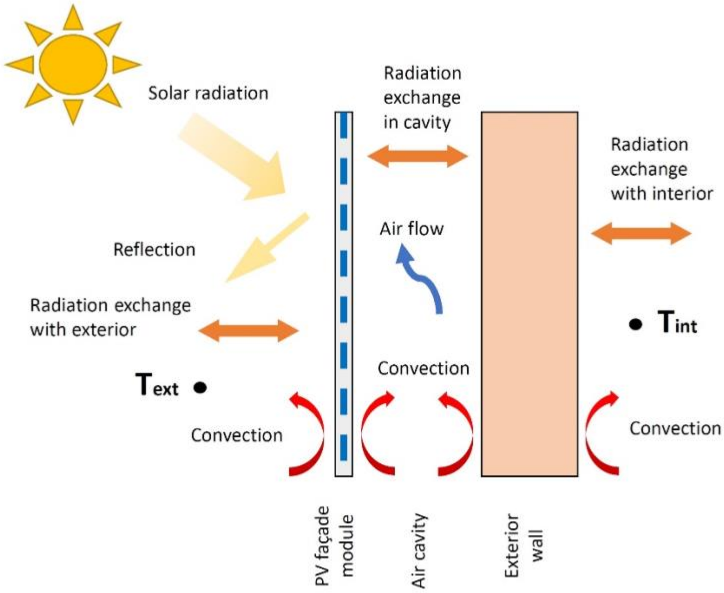

Figure 2.3.19 – Thermal building physics of naturally ventilated BiPV façade.

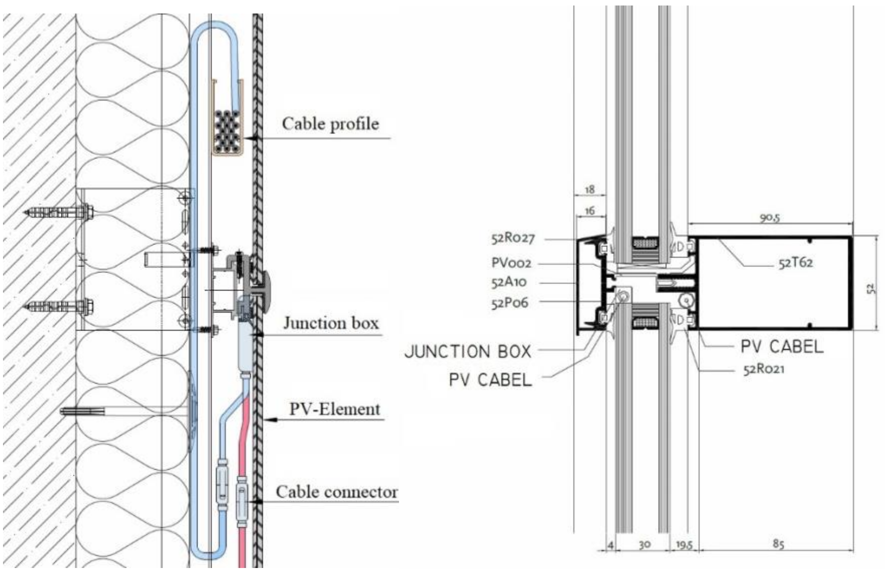

Figure 2.3.20 – Two basic types of BiPV façade: ventilated curtain wall BiPV façade (left) Source: Lithodecor, lightweight mullion-transom BiPV façade (right) Source: Ertex-Solar.

