Chapter 3

Low/Zero-Carbon Buildings for a Sustainable Future

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Additional information is available at the end of the chapter

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Abstract

Fossil fuel-based energy consumption is still dominant in the world today, and there is a consensus on the limited reserves of these energy resources. Therefore, there is a strong stimulation into clean energy technologies to narrow the gap between fossil fuels and renewables. In this respect, several commitments and codes are proposed and adopted for a low energy-consuming world and for desirable environmental conditions. Sectoral energy consumption analyses clearly indicate that buildings are of vital importance in terms of energy consumption figures. From this point of view, buildings have a great potential for decisive and urgent reduction of energy consumption levels and thus greenhouse gas (GHG) emissions. Among the available retrofit solutions, greenery systems (GSs) stand for a reliable, cost-effective and eco-friendly method for remarkablemitigation of energy consumed in buildings. Through the works comparing the thermal regulation performance of uninsulated and green roofs, it is observed that the GS provides 20°C lower surface temperature in operation. Similar to green roofs, vertical greenery systems (VGSs) also reduce energy demand to approximately 25% as a consequence of wind blockage effects in winter. Therefore, within the scope of this chapter, GSs are evaluated for a reliable and effective retrofit solution toward low/zero carbon buildings (L/ZCBs).

Keywords: buildings, energy consumption, energy-efficient retrofit, green roofs and facades

1. Introduction

Since the beginning of the industrial revolution (roughly 200 years), the dramatic increase in world population and technological advancements led to remarkable rises in global energy demand [1]. Scientists address a relationship between the global energy demand and the consumption of natural resources through the economic growth across the world, especially over the last two decades. Uncontrolled energy consumption due to human activities plays a vital role in biodiversity decline. According to the latest report, the greatest part of the decline in biodiversity has taken place within the last 50 years [2]. Urbanization is another significant problem of today's world in terms of growing importance of environmental issues. The urbanization rate is to rise by 75% until 2030 as shown in **Figure 1** [3]. Urbanization-related environmental matters can be illustrated as pollution, the depletion of natural resources, climate change, and global warming. Especially climate change notably affects the biotic systems as it has cumulative impacts on the global environment such as terrible weather conditions and deterioration of natural ecosystem (serious decrease in fishery stocks and in the productivity of lands) [4].

The European Commission primarily aims to slow down the increase in greenhouse gas (GHG) emission to prevent the hazardous impacts on the environment. Based on the roadmap reported by European Commissions in 2010, the abatement in the EU GHG emissions is aimed to be 80% by 2050 (as compared to the 1990 level). The target of the decrease in GHG emissions takes place in the range 25–60% between 2020 and 2040. To reach this goal, the increase in the global temperature should be 2°C less than the pre-industrial era [5]. A similar, national plan underlying the significance of climate change is adopted by the Government of China. Based on this plan, carbon emissions are expected to be reduced by 40–50% until 2020 compared to the level of 2005 [6]. However, it is a clear challenge to achieve the said targets concerned with global warming and GHG emissions. In this respect, appropriate investments in energy, transport, industry, information technologies, and building sectors are required for the desired outputs. Among the relevant sectors, buildings stand for the most promising field in terms of eco-friendly-mitigating energy consumption levels. The reduction of energy consumed in buildings does not have any negative effects on the welfare of the dwellers [7]. L/ZCB strategy can be accomplished by constructing new environmentally friendly building or retrofitting existing buildings with low-cost, energy-efficient, and eco-friendly technologies. The retrofit

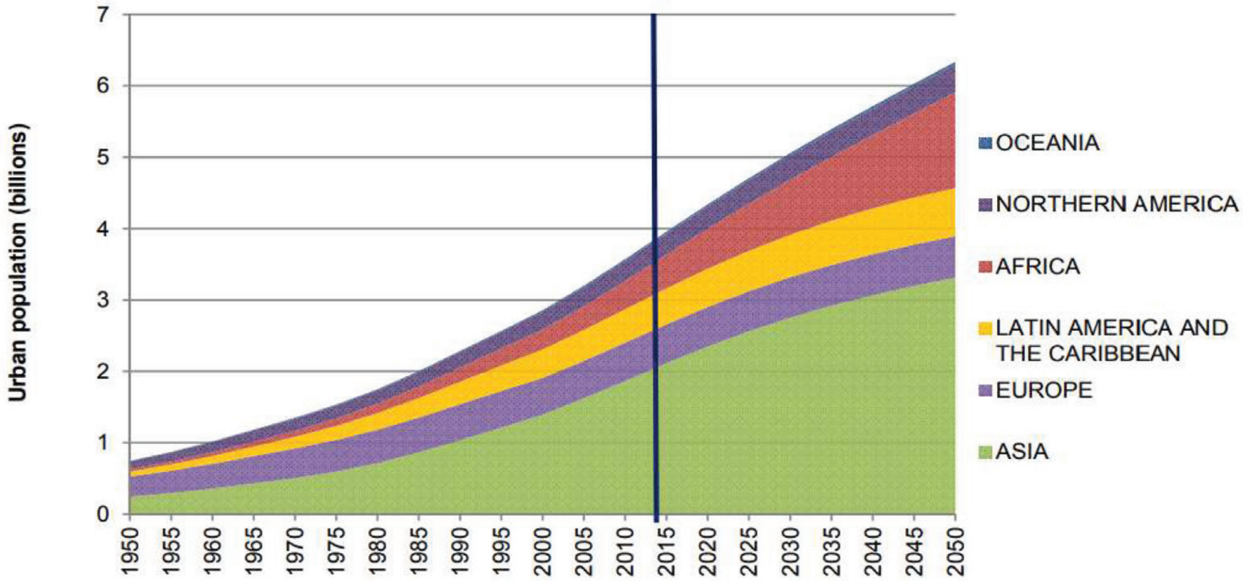

Figure 1. Urban population by major area, 1950–2050 [3].

of existing buildings can remarkably reduce energy demands and carbon emissions, as well as mitigating the depletion of natural resources. GSs are considered as low-energy concept for buildings, and they can be deployed in existing buildings as retrofit applications [8, 9].

In this context, the main goals of this research can be illustrated as to explain the L/ZCB for potential reduction of energy demand in the building sector and to introduce the GSs as retrofit applications to existing buildings.

2. CO_2 emissions

With respect to consensus among scientists, CO_2 emissions in the atmosphere have a remarkably rising trend since industrial revolution. In comparison to pre-industrial revolution, the average rise in CO_2 concentration with 403 ppm is reported to be about 40%. Depending on the recent assessment report on climate change, human beings have a considerable influence on the climate system due to the energy consumption [10]. Therefore, the energy usage is admitted to be the greatest contributor to GHG emissions. **Figure 2a** illustrates the shares of global GHG based on human activity.

