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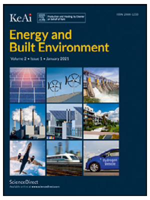

Global technological advancement and challenges of glazed window, facade system and vertical greenery-based energy savings in buildings: A comprehensive review

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ABSTRACT

There are many factors that have a major influence on reducing the energy expenditure in building sector. This research aims at qualitative and quantitative assessment of those factors such as double glazed windows, vertical greenery systems (VGS), integrating of semi-transparent photovoltaic device with architectural design of buildings, energy saving by using heat reflecting coating, passive climate control methods, energy saving by shading, building energy performance enhancement by using optimisation technique, double skin green facade, etc. through a holistic and thematic approach. Amongst the aforesaid techniques, VGS is found the most reliable, efficient and sustainable solution. Attractive VGS can improve the urban environment, increase biodiversity, mitigate pollution also results economic benefit of the buildings as like as energy savings and decreasing surface temperature. Four fundamental energy saving methods are used in VGS which are considered as passive energy saving mechanism. Firstly, interception of solar radiation due to the shadow risen by the vegetation; secondly, vegetation also provides thermal insulation; thirdly, plants evapotranspiration helps for evaporative cooling of building; finally, building blockage makes a variation of wind effect on building. The peak cooling load of ivy coated green building wall has been reduced by 28%. If a VGS is installed without windows and building facing on west, east, south and north correspondingly, the reduction in the cooling load capacity of the building is observed to be up to 20, 18, 8 and 5%, respectively. Very high thermally resistive glazed areas on building envelope can be secured via thin film PV glazing and vacuum glazing products with an average *U*-value of 1.1 and 0.4 W/m^{2}K, respectively. Energy use policies are also helpful to improve energy consumption scenario of buildings. For developing more energy-efficient, sustainable and eco-friendly buildings, these techniques might be helpful for the building designers and architects.

1. Introduction

Energy is the essential need for the automation, modernisation, economic growth and social development where the energy consumption figures are growing very fast. In the last two decades, the growth rate of primary energy consumption and CO$_2$ emissions is 49 and 43%, respectively with an average annual increase of 2 and 1.8% correspondingly from the year of 1994 to 2014 [1,2]. The annual average growth rate of energy consumption in the developing countries is 3.2% for 2017 which depends on continuous increase of population and urbanisation [1,3]. On the other hand, the average growth rate in developed countries is reported to be 1.1% for the same year [1]. From the year of 1995 to 2015, the annual average rise in energy consumption figures in China is 5.6%, which is extremely noticeable [4]. Due to higher energy consumption, British Petroleum (BP) indicates that the global oil consumption demand will be increased by 30% from 2007 to 2035 [3]. According to International Energy Agency (IEA), the half of the world's population lives in cities and consume 73% of world total energy with 70% CO$_2$ emissions. Moreover, according to International Energy Outlook report, from 2010 to 2040 the world energy consumption is predicted to grow by 56%. Further projections reveal that when sectoral energy consumption analyses are taken into consideration, building sector will play an outstanding role in total energy use.

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Nomenclature

BP	British petroleum
IEA	International energy agency
GHG	greenhouse gas
EU	European Union
TIM	transparent insulation material
PCM	phase change material
HISG	heat insulation solar glass
PV	photovoltaics
TRPVG	thermally resistive PV glazing
UV	ultraviolet
IR	infrared
BIPVs	building integrated photovoltaics
CIGS	copper indium gallium selenide
NTNU	Norwegian University of Science and Technology
NIR	near-infrared
HVAC	heating, ventilation, and air conditioning
DSF	double skin facade
DSE	double skin envelop
IAQ	indoor air quality
VGS	vertical greenery system
US	United States
UHI	urban heat island
CFD	computational fluid dynamics
ETTV	envelope thermal transfer value
WWR	window-to-wall ratio
OTTV	overall thermal transfer value
CF	correction factor
SC	shading coefficient
HF	heat factor
ESR	energy saving rate
DSGF	double-skin green facade
PMV	predicted mean vote
UTCI	universal thermal climate index
HF	high frequency
TiO_2	titanium dioxide
$T_{pv,m}$	mean PV module temperature
θ	tilt angle
Enh_{po}	enhancement in power output
TF-Si	thin film silicon
c-Si	crystalline silicon
CdTe	cadmium telluride
a-Si	amorphous silicon
U_w	thermal transmittance of opaque wall
U_f	thermal transmittance of fenestration
T5, T8 & T12	different types of fluorescent lamps