The combination of PV façades and green facades is system that can be used as the strategy for improving building energy consumption, energy savings, thermal performance, sound mitigation, and improving life quality: air quality, noise damping and aesthetics. The PV layer supports the growth of the climbing plants, while offering protection from the extremely high temperatures in summer and from the cold winds and rains during the winter (Fig. 2.3.21). At the same time the green layer provides a cooling effect for PV, due to the transpiration of plants. Each layer has a positive influence on the others, working in synergy to reach the desired goals

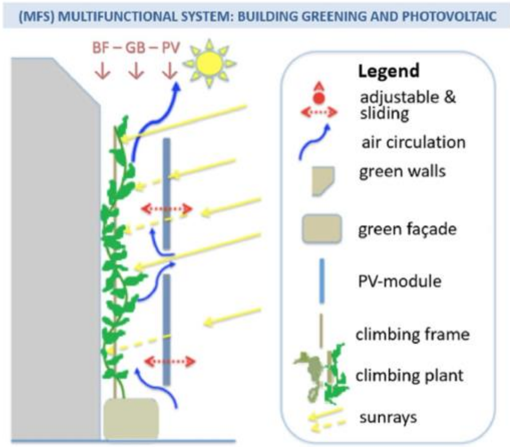

Figure 2.3.21 – Schematic of the PV – Green façade. Source: Penaranda Moren, M.S. and Korjenic, A. (2017)

Shading systems in facades could consist of PV panels in blinds that automatically track the sun and generate electricity from its solar radiation while reduce indoor cooling demands through their shading effect (Fig. 2.3.22). Shading devices can be classified into fixed shading panels and shading blinds. Whereas fixed shading panels are usually independent building components, shading blinds are often installed as an integral component of windows. BIPV blinds can be classified into outdoor PV blinds, indoor PV blinds and middle PV blinds according to the position of blinds relative to the windows.

Figure 2.3.22 – Outdoor PV blinds. Source: solargaps.com

Advanced shading systems in dynamic building envelopes are based on the utilization of soft-robotic solar trackers to actively modulate solar radiation for energy generation, passive heating, shading and daylight penetration at a high spatiotemporal resolution. This envelope consists of individual PV modules mounted on a lightweight rod-net supporting structure, as the outer layer of a glazed façade. Each module is equipped with a soft pneumatic actuator that allows individual orientation in two axes. Electrical cabling and pneumatic supply are integrated into the rod– net structure (Svetozarevic et al. 2019).

Fig. 2.3.23 shows working principle and use cases of the soft-robotic-driven adaptive building envelope:

a, b) A room with the adaptive PV envelope in summer (**a**) and winter (**b**) day and qualitative representations of physical effects that the envelope can modulate.

c) A room with a reflective adaptive envelope. This envelope allows redistribution of solar irradiation and daylight among buildings, by reflecting it to a neighbouring building, where the concentrated solar resource can be used for improving daylighting accessibility, or to the sky, to mitigate urban heat island effects. The blue arrows in **a)** and **c)** indicate enabling the view to the outside.

d) An individual envelope module.

