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A state-of-art review of retrofit interventions in buildings towards nearly zero energy level

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Abstract

Unmistakably, buildings retrofitting brings the possibilities to reduce energy use and greenhouse gas emissions. However, selecting specific retrofit strategies is complex and requires careful planning. There are already various technics of buildings retrofitting towards nearly zero energy level. Therefore, the focal point in this paper is the review of relevant solutions and the effect of their corresponding consequences on building energy efficiency as well as recommending renewable energy technologies. Further investigation on the feasibility of adopting these technics for cold climates requires thorough studies to be carried out through experiments or numerical simulations.

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1. Introduction

It is known that buildings are the largest energy using sector in the world, and over one-third of total final energy use and an equally important source of carbon dioxide (CO₂) emissions are imputable to existing buildings [1,2].

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Therefore, it is vital to reduce the total energy use by means of energy efficiency improvements through retrofitting of existing buildings to achieve a nearly zero energy building (nZEB) level that will bring environmental, economic, social, and health benefits. Generally, a net zero energy building (ZEB) is a residential or commercial building with zero net energy use, meaning total amount of energy used by the building on an annual basis can be compensated by on-site production of energy via renewable energy technologies.

The nZEB has a very high energy performance. The low amount of energy required is covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby, which the latter technically may mean existing district heating and cooling or any other technical system serving a group of buildings. It is important to emphasize that there are many definitions and ambition levels towards ZEB depending on the climate zone [1].

The energy efficiency retrofits for buildings towards a nZEB level are defined as actions that allow an upgrade of the building's energy and environmental performance to a higher standard than was originally planned [3]. An overview of potential retrofit strategies and retrofit actions which may improve performance figures can be categorized into three main strategies: (1) actions regarding building envelope and design aspects including insulation upgrades, air leakage reduction, improvement of doors and windows, control and exploitation of solar gain and daylight, etc.; (2) actions for building systems and installations including installation of high-effectively HVAC systems, improvement of electrical lighting systems, improvement of domestic appliances, installation of renewable energy, etc.; (3) actions associated with building services and management tools including monitor and control of building during operation, utilization of metering services, clock controls, sensors, etc. [4]. Thermo-active building systems for thermal stability and natural lighting for a better quality of illumination are also other operational examples of retrofit strategies [5,6]. The overall consequence of these retrofit strategies would be an energy efficient building with low greenhouse gas emission that is both comfortable for occupant and cost effective.

Another important factor in studying nZEB is climate of the region where retrofitting is performed. It's generally accepted that buildings in colder climates use more energy for heating than those in warmer climates use for heating of building space and air ventilation. So, it takes less energy to achieve indoor comfort in cooling-dominated climates as well as it's easier to build a nZEB, indicating differences in approach towards nZEB in cold and warm climates. For instance, while thick layers of insulation get most of the attention in cold climates, insulation needs less emphasis in warm climates [7].

This paper aims at providing an overview of retrofit technologies, strategies, and renewable energy systems applied to different areas of existing buildings as well as their energy performance and environmental effects, mainly for cold climate and partly for warm climate, to achieve a nZEB level. A thorough discussion on each level of building retrofitting is presented and some alternative solutions are also suggested.

The review research methodology considers the different scholarly studies mostly related to the potential of employing building retrofit interventions, with promising results in improving of two key parameters; building energy use and indoor environmental quality. The results are classified into three categories including the most popular and innovative interventions regarding building design, building envelope, and building system and services recognized in the literature as appropriate solutions to achieve a nZEB level. Finding are subsequently interpreted, and presented.

2. Retrofit interventions and performance criteria

The main criteria for efficiency and sustainable performance of retrofit measures in all building areas towards nZEB level include: (1) decreasing of energy use, (2) limited impact on global greenhouse gas emission, (3) improvement of indoor environmental quality, and (4) upgrading of functionality and architectural quality. Furthermore, the expected cost of a specific retrofit is key to its effective value. However, several of these criteria often appear to be in conflict, for example, energy use improvements versus architectural quality [4]. In some cases, retrofitting of building service and systems requires less cost investment while providing more environmental benefits than retrofit measures using renewable energy technologies [8]. Therefore, finding the optimum retrofit strategy is a complex procedure and needs to be critically investigated.

2.1. Building design

Despite the fact that the building design can be affected less significantly during the retrofitting of an existing building, its essential role in improvement of architectural quality and, most importantly, in energy saving through retrofitting cannot be ignored.