The level of CO_2 emission is represented in **Figure 2b**. It is clear from the data that the CO_2 emissions have a steadily rising trend from industrial revolution up to 2014 [11]. It is reported by Boeck et al. [7] that the emissions are expected to increase to 52% from 2005 to 2050 if no decisive measures are taken. During the said period, carbon emissions are predicted to increase by 78%, which is notable. Also the annual increase in GHG emissions between 2000 and 2010 is found to be 1 giga tone of CO_2 equivalent. When the emissions from 1970 to 2010 are analyzed, the growth is reported to be around 0.4 $GtCO_2$eq. Moreover, carbon emissions dramatically increase with the explosive growth in global economy and world population. On the other hand, within the last decade, the emissions have a decreasing tendency because of the global economic recession between 2007 and 2008 as shown in **Figure 2b** [7]. In 2015, global CO_2 emission level is predicted to be 32.3 $GtCO_2$, which is 0.1% lower than the level in

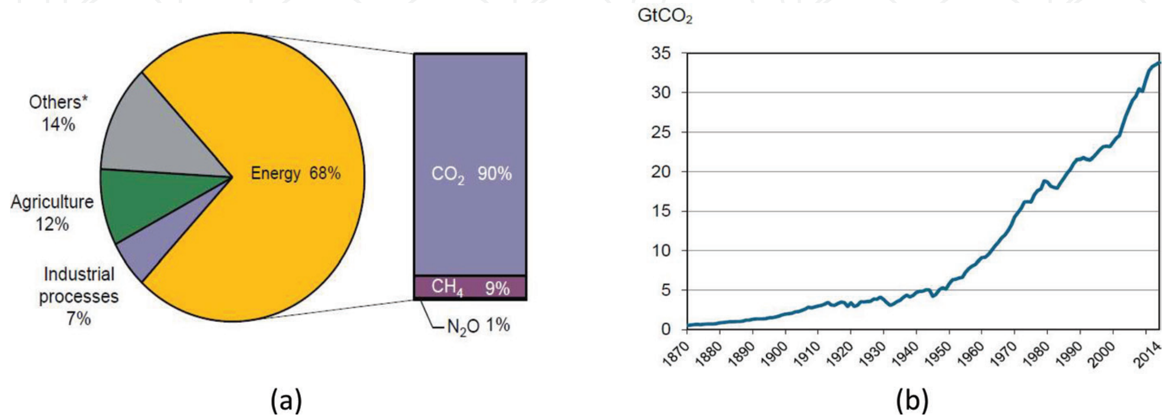

Figure 2. Estimated shares of global anthropogenic GHG, 2014 (a), trend in CO_2 emissions from fossil fuel combustion, 1870–2014 (b) [11].

2014. For 2013 and 2014, the growth rate of CO_2 emission is given to be 1.7 and 0.6%, respectively. On the other hand, the annual rise of the emissions is reported to be 2.2% since 2000. From this point of view, it can be easily understood that the growth in global economy is independent of the reductions in GHG emissions [11].

As a consequence of rising welfare of the countries at growing economic indicators, global energy demand remarkably increases. Between 1971 and 2015, the rise of global energy demand is reported to be 150%. While expressing the energy demand, total primary energy supply (TPES) is widely used to determine the rates as shown in **Figure 3** [11]. With respect to the emissions from fuel combustion in 2015, the largest share of CO_2 emissions is attributed to coal. However, the percentage of coal consumption (28%) is lower than the oil consumption (32%) according to the TPES data.

The major CO_2 emission sectors are electricity and heat generation, which are responsible for 42% of the total emissions in 2015. Although the share of oil utilized in electricity and heat generation decreases, the coal and gas consumptions have an increasing trend in 2015 as compared to the year of 1990 as depicted in **Figure 4**.

2.1. Climate agreements

Kyoto protocol is known as the first agreement to mitigate GHG emissions and the protocol commitment covers the period between 2008 and 2012. The protocol indicates that 5% of reduction in the domestic emissions compared to the 1990 level is required to be fulfilled by the industrialized countries during the said period. Moreover, the countries are expected to reach the targets of Kyoto by mitigating emissions from fossil fuel consumption and emissions in other sectors such as direct industrial emissions. The second commitment period from 2013 to 2020 is defined as The Doha Amendment. The amendment was approved by 80 parties on August 9, 2017. The Kyoto target regarding the GHG emissions, approved by parties, is 19.3% mitigation in CO_2 emissions. Based on the data between 1990 and 2015, it is observed that the said target is already achieved with 20% reduction in the emissions. Paris agreement is defined

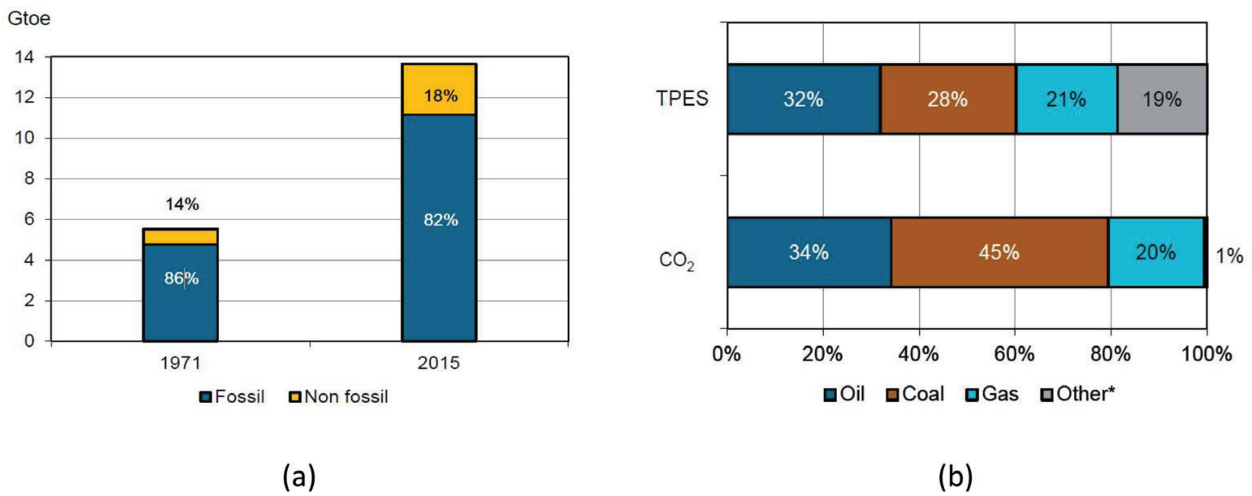

Figure 3. Energy supply by fossil and nonfossil fuels (a), world primary energy supply and CO_2 emissions: Shares by fuel in 2015 (b) [11].