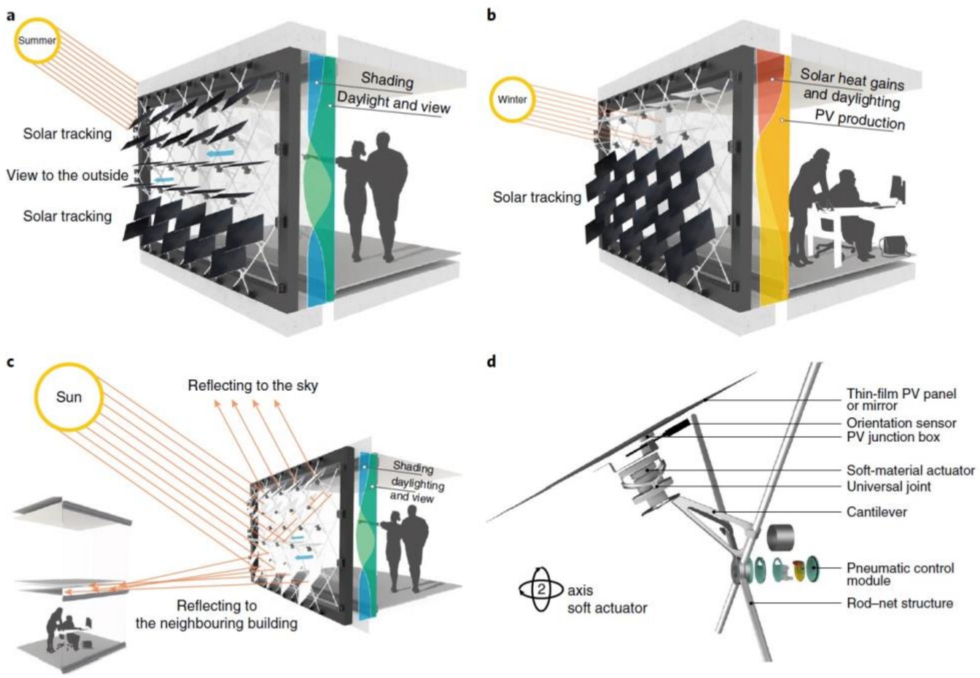

Figure 2.3.23 – Working principle of the soft-robotic-driven PV modules. Source: B. Svetozarevic et al. (2019).

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2.3.4 SOLAR THERMAL ENERGY STORAGE FACADES

Thermal heat energy flow constitutes a major part of energy flows in overall building energy system. Boundary conditions on exterior side (climatic conditions) as well as on interior side (building energy demands) are mutually influenced by dynamic nature of their changes. Overall building energy flows are determined by the demands of interior thermal comfort (Fig. 2.3.24). This is based on delivery of thermal energy, which can be more viable by using solar radiation. Harvesting of solar thermal energy is possible only during the sunny period of a day. For ensuring thermal energy during cloudy days and night period it is necessary to integrate a viable device for thermal energy storage (TES). There are several methods for storing/releasing thermal energy (Fig. 2.3.25).

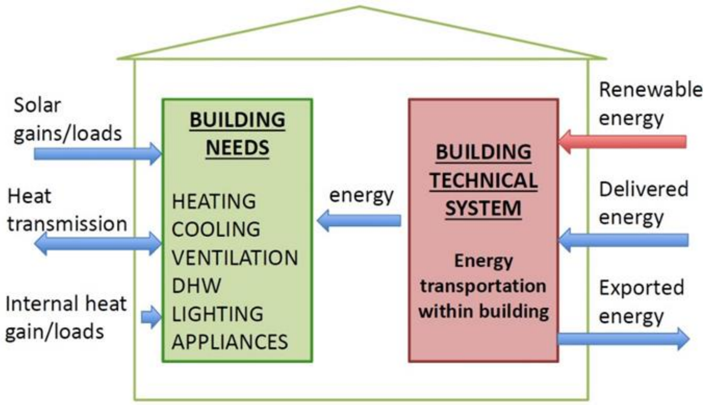

Figure 2.3.24 – Building energy flow diagram.

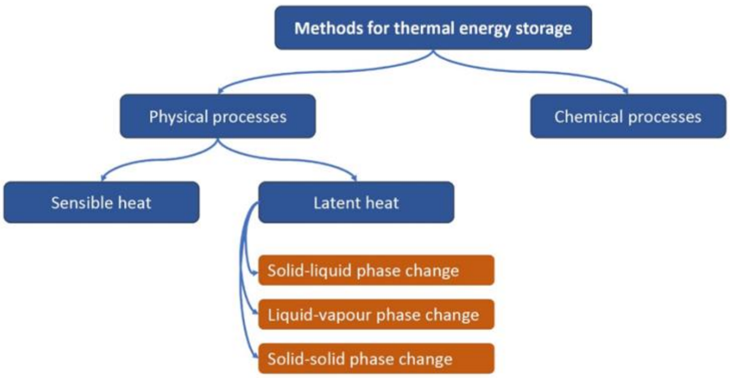

Figure 2.3.25 – Methods for storing/releasing thermal heat energy.