Table 1 presents the application of different retrofit measures integrated into building design and the summary of key findings from previous studies. As it can be seen, large body of researches in this regard indicate the importance of building design retrofitting in the enhancement of energy saving and aesthetic value of the building.

Table 1. Retrofit interventions integrated into building design elements and summary of important findings

Element	Type of building	Major retrofit technologies used	Major results	Reference
	Residential (multi-family apartment)	Solar thermal collector; BIPV (Building integrated photovoltaic system; Green façade; Meefs (Multifunctional energy efficient façade system)	The use of Meefs system in cold climate building apartments in Finland and Russia can offer considerable energy saving (63%).	[9]
	Non-residential (University Laboratory)	BIPV/T Collector (Building integrated photovoltaic system collector combined with solar air collector)	The experimental study on the BIPV/T system prototype in cold climate in Canada. indicated 10-15% higher combined efficiency than the reference system.	[10]
	Commercial	Curtainwall (Metal frame, infill panels of glass metal or composite structure)	<ul style="list-style-type: none"> • Employing Curtainwall building façade improves both building energy performance and appearance towards nZEB in New York city. • Employing a cassette system can answer the need for adaptability and future renovation. 	[11]
	Residential and non-residential	Trombe walls; Integration with PV	<ul style="list-style-type: none"> • In humid regions, Trombe wall reduces the energy use of building and decreases the moisture of interior spaces. • The indoor temperatures are more stable than those in most other passive systems. • The time delay between absorption of the solar energy, and transfer of the thermal energy to the living space can be used for non-sunny period heating. • Installation cost is relatively low for retrofitting existing buildings with uninsulated massive exterior walls. 	[12-15]
	Residential (dry climate) and non-residential (Tropical schools)	Solar chimney; Passive evaporative system	<ul style="list-style-type: none"> • The buoyancy effect of solar chimney provides increased indoor air movement and approximately 64% energy saving to Singapore standard. • Integration of solar chimney with evaporative system can decrease indoor temperature around 9-14 °C and increase relative humidity around 28-45% in warm and dry climate in Yazd, Iran 	[16,17]
Roof	Residential and non-residential	Roof-mounted PV system	<ul style="list-style-type: none"> • A detailed numerical analysis revealed a maximum emission of 69 g CO₂/kWh during 30 years of operation with an embodied energy payback time of 3.9 years by the m-si PV module in cold climate in Norway. • Energy saving of 70 kWh/m² can be achieved per year for a tropical school in 	[16,18,19]

			Singapore.	
			<ul style="list-style-type: none"> • The use of this system in a main school building with a total surface of 1120 m² in cold climate in Germany covers the total energy demand in the annual balance. 	
Lighting	Non-residential historical building	Different types, arrangement, mounting height of luminaires, glass to window area, and walls reflectance values	<ul style="list-style-type: none"> • The best measure to reduce the energy use and LENI in a Mediterranean office building in southern Italy (Lighting Energy Numeric Indicator) is the substitution of the existing luminaires with more efficient luminaires. • The increase of the glass to windows area does not guarantee a reduction of LENI. 	[20]

Interestingly, there are several methods which their integration into building design can achieve a higher efficiency in terms of architectural quality and functionality. A case in this point is school building. Some of the boundary conditions for existing school buildings include: high ceilings to provide suitable air volume and together with large window areas placed mostly on one side of the classroom, rather high artificial lighting installations to compensate the daylight in the early and late hours or winter. In this respect, it is suggested that making use of domed-roof-mounted PV system will provide these demands. Fig. 1a indicates the modification of a domed roof for proper installation of PV panels. Integration of transparent or semi-transparent PV panels with the domed roof can also assist in providing daylight requirements (Fig. 1b). However, efficiency of the proposed system may be questioned in some regions, northern Europe for example, with low sunshine period in winter and, in turn, the building energy performance can reduce due to reverse heat transfer from the domed roof.