The energy consumption in buildings depends upon some factors which have an influence on the building energy demand. These factors are classified into two groups named “physical environmental factors” and “artificial designing parameters”. The physical environmental factors include the amount of solar radiation, outdoor temperature and wind speed, etc. whereas artificial designing parameters cover building form factor and orientation, transparency ratio, optical and thermophysical properties of building material and the distance between buildings [5]. The increasing use of energy creates concerns over supply difficulties, exhaustion of energy resources, geopolitics and heavy environmental impacts such as global warming, increasing greenhouse gas (GHG) emissions, ozone layer depletion and climate change [1,3,6]. Also concern grows about utilisation of fossil fuels and its implications for the environment [4]. The energy consumption will increase by 33% from 2010 to 2030 in the world [7]. It is also underlined that building energy consumption constitutes 33% of GHG emissions in 2010. The amount of GHG emissions produced by building energy consumption is about 10 Gt CO_2eq/year in 2010 [3]. Since the building sector consumes major part of overall energy consumption and causes notable GHG emissions which have negative impacts on environment, research related to the energy savings in building sector attracts attention due to its potential of mitigation. From this point of view, it is highly required to investigate the building energy consumption characteristics and to make it more efficient. It is unequivocal from the abovementioned information that there is lack of comprehensive knowledge about the technologies of building-orientated energy saving strategies. The objective of this study is to review building energy saving techniques to reduce building energy consumption in a sustainable way. Consequences of building energy saving reflects the GHG reduction and mitigate global warming.

2. Passive energy saving technologies in buildings

Generally, energy used in building can be accrued in various ways and statistical process can be used for studying the building overall performance and minimising the energy requirement of the building. Different statistical models are used to interpret the real-world data in terms of individual theory to improve energy efficiency in buildings. However, this part of the research mainly identifies the components which are responsible for consuming most of the energy, and the energy-efficient options/alternatives for these components.

2.1. Double glazing windows

The buildings with a good-insulation can reduce their energy consumption as a consequence of lower losses in cooling or heating system [8]. It is emphasised in many works that most of the heat loss or heat gain, for the case of cooling, occurs through the windows of a building [9]. According to the latest reports, 47% of heat losses from building envelope occurs in windows [10]. This is because of the higher overall heat transfer coefficients (*U*-value) of windows compared to the other components of the building envelope [11]. Double glazed windows as a specific multilayer glazing technology can be an ideal solution to overcome the abovementioned challenges. The use of double glazed windows can play a vital role in enhancing energy efficiency of lighting [12], buildings heating and cooling system, along with the improvement of temperature and acoustic comfort environment of that building for the indoor conditions [13]. In most parts of the developing countries, single layer glazed areas are still considered in the building fabric. However, the heat transfer coefficient of double glazed windows is about half of that of the single glazed windows [14]. For these reasons, in the present time, the double-glazed window has become a widely adopted standard for newly developed housing or commercial buildings owing to its competitive *U*-value range [15]. In recent years, normally double-glazed windows are used in construction of new and commercial buildings. This led to the changeable of building regulation which is inspiring to reduce heat loss through building construction materials. Double-glazing can considerably lower the *U*-value of the glazed areas in a building and it has become trendy [16,17]. Research on energy saving of commercial buildings in the UK discovered that about 39 to 53% energy could be saved by replacing single-glazed windows with double-glazed windows [18]. As a matter of fact, regulation on heat insulation in Greece, also known as “Thermal Insulation Regulation” of buildings was familiarised in 1979, where it was mandatory to use double glazing windows for newly constructed buildings to fulfil the EU’s regulation. The buildings which were built before 1979 now use double pane windows (also known as double-glazed) instead of single pane windows. Effective replacement of window frame also could save energy in buildings. The retrofitting of old window frames with new alternatives improves energy efficiency but at a high cost [19].

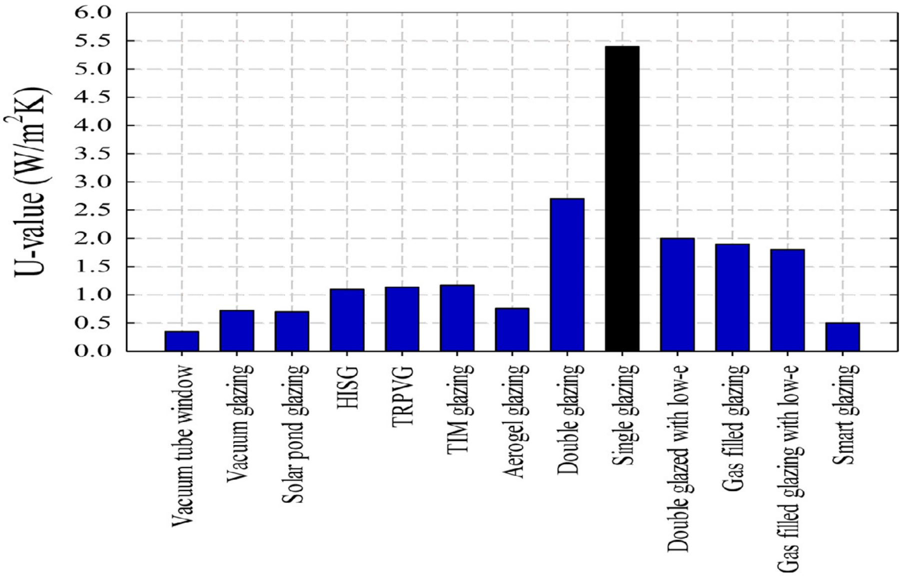


Fig. 1. Comparison of *U*-value of glazing technologies in market.