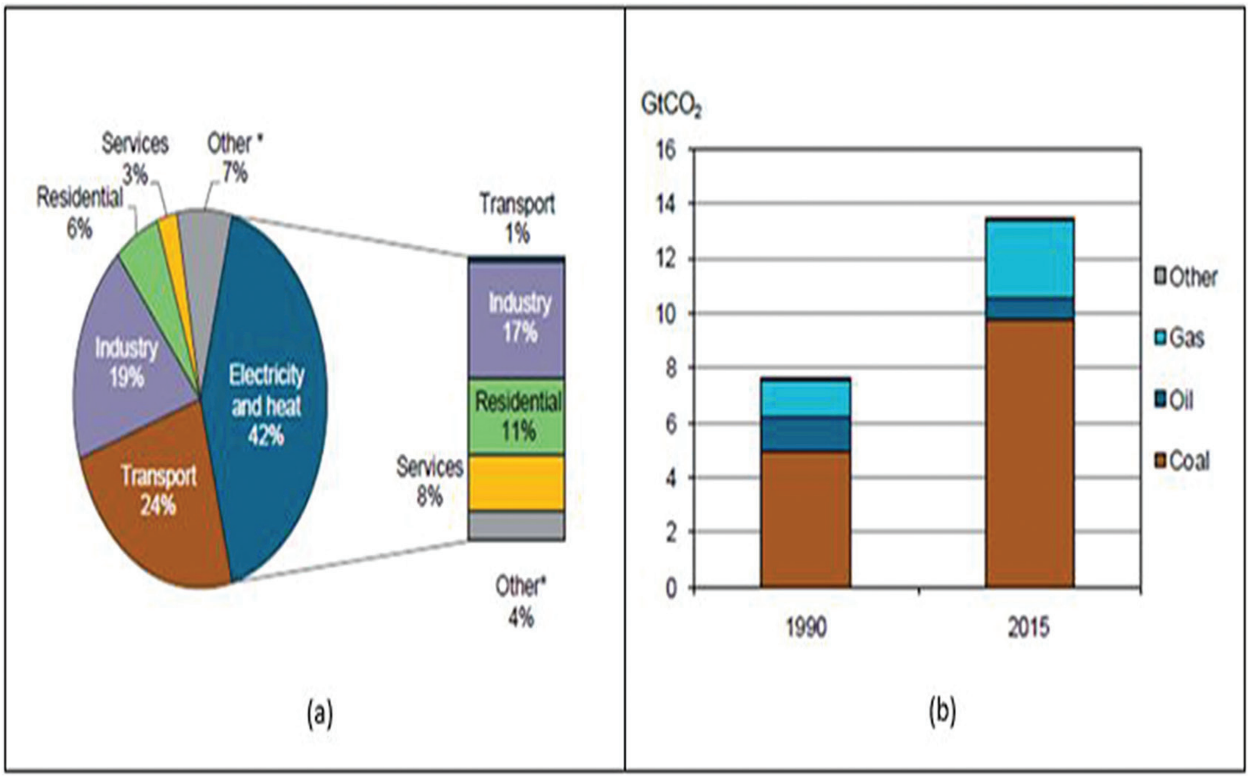

Figure 4. World CO_2 emissions from fuel combustion by sector, 2015 (a), CO_2 emissions from electricity and heat generation, 1990–2015 (b) [11].

as the first international obligatory climate agreement related to decisive reduction of CO_2 emissions. Both developed and developing countries ratified the agreement in 2016 [11]. Paris agreement covers the shift to low-carbon energy and emissions. For this reason, renewable energy technologies (RETs) are of crucial importance in developing low/zero-carbon technologies (L/ZCT) and green energy solutions. Owing to the improvements in these technologies, the cost of such systems remarkably decreases year after year, for instance, the cost of solar electricity is reported to reduce by 65% between 2010 and 2015 [12]. The target of this agreement is to provide the maximum 2°C change in global surface temperature (2DS) by 2050 [13].

3. Building sector

About 40% of the total energy consumption is attributed to the building sector in the world since both building construction and usage play a vital role in global energy use. In this respect, it is firmly believed that buildings contribute substantially to the world GHG emissions [14]. For instance, GHG emissions from buildings in the United States, China, the UK, and Australia are reported to be 43, 50, more than 50, and 23%, respectively [15]. The final energy consumption in European member countries is about 1104 million tons of oil equivalents (based on the data of 2012). A total of 26.2% of this amount is used in residential buildings. The amount of total buildings present in the EU27 overweighs by 25% compared to the residential buildings. Energy consumption in the residential buildings can be split into two major parts such as space heating (68.4) and heated water (13.6) [7]. As emphasized in a research, the rise of global space cooling is found to be about 60% between 2000 and 2010, and space cooling attributed 4% to the global energy consumption in 2010 [16].

The building sector plays a leading role in mitigating energy consumption with energy-efficient building concepts, which also reduce the amount of carbon emissions. Many countries implement new policies to reduce energy consumption based on building performance. However, the average amount of energy used in building per capita does not show a noticeable change for the last two decades in the world. Since 2010, the rise in CO_2 emissions is reported to be about 1% per year. Furthermore, the increase in CO_2 emission with regard to buildings is found to be 45%. While the natural gas consumption increases by approximately 1%, the rate of oil and coal consumptions seems stable. In addition, the expectation related to improving energy performance of the buildings is about 10% and more. In 2010, average energy use per capita seems to have peaked—that is roughly 12 MWh in the Organization for Economic Co-operation and Development (OECD) countries, and from this point, the consumption decreased gradually due to winters passing warmer regions in comparison with previous years. Also, it is observed that the share of space heating in buildings in terms of final energy consumption is 45% in OECD countries. In terms of non-OECD countries, the average final energy consumption increases almost 15% for a period of 15 years. While reaching 2DS target, the rate of average building energy consumption per capita should be at least 10% and the average consumption is not expected to exceed 4.5 MWh by 2025. **Figure 5** illustrates the amount of final energy demand and the share of final energy use by fuel and per capita [17].