Phase change material (PCM) or also referred to as latent heat storage material represents a special type of responsive material which can absorb high amount of heat energy within its

high latent heat capacity during the phase transformation in certain narrow range of temperatures (entropy change).
The phase change (isothermal process) means from solid to liquid, from liquid to gas, or vice versa. The ability of certain types of PCM to transmit (part of) the visible spectrum of the solar radiation, it is possible to combine a PCM layer with transparent/translucent layers, to create a façade component that exhibits a (relatively) high thermal inertia, together with transparency in the visible spectrum. These characteristics of PCM make it possible to replace solid walls with glass elements (Fig. 2.3.26). It prevents the building from overheating in summer while maximizing natural lighting.

Figure 2.3.26 – The window filled with PCM. Source: glassx.ch

2.3.5 BIOREACTIVE FACADES

Bioreactive façades are considered as new technology for high-performance buildings. They have the potential to contribute to lower ecological and carbon footprint of buildings and their fossil fuel depletion. The integration of microalgae bioreactor with the building can also affect the building's thermal loads and significantly decrease the building's energy demands. The façade elements – vertical glass louvres are filled with water containing nutrients which convert daylight and CO_2 to algal biomass through the bio-chemical process of photosynthesis; at the same time the water is heated up by solar-thermal effects (Fig. 2.3.27).

The biomass and heat generated by the façade elements are transported by a closed loop system to the plant room, where both forms of energy are exchanged by a separator and a heat exchanger respectively. The temperature levels of the heat generated can be increased by using a hot water pump for the supply of hot water and for heating the building. Excess heat can be stored by use of a geothermal system.

Converting light into heat and biomass by photosynthesis process is a key function performed by microalgae bioreactive facades. Microalgae biomass not only can generate biofuel in form of biodiesel, hydrogen, ethanol, and syngas, but also can be a source of other types of energy including heat and electricity.