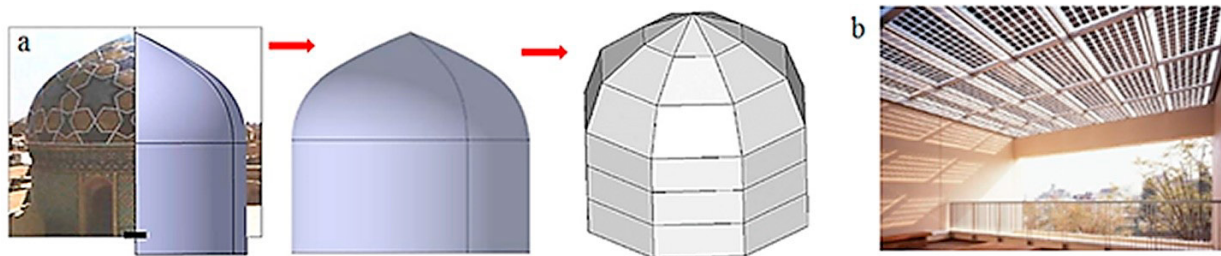


Fig. 1. (a) Schematic of modification of domed roof design for proper installation of PV panels in dry climate in Yazd, Iran; (b) An example of glass ceiling with transparent PV modules in China [21].

Integration of Trombe wall with new designed channel into building façade can also be considered as a practical way to improve energy performance of commercial buildings to possibly achieve a nZEB. The new designed Trombe wall has two ascendancy over normal one. The first one is receiving higher solar intensity by replacing lateral sides of the channel with glass leading to an increase in channel temperature and airflow circulation inside the channel and the room for meeting comfortable condition. The other is the capability of adopting window on the same surface of the room due to occupying less area of the wall compared to normal Trombe wall (Fig 2a) [22]. Integration of new designed Trombe wall with solar chimney and water spraying system can be also implemented for cooling applications in warm climates with mild winters and hot summers to avoid overheating problems (Fig 2b) [23]. For ensuring the system effectiveness in widespread climatic conditions, adopting PCM within the Trombe wall is an operational method. For example, in a climate with extended cloudy periods that the wall may become heat sink, employing PCM Trombe wall can remedy the problem by increasing the time delay between absorption of the solar energy and its transfer to living space.

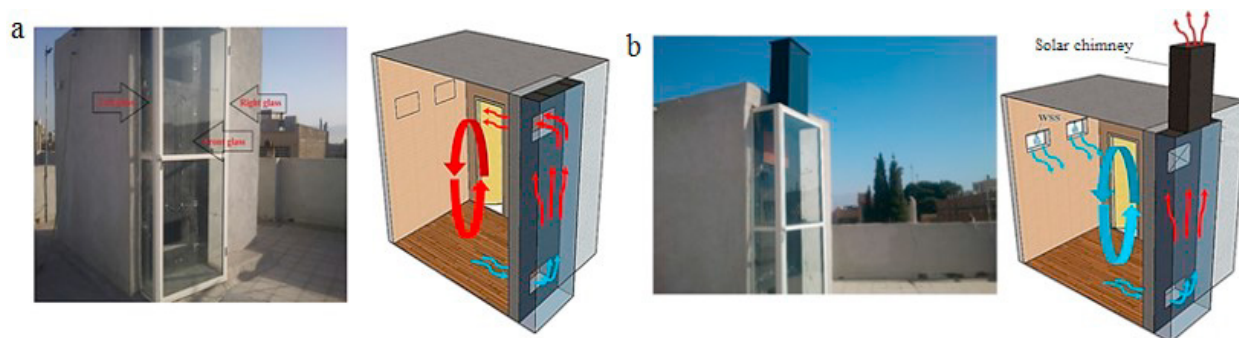


Fig. 2. (a) Schematic of winter performance and empirical model of new designed Trombe wall in dry climate in Yazd, Iran [22]; (b) Schematic of summer performance and empirical model of new designed Trombe wall with solar chimney and water spraying system in Yazd, Iran [23].

2.2. Building envelope

It is undeniable that in addition to the architectural influences, the building envelope quality has a huge impact on the energy performance of a building. The thermal quality of the envelope (insulation with high thermal resistance and low or no thermal bridges), the airtightness and the ventilation losses define the net heating energy demand of the building [24].

Table (2) summarizes the retrofit interventions for building envelope and their impacts on the energy performance of building. Almost, most of studies dealing with envelope retrofitting have pointed out that insulation and PCM integration are the most effective practices for retrofit of building envelope.