The potential reduction in carbon emissions from the buildings is expected to be 30% by 2020 [18]. To be able to reach this target, measures to mitigate the energy consumed in residential buildings are primarily concerned as they are much more suitable to energy-efficient retrofitting. For this reason, various energy efficiency measures are adopted by the European Union

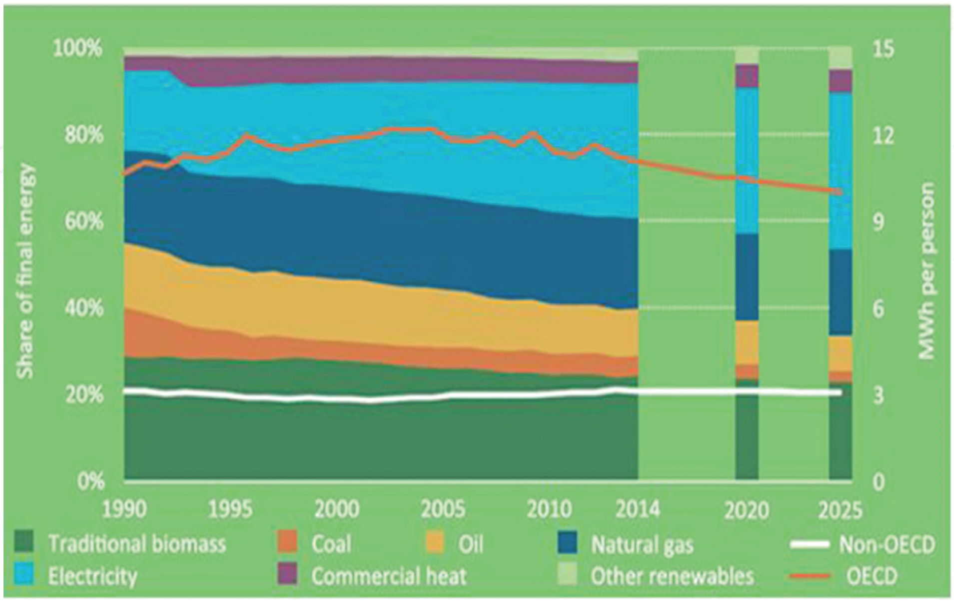

Figure 5. Final energy use by fuel and per person [17].

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that can be implemented in the existing buildings. The commitments of the said agreements impose the member countries to implement energy performance certification and to improve the devices used in the buildings for providing space cooling and heating [19]. With regard to efficient building codes, the first five countries are Austria, Denmark, the UK, Finland, and France. Germany also follows the first five countries [20]. Through the directives of 2010/31/EU, the Energy Performance of Building Directive (EPBD) suggests the concept of nearly zero energy buildings (nZEBs) to improve energy performance with insulation properties, heating, ventilation, and air-conditioning (HVAC) systems, the building orientation, and comfortable indoor quality for both new and existing buildings in Europe [19].

Likewise, national governments take decisive measures to improve the building energy performance for the transition to the net-zero energy buildings [21]. Some European member countries including the UK implement the amendments regularly before the proposed date. According to Sustainable Homes Code introduced by the UK, the newly constructed building from 2016 is expected to consume less energy for heating, cooling, and lighting [22]. Similar to the UK, Italy also adopts a code which is inspired from the directive 31/2010/EU. The law embraces both energy performance of buildings in terms of particularly thermal features and HVAC systems (nZEB). For the new public buildings, the starting date is considered to be 2019, but the nonpublic buildings are planned to be built as nZEB from 2021 [23].

The American society of heating refrigeration and Air-conditioning Engineers (ASHRAE) code and the International Energy Conservation Code (IECC) emphasize new advancements in relation to the efficient use of energy in the building sector. Unlike the EU, the energy labeling in the building certification is not commonly used since it is not mandatory in the United States [24]. The US building energy codes address energy and cost savings of the buildings without underlining the abatement of CO_2 emissions [25]. Like ASHRAE, the design standard for Energy Efficiency of Public buildings is implemented to have noticeable improvements in the energy performance of buildings and accomplish a notable decline in energy demands in China [26].

In 2012, European Commission revised the advanced energy-efficient directive to be implemented by each member countries as a long-term project to enhance the energy performance of the existing buildings with low cost [22]. According to the report presented by International Energy Agency, the retrofit of the existing buildings improves overall energy performance, and this approach is approved as applicable and economically viable. The International Energy Agency (IEA) mentions that the energy-efficient building code is relatively important for forming net-zero energy houses [27]. Moreover, the energy demand in buildings can be decreased by improving building code and utilizing energy-efficient household appliances. Through the said phenomenon, the reduction in energy demand in both commercial and residential buildings is expected to be about 50% by 2050 when compared to 1990 [22].

4. Nearly zero energy buildings

Building sector has unequivocal effects on the economic growth and the employment rate of the countries. Buildings are also of vital importance in terms of growing significance of environmental issues [22]. Energy consumed in buildings is in the range of 25–40% for

OECD member countries. Buildings account for 40% of primary energy use in the United States and Europe. For China, the rate is given to be 30% of the energy consumption [28]. The energy demand related to buildings can be reduced by energy-saving technologies and energy-efficient regulation on the buildings. The increase in energy performance of the buildings leads to the concept of low energy building (LEB) or nZEB. In the literature, numerous studies define the concept of the nZE/CB. According to Esbensen and Korsgaard [29], a zero energy house is a concept which does not need extra energy demand for space heating and cooling through normal climate such as Denmark. Based on the definition of European Parliament [19], the nZEBs are expected to use renewable energy technologies (RETs) on-site or nearby to meet energy demands. The definition of EISA [30] consists of (1) reducing the energy demands, (2) meeting the energy needs from the non-carbon emission energy generations, (3) increasing the practice related to nZGHG, and (4) minimizing the installation and running cost. According to Riedy et al. [31] zero emission buildings can be defined as near zero energy, zero energy, passive house, 100% renewable, carbon neutral, climate positive and positive advancement, energy plus, and zero net energy. Moreover, some organizations such as IEA and solar heating and cooling programs highlight the net-zero energy building research, and these organizations promote the task 40 with respect to net-zero energy solar building since 2008 [28]. The task 40 formed by eight different definitions of Department of Energy in the United States supports the shift to net-zero energy commercial building for new buildings by 2030 [32]. In addition, the European Union also declares the target of net-zero energy building. The newly constructed buildings are aimed to have high-energy performance and to generate their own energy to consume on-site. The project is planned to be started at the beginning of 2019 [33]. The UK, Japan, and Canada also implement characteristic regulations to buildings related to net-zero energy.

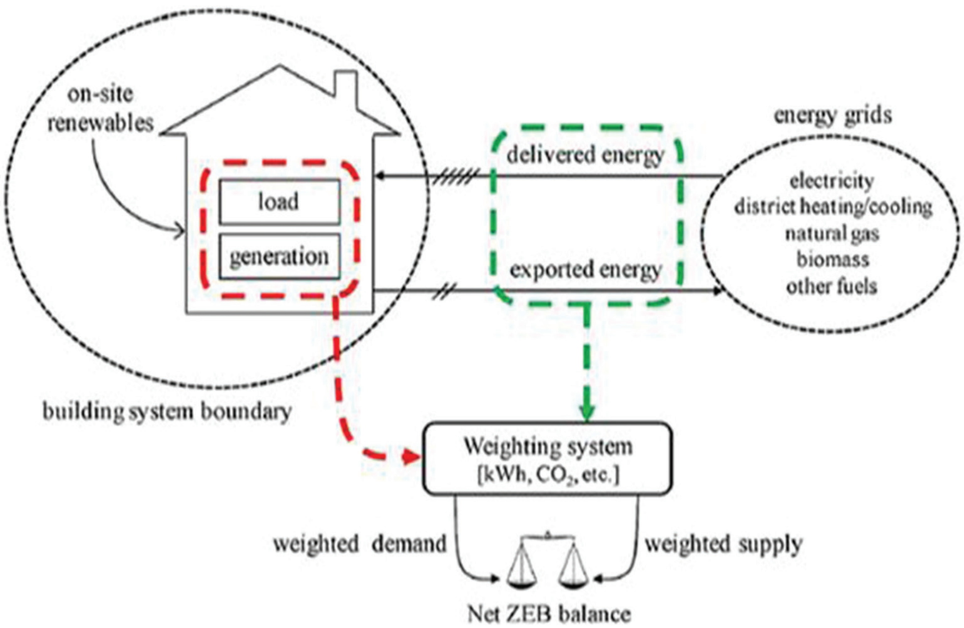

Figure 6. Systems structure and basic elements of nZEB [28].