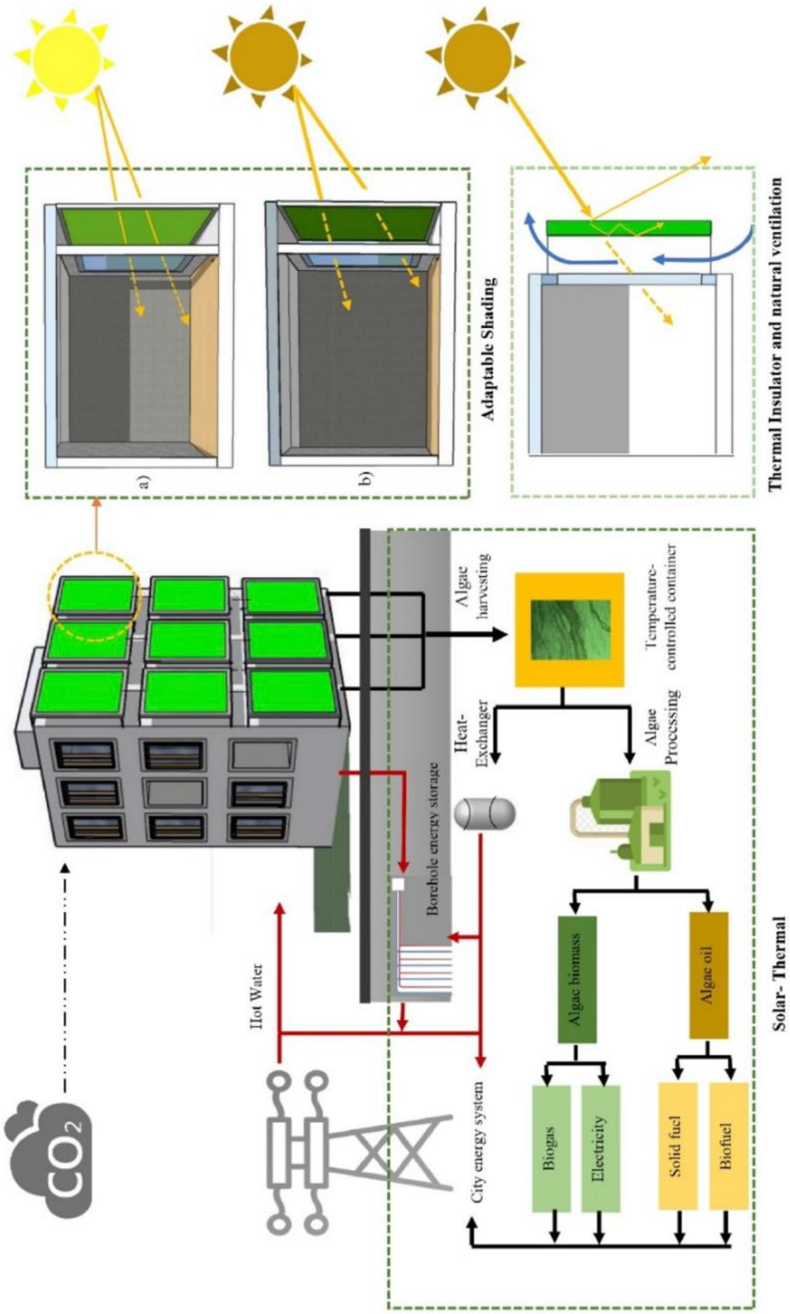

Figure 2.3.27 – Schematic performance of bioreactive façade. Source: Talaei et al. (2020).

2.3.6 WIND ENERGY UTILIZATION BY FACADES

Additional type of renewable energy harvesting system which can be integrated in façade system is wind turbine. However, there are the challenges associated with the application of wind energy harvesting systems, including low velocity and high turbulence of urban wind, building-mounting difficulties, vibration, and noise problems. Identification of suitable locations in the built environment in and around a building which helps to efficiently exploit wind energy is an essential step to integrating wind turbines to a building. Basically, there are three types of wind turbine in building system:

BIWT – Building Integrated Wind Turbines
Turbines are attached to the building but not necessarily connected to them.

BMWT – Building Mounted Wind Turbines
Turbines are connected to the structure of the building. Usually, building have a tower shape and its geometry has to be able to provide to install turbines and have to be vibration, load and noise proof.

BAWT – Building Augmented Wind Turbines
Building is purposely used to profile and strengthen wind flow through the installed turbine. This effect is achieved by a special roof construction which is used as a flow concentrator or mounted turbines on the roof edge.

Figure 2.3.28 – Two basic types of turbines – with vertical and horizontal rotation axis.

In general, possible locations for incorporating a wind turbine system to a building, particularly high-rise buildings, can be classified into four groups as shown in Fig. 2.3.29: (a) on rooftops, (b) in between two buildings, (c) inside through-building openings, (d) integration into building's skin.

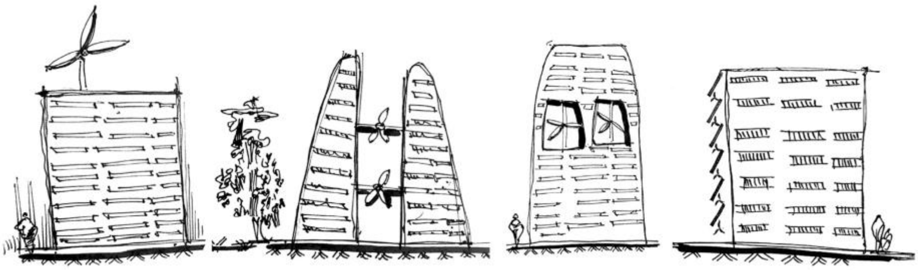

Figure 2.3.29 – Possible locations for mounting wind turbine systems. Source: Hassanli et al. (2017).

In addition to wind turbines installation in existing buildings, one approach being used in several benchmark buildings is to integrate micro wind turbines into buildings by taking advantage of architectural aerodynamic design of buildings (Fig. 2.3.30). Properties of the wind flow are very complex around the building envelope.