Table 2. Retrofit measures for building elements and key summaries of important findings

Element	Technique	Type of Materials	Important findings	Reference
Internal/external insulation		Internal: Non-rigid insulating materials with necessary thickness to reach specified U-values; VIPs (vacuum insulation panels); Aerogel (Dried gels with a very high porosity) External: Mineral wool and polystyrene with cover; Aerogel; Multi-foil insulation (multi-layered reflective films separated by foam or wool); Thatch mixture, Xlam panel (cross laminated timber panels)	<ul style="list-style-type: none"> • The use of VIP leads to decrease of wall moisture content by 50% with lower fluctuations in cold climate in Sweden. • Combination of aerogel and VIP in cold climates prevents water inclusion and reduces thermal conductivity. Translucent aerogel also helps for daylighting purposes while granular layers of silica aerogel have the acoustic absorption properties. • A numerical simulation in Mediterranean climate building in Italy indicated that combination arrangement of mineral wool, Xlam panel, and brick wall is the best in terms of environment impact, thermal performance and cost effectiveness. 	[19,22,24-28]
PCM integrated wall; Immersion; Attachment		Paraffin wax; Fatty acid; Composite PCM	<ul style="list-style-type: none"> • Reviews revealed that addition of PCM to internal partition walls and envelope increases the building's thermal mass for meeting passive house level based on Norwegian standards. • Experiments demonstrated a 45–74% reduction of interior wall surface temperature fluctuation in mid-seasons as well as around 24% and 10–30% reduction of the cooling and heating loads, respectively due to integration of SSPCMs (shape-stabilized PCMs) into the wall 	[29,30]

Roof/ceiling	Insulation (above, beneath, or within the existing structure); Skylights	<p>Pitched: Loft insulation (Insulation is installed directly from above the top floor ceiling between the ceiling joists); Mineral fiber; Natural material (sheep wool)</p> <p>Flat: Vapor permeable materials (fibrous or granular); Vapor control membrane (fully impermeable sheets of polythene); Impermeable insulation (fully impermeable foamed sheets of glass or plastic)</p>	<ul style="list-style-type: none"> • The implementation of insulation using wood fiber and water tight covering decreased the roof U-value around 85%. • The lowest densities and highest values of vapor permeable materials are gained from soft fiber rolls or unformed loose-fill materials. • The use of vapor control membrane in historic homes across England prevents moisture vapor from entering and condensing within the construction. • Installation of impermeable removes the risk of interstitial condensation forming within the insulation itself. However, its installation between joists will leave gaps where moisture vapor can penetrate and condense. 	[19,31-34]
	PCM integrated roof	Paraffin wax mixed with an ethylene copolymer and sandwiched between two sheets of aluminum sheet; BioPCM; Eutectic mixture of lauric-stearic acid	<ul style="list-style-type: none"> • Material analysis of equal volume has shown that in comparison with PCM roof, concrete offers only approximately 17 % of the energy capacity in Australian buildings. • Application of PCM in gypsum board as a ceiling component in Malaysian buildings showed the boards decreases the peak indoor temperature by about 2 °C 	[34,35]
	Triple-glazing; low-E coating; gas filling; Insulation; electro-chromic (EC) windows	Mineral wool insulation; Aerogel based; Argon filled	<ul style="list-style-type: none"> • Simulations on aerogel based indicated an energy saving of 19% and 34% respectively for 13.5 and 20 mm for a house built according to the Danish standard and for a house insulated to the passive house standard in Danish climate condition. • The use of high insulation reduces the window U value around 35% in warm climate in Northeast of Italy • The EC case reduces peak cooling load, due to solar heat gains, around maximum of 26% and 19% compared to an unshaded and shaded reference case in Chicago if the EC is controlled to its lowest transmittance. • The EC case saves the total primary annual energy use approximately 10% in Chicago and 4% in Houston. 	[19,32,36,37]
	PCM integrated window; PCM shutter	Paraffin wax; polyethylene	<ul style="list-style-type: none"> • Integration of paraffin in the large window area can reduce peak temperature in passive houses with a highly glazed façade in a temperate climate. • Advanced materials such as Nano-treated PCMs can be considered in order to improve the transparency of the PCM-based window glass. 	[22,38,39]
	Insulation	Suspended floors: wood fiber, compressed hemp, wool of sheep (from below the floor); semi-rigid batts, foam boards or loose fill cellulose (from above the floor)	<ul style="list-style-type: none"> • The energy saving resulting from insulating solid ground floors of historic buildings in England can be very lowered mainly since the ground beneath maintains a stable temperature of around 10°C. 	[26,40,41]