The system structure of the nZEB is illustrated in **Figure 6**. Inside typical building systems boundary, the building consumes delivered energy on-site such as electricity district heating/cooling, natural gas, biomass, other fuels, and finally renewable energy generation. Excessive electricity is also sent to the grids. The nZEB can be described as annual energy consumed by the building irrespective of the life cycle. The target of conventional nZEB provides the balance between loading and generating the energy within the buildings [34].

Figure 7 presents three different energy-efficient techniques such as passive service system and renewable energy systems. Passive systems consist of building orientation, envelope, airtightness, and shade. When implementing the passive systems to buildings, thermal and electrical energy consumption decreases effectively. In addition, in order to offer comfortable temperatures to the buildings, HVAC, domestic hot water systems, and lighting indoors can be reinvented to reduce energy loads. In this way, the performance of building energy systems is increased through integration of RETs. RETs are used not only to generate electricity but also to heat and cool the indoor environment via combined heating and cooling and power solutions (tri-generation systems) [28]. Through nZE/CB, thermally comfortable living spaces can be achieved for dwellers.

With respect to the roadmap (proposed by Sustainable Energy Authority of Ireland) aimed to provide 90% reduction in carbon emissions from the residential buildings, four essential measures are considered to enable this decrease in the building's carbon emissions. These measures are composed of energy-efficient retrofit (improving building energy performance), utilization of the RETs, low/zero energy technologies, and electricity generation with low carbon emissions [35].

There are many LE/CB standards adopted to mitigate energy consumption levels across the world. Some of the directives can be listed as Building Research Establishment

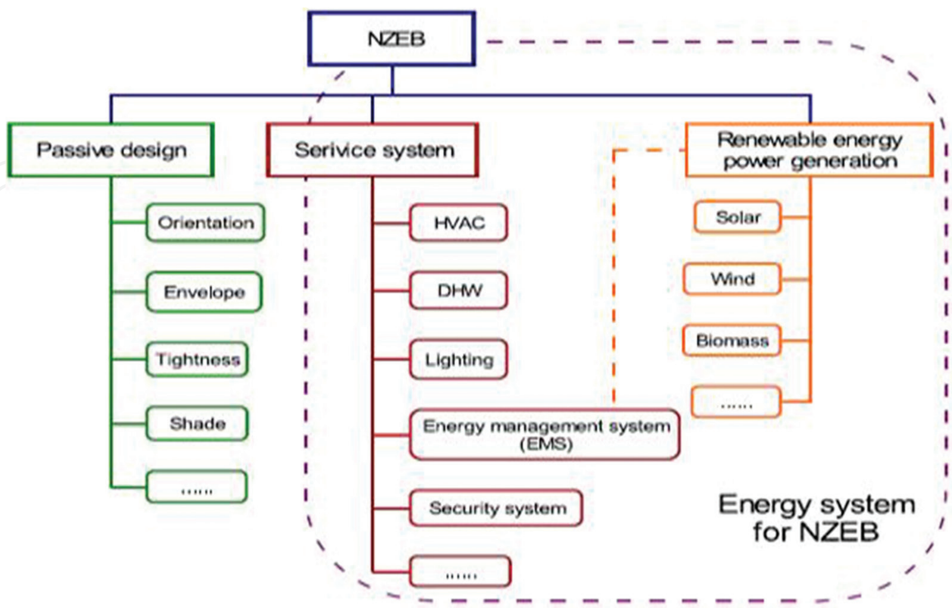

Figure 7. Design elements for nZEB [28].

Environmental Assessment Method (BREEAM), International Energy Conservation Code (IECC), Leadership in Energy and Environmental Design (LEED), Canada National Electrical Code (NEC), LEED Canada, Bureau of Energy Efficiency (BEE), Energy and Climate Studies (ECS), Comprehensive Assessment System for Built Environment Efficiency (CASBEE), Nationwide House Energy Rating Scheme NatHERS, and Internal Environmental Management–Environmental Performance (H1EE) [4]. **Figure 8** indicates some key parameters in the LEB standards. It can be easily observed that the requirements of thermal performance and airtightness for buildings dominate the other parameters. Major parameters of the L/ZEB standards are depicted in **Figure 8**.

The retrofitting of the existing buildings toward nZEBs is really important than the newly constructed buildings. Since the energy-efficient materials for the new buildings are commercially available on market, the main challenge comes from the existing buildings. By looking into reports, the buildings that existed from the 1960s in Europe are about 40% of all buildings in Europe nowadays. Newly constructed buildings in Europe are attributed to 1% of the building stock. It is predicted that the buildings existing in Europe today might be utilized until 2050. The energy performance of the existing buildings is relatively poor. Hence, the retrofits of these buildings are vital parts of the target of 2050. Along with improving energy performance of the building, the economic growth and the life quality also increase proportionally [5]. It is widely believed that the application of retrofitting the existing buildings will comprise a wide range of developments including thermal insulation of building facade and roofs, upgrading the space heating and cooling systems, renovation of electrical and electronic appliances, and utilizing RETs on-site or nearby [23]. Looking at the report presented by European Commissions, it is predicted that minimum energy saving can be targeted by 2020 and the amount saved would be in the range of 60–80 Mtoe/year [37]. Moreover, the study carried out by Williams et al. [4] focuses on the retrofit of the buildings in such a way that the expectation is considered to be 2.77 billion buildings in case the world population