Every building has its own wind flow around itself due to its form and arrangement with neighbouring structures. To concentrate the dispersed wind flow into a rotor efficiently of micro-turbines, a guide vane should be introduced in the proposed system and plays an important role in increasing the wind speed (Fig. 2.3.31).

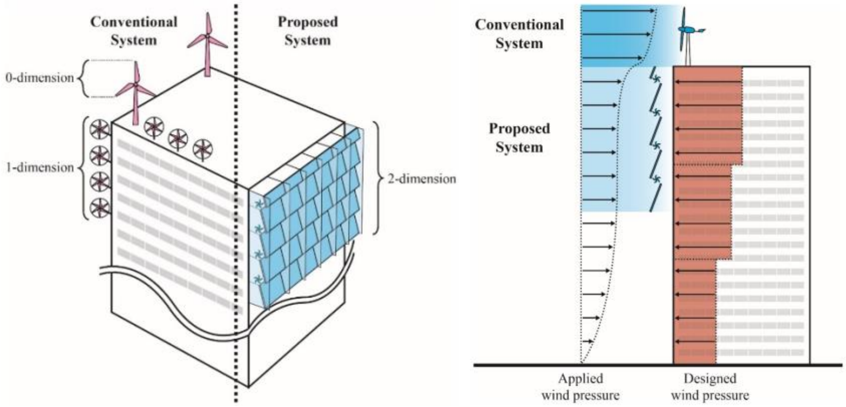

Figure 2.3.30 – Installation areas and structural aspects of wind energy harvesting systems in building envelope. Source: Park et al. (2015).

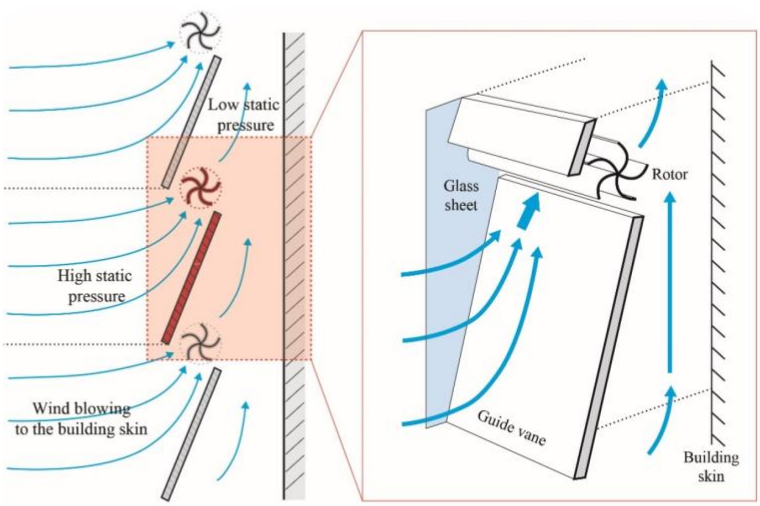

Figure 2.3.31 – Schematic diagram of micro turbines with guide vane. Source: Park et al. (2015).

Various factors in wind energy harvesting system have to be considered:

- The basic principle determinates to strengthen the wind flows near the building.
- The main problem of the integration is to design a suitable building shape in an area with good wind conditions
- Wind environments in urban areas are quite different from those in hilly or coastal areas.
- BIWT system would produce almost 20% of the necessary energy for the building operation.
- Noise and vibration problems caused by the large turbine.
- Safe operation in the urban environment.
- The need for structural strengthening to resist the additional force, except of small-size wind turbines.
- Minimised maintenance.
- Large turbine = large energy production, Small turbine = small energy production.
- Payback period?
- Studies show that such wind turbine installations may satisfy up to 20% of the building's energy needs
- Wind speed could be increased by up to 40% only by design an optimal building geometry.
- In a design process, work with numerical model by CFD (Computational Fluid Dynamics) methods
- Two main parameters: **wind speed and wind direction**

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