	Solid floors: VIP panels; wooden floors or tiles; polystyrene hard foam insulation	<ul style="list-style-type: none"> • For suspended floors, insulation from below has the advantage of minimal disruption to occupants, but limited space may make insulation difficult 	
PCM integrated floor; Under-floor heating system	Paraffin wax; BioPCM (waste product derived from the manufacturing process of soy, palm, coconut oil)	<ul style="list-style-type: none"> • BioPCM system can reduce air conditioning demand by 17.7 % compared to a typical concrete slab floor in Australian buildings. • Heating the PCM at night shifts the use of electrical energy from peak to off-peak periods and ensures the economic advantage of cheap electricity at off-peak periods. 	[29,34,39]

Natural insulation is an environment-friendly method that can improve the energy performance of building. A good example of this is green roof, which is more effective within the context of temperate maritime climate. It can reduce the amount of heat penetration through the roof and play a similar role to roof insulation. Herbaceous plants can also reduce the roof temperature and surroundings by absorbing heat into its thermal mass and due to evaporation of moisture [42]. In dry climate, earth-based materials such as adobe can be considered as a suitable retrofit measure for building envelope. These materials are capable enough to restrict less intense sun rays and prevent them from penetrating in to warm the inner side of walls and begin to transfer heat to the living space. In fact, these adobe walls can act as a better heat reservoir due to the thermal properties inherent in the massive walls typical in adobe construction, making them very desirable for climate with hot sunny days and cold nights.

2.3. Building system and services

On account to the reduced net energy demand due to the proper retrofitting of building design and envelope, heating and cooling systems having high efficiency and low capacity can be installed. The exact values have to be determined by a detailed calculation based on national standards. The limited heating and cooling energy can also be provided by low heat temperatures, which has the positive consequences of possibility to integrate solar thermal or geothermal contributions into the heating and cooling system. Therefore, the following section will be focused on passive and energy technologies for heating, cooling, and ventilation system (Table 3).

Table 3. Summary table for the retrofitting practices regarding HVAC system

System type	Technology and strategy	Major results	Reference
Geothermal heat pump (GHP)	Borehole heat exchangers; Energy piles (heat exchanger pipes integrated into the building' foundation pile); Ground absorber; Direct use of ground water Open loop; Closed loop (pond, vertical, horizontal, and slinky)	<ul style="list-style-type: none"> • Closed loop GHP can reduce energy use and air pollution emissions-up to 44% compared to air source heat pumps and up to 72% compared to electric resistance heating with standard air-conditioning equipment in buildings in Germany. 	[19,43]
Passive solar cooling and heating system	Thermal storage; Evaporative cooling; Natural ventilation	<ul style="list-style-type: none"> • PCM integrated passive solar system (Trombe wall, ceiling board, wall board, assisted under-floor electric heating) can reduce indoor temperature fluctuation, energy use, and CO₂ emissions. • Hybrid ventilation (solar chimney and controllable assisting fans) intensifies the ventilation rate depending on the purpose. • Solar chimney integration with water injection is the best option for cooling application in dry climates. 	[17,19,29, 35,39]
Other renewable technologies	Biofuel and biogas used by (micro-CHP: combined heat and power; boilers; As a part of a district heating system; trigeneration:	<ul style="list-style-type: none"> • The use of bio micro-CHP allows for the generation of electrical power and heat at the same time with low CO₂ emission factors. 	[19,44]

combined cooling, heat, and power (CCHP))

• Techno-economic analysis of three modelled trigeneration systems indicated efficiencies of around 64–70% in a test building in the UK.

An innovative system for building retrofitting is making use of hybrid system of BIPV/T-GSHP systems (combination of building integrated photovoltaic panels and thermal system (BIPV/T) with ground source heat pump system (GSHP)) to achieve a nZEB level. The dual technology of a PV/T system creates a much more efficient panel and can provide both electricity and hot water supply (water-based), simultaneously. In fact, the flow of water at the back of the module acts in cooling down the PV cells, thus increasing the electrical output around 15–20% on annual basis. The excess heat removed from the BIPV/T system can be utilized by the GSHP (Fig. 3) for charging of the ground borehole. Reasonably, feasibility of the system necessitates a comprehensive set of investigations.