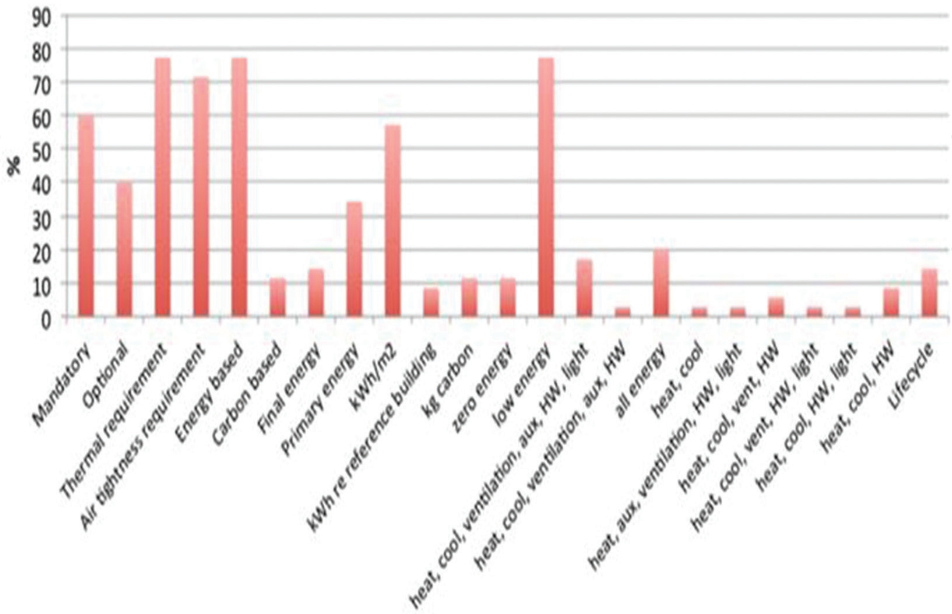

Figure 8. Major parameters of the 35 major low or zero energy building standards around the world presented as the percentage that are presented in terms of each parameter [36].

stays stable. So, to attain the target of near zero carbon world in 2080, 43 billion buildings would need to be constructed or retrofitted based on the zero energy standards per year [4].

The findings indicate that nZEB can reduce the environmental impacts with an energy-efficient building concept, and it is also financially viable. Although the initial investment cost is relatively high, the low energy consumption contributes to increasing the energy saving and reducing annual running cost [38]. The other study carried out by Kuusk and Kalamess [39] provides additional evidence to these problems by considering economic aspects of the renovation complying with net-zero energy buildings. As a result of the findings, the decline in both annual energy demand and energy expenditure is found to be 70% in comparison with the existing buildings in Estonia. But, for the owners of the buildings, the payback period is approximately 30 years and the period is really long. It is concluded that the nZEB retrofits do not seem economically viable. If annual rental income is increasing gradually, the payback period could be decreased as much as 8 years which may be considered as the best scenario.

The results from the case study conducted by Ferrari and Beccali suggest that there is an association between the building retrofits and primary energy consumption. The retrofitting of buildings reduces the GHG emissions by 40%. The increase in thermal performance of buildings with regard to roof and facade would diminish the emission proportionally. Also, the reduction in the energy consumption is found in the range of 2 and 6% depending on the thickness of thermal insulations [23].

Fraunhofer institution mentioned the reduction in the fuel consumption in the built environment with the application of energy-efficient measures was found to be 22 and 46% (compared to 2005) in 2020 and 2030, respectively [40]. Based on another study about mitigating GHG emission, the target of reducing GHG emission is planned to be 40 and 60% by 2020 and 2030, respectively. When these rates are designated by comparing to the data of 2005, RETs are applied to increase the energy saving of the buildings [41].

The retrofit of buildings presents two types of benefits such as co-benefits and direct benefits. Direct benefits are the reduction in energy consumption and carbon emissions. As for co-benefits, they consist of improving overall quality of the building, improving users' well-being, and financial benefits. In addition to these, macroeconomic benefits also are considered to be mainly composed of environmental economic and social subcategories. The economic benefits encompass a wide variety of opportunities such as lower energy cost, a decrease in unemployment rate, and setting up new business activities. In the same way, social benefits fully embrace the considerable improvement in productivity, social welfare, and comfort, the largest decrease in morbidity and mortality, and enormous advances in energy security. Environmental benefits are defined as a reduction in air pollution and waste reduction associated with constructing or renovating buildings [42].

Annual savings based on benefits resulted from the renovation of the existing buildings in Europe are estimated to reach approximately €104–175 billion by 2020. The savings are divided into three categories such as lower energy bills, suppression of carbon emission through energy generation, and enhanced indoor quality to provide healthier ambience. The resulting amounts are €52–75 billion, €9–15 billion, and €42–88 billion, respectively. Based on the growth estimation in economic activities, it is observed that approximately 760,000–1,480,000 people will have opportunities to work in new business sectors [43].

Furthermore, based on a research carried out by Stoecklein et al. [44] it is assumed that the benefits resulting from non-energy sectors are much higher (around 2.5 times) than energy-savings sectors occurring in the retrofit of existing buildings [44].

The main criteria for well-being of dwellers living in buildings are composed of thermal comfort, indoor air quality, internal and external sound level, natural lighting, and esthetic view. Thermal comfort is mainly dependent on temperature differences and air humidity. The indoor quality is associated with microbacterial contaminants resulting in hazardous conditions to residents. Internal and external noise can be decreased by using acoustic insulation materials, and so on, which are applied to both exterior and interior of buildings [42, 45, 46].

When constructing, renovating, and operating the buildings, both energy consumptions and GHG emissions are growing rapidly. Health threats due to environmental issues have damaging effects on a part of society, especially young, old, and poor persons. For instance, children and elders are in vulnerable groups that can be affected easily from tough weather conditions, especially during summer time. Since the mortality and morbidity are growing due to excessive heat-waves [47]. A research report shows the correlation between threshold temperature and mental and behavioral disorder. In order to provide better conditions, the indoor temperature must not be more than 26.7°C (threshold temperature) [48]. Moreover, these threats may cause inefficient resources including food, water, and power. While reducing energy consumption and air pollution, public health could be enhanced greatly [13]. The retrofit of the building provides not only less energy use but also positive contributions to the building and dwellers. These contributions consist of the value and life span of the building, more comfortable and healthier environment for the dwellers to live in, and work in the retrofitting building. By improving the ambient air quality of the building, the productivity and health of the dwellers are rising due to reducing undesirable conditions such as excessive moisture and mold [5]. To be able to achieve the said benefits, quick implementation of regulations on energy is necessary in the building sector.

Energy-efficient buildings consist of three main categories that present the impacts on suppressing energy consumption associated with buildings as follows [26]:

- Building envelopes including thermal insulation, thermal mass, windows/glazing, and roofs.
- Internal conditions consisting of indoor design conditions and internal heat loads.
- Building services systems divided main three subjects HVAC, electrical services, and vertical transportation used in buildings such as lifts and escalators.

4.1. Building envelopes

Nowadays, a large number of countries and local administrations are aware of the numerous impacts of building envelopes on the building energy performance. So, building energy codes released by policymakers are growing gradually on a yearly basis. Although this progression is conducted through the energy codes, two-thirds of the countries have not still implemented the energy codes for building sector. As per reports, building envelope performance has increased by approximately 6% in the last 5 years as shown in **Figure 9**.

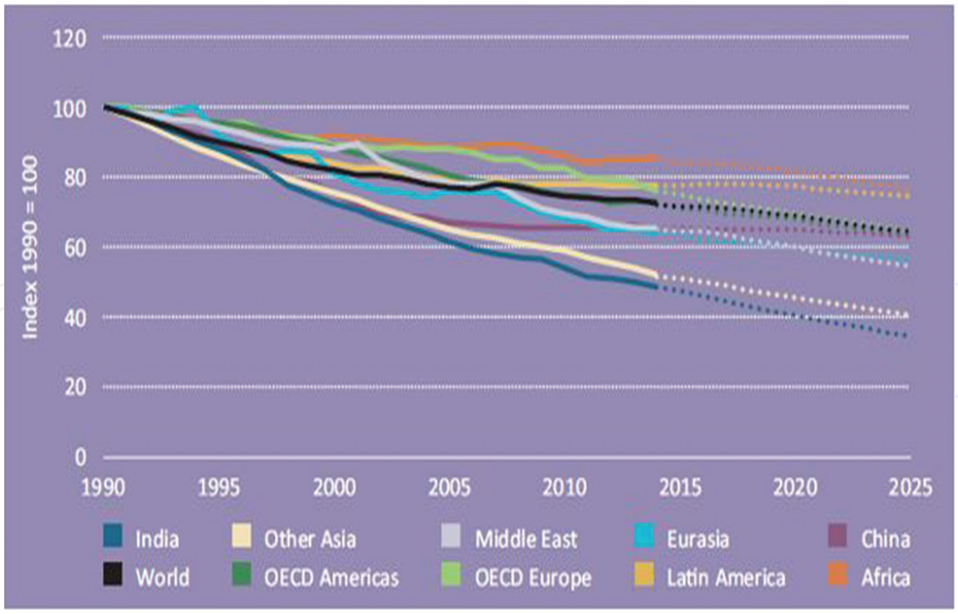

Figure 9. Change in building envelope performance [17].

The rates in the developing countries are greater due to rise in the floor areas and thermal comfort demands. The building envelope performance has considerable influences on the heating and cooling needs. It can, therefore, be assumed that high building envelope performance can be managed by deep renovation and retrofitting of the existing buildings. For this reason, the energy codes for building should be revised to meet the target of the building performance. The rate of retrofitting the existing buildings is in the range of 1–2% today, and the percentage is expected to rise by 2 and 3% per year up to 2025 [17].

5. Greenery systems

Greenery systems have a leading role to improve the energy performance of the buildings due to its relation with building envelopes. For this reason, GSs could be utilized to achieve zero energy or carbon buildings. While enhancing the energy efficiency of buildings, both energy consumption and carbon emission steadily decrease as well. The systems can cover both the surfaces of buildings, especially roof and wall. Also, it is mainly divided into two parts such as green roofs and green walls [8]. While contributing to energy efficiency and providing lower carbon emissions, the GSs applied in the existing building have substantial benefits to not only the environment but also economy and the society. In addition, these systems are used as passive design, which offers insulation, shading for heating, and cooling period for buildings, respectively. By applying the GSs to existing buildings, building dwellers could reach improved indoor microclimatic conditions by cost-effective and eco-friendly means [9, 49–51].

5.1. Green roofs

Building roofs occupy approximately 25% of total surface areas in the urban environment [52]. Green roofs have potential benefits associated with environment and society.

The environmental benefits consist of mitigating GHGs and threat of urban heat islands, decreasing the depletion of energy resources, improving urban life, and preventing devastation of wildlife [53–57]. Furthermore, green roofs also improve health of residents living in green roof buildings. The roofs, thus, provide better indoor air quality for dwellers, for instance, lower noise levels and ideal microclimatic ambience [56]. Among all, the main subject related to green roof is to improve energy performance of buildings. That is why energy-efficient buildings lead to reduction in energy consumption and carbon emissions as a result of heating and cooling the indoor ambience of buildings [8].

Figure 10 illustrates components of the green roof design that includes vegetation, substrate for growing, drainage element, protection layer, root barrier, insulation layer, membrane for preventing water leakage, and roof deck. Moreover, there are three categories in the design of green roofs such as extensive, semi-extensive, and intensive roof designs. The main differences between these categories depend on weight, system height, type of plants used in the roofs, maintenance, irrigation, and, surely, cost [52].

5.1.1. Thermal benefits of green roofs

Green roofs are considered as one of the primary solutions to mitigate energy demand with increasing energy efficiency in buildings [59]. According to a research in Italy, where traditional roofs were compared, temperature of the green roofs applied in buildings is found by 12°C lower in summertime. As for heating seasons, the green roofs are 4°C hotter than conventional roof systems [54].

Many studies highlight the thickness of growth substrate affecting thermal insulation performance of green roofs. The study considering optimization of thickness reveals that the increase in the thickness of growing media used in green roofs reduces energy consumption and heat transfer compared to conventional roofs. The reductions are estimated between 59

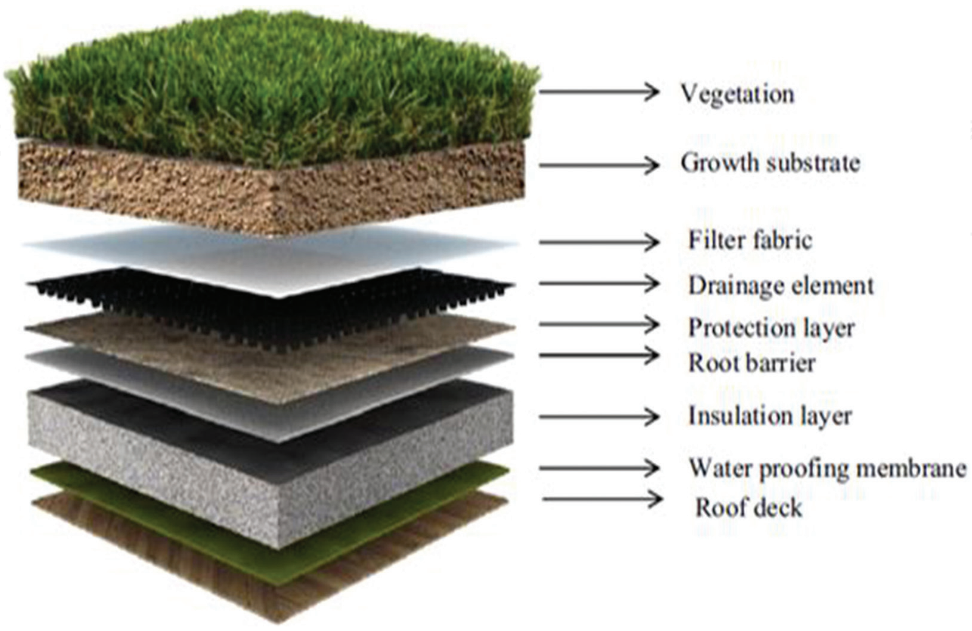

Figure 10. Schematics of different green roof components [58].

and 96% and in the range of 31 and 37% from the viewpoint of energy consumption and heat transfer, respectively [60]. Another research reveals that the increase in soil moisture reduces thermal resistance of green roofs. Briefly, thermal resistance of dry soil increases by 0.4 m^2K/W using 100-mm thickness of growing substrate [61].