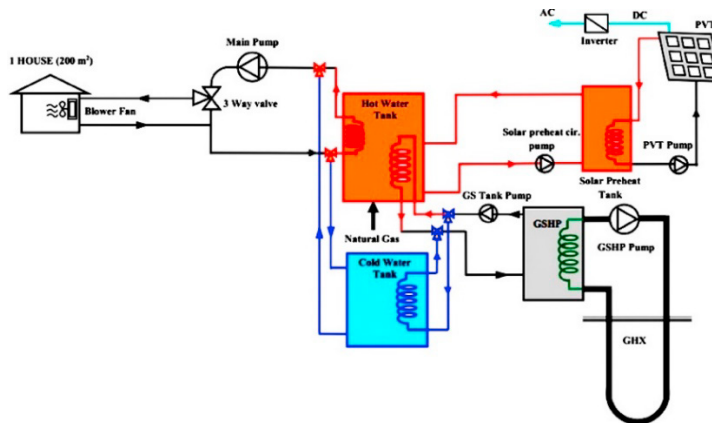


Fig. 3. Schematic diagram of BIPV/T-GSHP system [45]

In another innovative method, the BIPV/T system can be integrated with wind catcher technology and solar chimney to achieve a nZEB level (Fig. 4a). The combination of wind catcher-earth air tunnel and horizontal and vertical solar chimneys (Fig. 4b) can secure a consistent passive air ventilation in the building, even when there is no suitable and reliable wind and a passive ventilation is problematic.

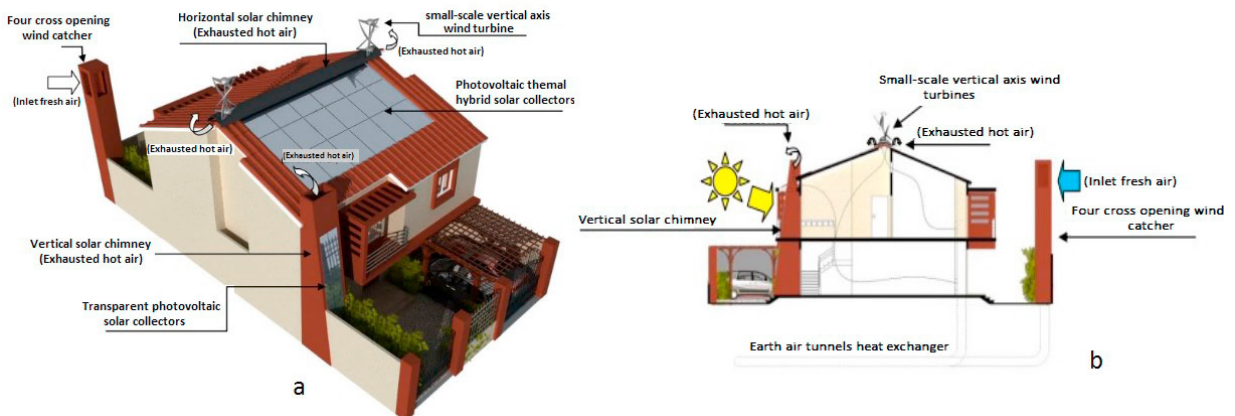


Fig. 4. (a) Schematic of integration of BIPV/T system with wind catcher and solar chimney; (b) Cross section of hybrid system combined with the earth air tunnels [46].

The BIPV/T can be employed as a source for both electric power and solar thermal energies. The electricity can be generated by the small-scaled vertical axis wind turbines, located on the horizontal solar chimney, taking advantage of exhausted hot air from the chimney and the PV panels, located on the solar chimney and roof, simultaneously. The generated heat by PV panels, can be transferred to a heat exchanger which heats water in a storage tank for possible use in the hot water, heating, and optional cooling systems.

3. Conclusion

The concept of energy efficient retrofitting and its fundamental phases and interventions were discussed in this paper. An energy efficient retrofitting focuses on reducing the energy use of a building in order to extend its life cycle and reduce its impact on the environment on the long-term future. In this regard, an overview of large body of previous studies related to investigation and evaluation of mostly energy performance and some environmental impacts of various retrofit measures were carried out in different areas of building in different climatic conditions towards nZEB level. The reviews revealed that integration of passive and renewable technologies, especially those dealing with passive solar energy and PCMs with different building elements such as BIPV/T systems are the most effective methods to satisfactorily reduce the building energy use and possibly create an opportunity to achieve a zero or plus energy level. Furthermore, study of some possibilities for future researches suggested that the energy saving potentials of all the various options and combinations need to be critically evaluated and investigated. Last but not least, an exhaustive economic and environmental review of the integration of these technologies into building areas should be also performed as future work.

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