5.1.2. Heat flux and energy saving

Green roofs are easy-to-use structures to increase energy saving by mitigating heat flux and improving shading effects. Shading effects have a key role to provide thermal comfort for the dwellers living in green roof buildings. Due to the substantial contribution to the thermal comfort, energy consumption and energy spending by dwellers tend to decrease after the installation of the green roof systems on the buildings [62]. Based on the studies with related leaf thickness and coverage thickness, these parameters play an important role in the thermal regulation for buildings. For instance, in comparison to bare soil, covering the building with plants reduces the temperature by about maximum 6°C during March and April. A further study, also, exposes that the features of vegetation have several effects on daily surface temperature, and it is found to be about 26°C [63]. Depending on the case study, temperature with respect to bare soil, uninsulated roof, and roof covering with GSs is determined to be 42, 57, 26.5°C [52]. Compared to black roof, the temperature falls from 80 to 27°C by deploying green roof systems on buildings [59, 63].

5.2. Vertical greenery systems

Many researchers mention about the advantages of VGSs such that they can provide energy-saving and ecological improvements for buildings placed in (sub)urban areas. Buildings integrated with these systems have potential benefits that cause the reduction in wall temperature arising from wind barriers and shading effect and thermal insulation based on growing media and vegetation [8]. In accordance with green roofs, the vertical systems can also affect both indoor thermal comfort and outdoor environment such as biodiversity and air quality. Some benefits are associated with thermal performance and environmental issues, but the rest of them are linked with architectural aspects and human psychology [64, 65]. The positive effects of VGSs on environment and buildings greatly outweigh in comparison to green roofs because of covered surface areas. The surface areas of VGSs are about 20 times wider than those of the green roofs [66].

In the literature, the VGSs are also called as vertical garden, green wall, vertical green, and bio walls [9, 49]. Green walls comprise green facade and living wall. The main difference between green facade and living wall is the growing style of vegetation such as naturally growing vegetation over building envelope and growing media placed on the ground for green facade [9].

5.2.1. Thermal benefits of green wall

Thermal performance of buildings can be improved by green walls due to shading effects and the effects depend on density of vegetation and coverage. Green walls are vital in mitigating energy demand and thermal comfort for dwellings. These advantages lead to reduced temperature differences between interiors and exteriors of walls due to shadowing and thermal insulation effects. Findings related to surface temperature under green walls reveal that average temperature is assessed by 8°C and the maximum effects on temperature differences between under vegetation and front of the plants are found to be 16°C [67]. According to the same research, the west-facing green walls exposed to solar radiation (189 W/m^2) absorbed 133 W/m^2 of overall radiation; 25 W/m^2 was reflected by foliage; and the rest of them passes through the vegetation.

In the literature, many researchers focus on the reduction in external wall surface temperature. There are some parameters such as location and period of the study, orientation, and foliage thickness which can directly affect the reduction in external wall surface temperature. For instance, several researches carried out by Sternberg found foliage thicknesses to be between 10 and 45 cm, and the reduction in temperature was found in the range 1.7–9.5°C [68]. **Table 1** illustrates some researches with respect to energy savings arising from shading effects.

5.2.2. Blockage of the wind

Previous literature focuses on the effect of VGSs on wind effects, since the wind effects have negative potential influence on energy performance of the buildings. Hence, the blockage of wind is of vital importance to mitigate energy demands on both cooling and heating periods for dwellings integrated with VGSs [69].

During the winter period, the decline in interior temperature of buildings occurs naturally because of the cold wind [73]. The wind blockage used in VGSs contributes to less energy consumption. The blockage feature can be improved by foliage density and characteristics and orientation of green walls, especially wind speed [74]. It is clearly illustrated in literature that energy consumption of buildings notably reduces by the decrease in wind strength. From this point of view, energy demands are mitigated by about 25% by applying VGSs on buildings [75]. The findings reported by another research reveal that when comparing with the bare wall, heating energy expenditure decreases by 8% for cold climates [66].

These findings mentioned earlier show that not only green roofs but also VGSs play a prominent role in mitigating energy demands and carbon emissions owing to having potential effects on energy performance of buildings. In addition to these, GSs provide indoor air quality and better productivity for dwellers. Moreover, the vegetation has an ability to absorb the sound and to reduce the noise level yielding to improved productivity [8, 76]. Furthermore, the excessive temperature increases the number of deaths among older people (≥65) and negatively affects sleep quality of residents [77]. The indoor temperature can be properly regulated by using GSs [78].

5.3. Cost

It needs to be reported that the maintenance and investment costs of green roofs and facades are required to be analyzed in detail. The previous studies indicate that the integration of green roofs

Authors	Orientation	Foliage thickness (cm)	External wall surface temperature reduction (°C)
Perini et al. [70]	North-west	20	1.2
Cameron et al. [71]	North-south	—	7–7.3
Yin et al. [72]	South	4	Max:4.67

Table 1. Green walls highlighting passive energy savings [8].

into existing buildings as a retrofit solution might not be commercially viable in some cases despite their notable beneficial impacts on energy saving [74, 79]. Thermal performance reports reveal that the buildings with full green roofs can provide an energy saving of about $215/year. However, it is underlined that GSs as a retrofit application still have challenges because of long pay-back periods of these systems. It is also reported that GSs might not be suitable for the buildings located in cold climate regions [8, 74]. In spite of the said challenges, there are numerous benefits of GSs such as economic, environmental, and social impacts on city life with mitigating urban heat islands effects, air pollution, and energy demands, as well as providing indoor environment quality [80, 81]. For these reasons, the cost of green roofs can be neglected to be used in the existing buildings.

6. Conclusions

Within the scope of this chapter, GSs are evaluated in terms of a potential energy-efficient retrofitting solution toward low/zero carbon economy. GSs are found to have a leading role to improve the energy performance of the buildings owing to several multifunctional benefits such as thermal regulation of building envelope, remarkable reductions in energy consumption figures, and greenhouse gas emissions, providing indoor air quality, and minimizing urban heat island effects. We can conclude from the results that the building surface temperature can be reduced by about 12°C with green roof retrofit. Moreover, GSs can provide up to 20°C of lower surface temperature in comparison with conventional facades. Furthermore, vertical greenery systems (VGSs) can reduce energy consumption in buildings by about 25% owing to the wind blockage effects in winter.

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