2.2. Multifunctional and highly thermal resistive windows

Buildings have a remarkable potential to mitigate the total energy consumption worldwide, and glazed areas are of significant relevance to reduce heat losses from building envelope. Besides double glazed windows, outstanding efforts are made at global scale to develop novel, eco-friendly, sustainable and multifunctional glazing technologies. These technologies can be listed as transparent insulation material (TIM) glazing [20], vacuum glazing [21], low-emissivity coated (low-e) glazing [22], phase change material (PCM) glazing [23], smart glazing [24].

Amongst the aforesaid glazing systems, especially vacuum glazing technology is capable of providing very high thermal resistance (U-values below 0.4 W/m^{2}K). Solar pond and TIM glazing units are ideal for harsh climatic conditions for effective thermal regulation of building envelope in summer. Smart and self-cleaning glazing systems like heat insulation solar glass (HISG) and thermally resistive PV glazing (TRPVG) are preferable for multifunctional features like electricity production, self-cleaning, acoustic and thermal comfort. When the novel glazing technologies are compared in terms of thermal resistance feature, an illustrative U-value comparison can be done as shown in Fig. 1. Amongst the said glazing solutions, TRPVG and HISG have extra multi-functional features owing to their semi-transparent structure. Thin-film amorphous silicon PV cells are utilised within these glazing systems for electricity generation purpose, and TiO$_2$ nanocoating is implemented on cell surface to minimise reflection losses. Their translucent structure allows these glazing systems to be considered in the built environment not only for thermal resistance and clean energy generation but also for optical, acoustic and thermal comfort features. Appearance of some novel glazing systems with the thermal performance properties are illustrated in Fig. 2. TRPVG blocks 100% of UV and IR part of incoming sunlight. It can also reduce about 33% of outdoor noise. 92% of solar radiation penetration can be reduced by TRPVG and HISG. This is of vital importance to minimise cooling expenditures especially in the regions like Middle East and India.

2.3. Integration of semi-transparent photovoltaic devices

Bizzarri et al. [26] suggested that there is a need to have immediate transfer of advanced renewable energy technologies developed in laboratory to the industry. The present market is keen on and attentive to the architectural integration of photovoltaic cells to the building envelope, which is known as building integrated photovoltaics (BIPVs). Semi-transparent photovoltaic devices have distinct quality which allows its use as an advanced glazing technology. When integrated as a glazing surface, such devices can provide a passive function of reducing solar radiation penetration into the building, and at the same time, generate a considerable amount of energy. This particular property can be used in public or office buildings or any other architectural typologies where vital glazing is needed for building facades [27].

For the abovementioned case, semi-transparent type photovoltaic cells can enhance their role by counterbalancing their limited photovoltaic performance, given by improper position (high tilt angle on facade) with static function in order to lower energy requirement in cooling system. Thus, in such type of PV devices there is an increasing interest in Mediterranean region, where the lower solar azimuth allows for steeper applications of the PV system. Recently, the Norwegian University of Science and Technology (NTNU) has constructed an innovative BIPV building that uses an axillary PV layer on its main facade [28]. It has been reported that about 16 kWp (kilowatt peak refers to the power produced by a solar module under full solar radiation i.e. peak power) is produced from the BIPV building [29], while at the same time about 10 to 15% energy consumption for cooling purposes is saved through the reduction of solar irradiation. About 2730 solar modules of amorphous silicon have been integrated at roof surface of the Stillwell Avenue Station, Coney Island in New York city which fabricated by an architectural firm. The above mention setup has been produced about 240 MWh per annum and used to restrict the direct sunlight allowing about 25% solar transmission simultaneously [30]. Tilt angle optimisation and passive cooling strategies are of vital importance for performance enhancement of BIPV systems as shown in Fig. 3.

2.4. Energy efficient lighting

From the previous literature, it can be said that modern official buildings are built with more energy efficient design and technology [31]. In particular, specific amount of energy can be saved from electric lighting equipment in both newly constructed and retrofitted buildings. One recent research [32] proved that power-saving lighting is an excellent cost-efficient means to control CO$_2$ emissions. Many researchers report that electrical energy consumption for lighting purposes could be lessened 50% by applying present innovative technology [33,34]. Marie-Claude Cubois et al. investigated the strategies and potential of energy saving in office lighting consisting of control structural in North Side of Europe with gathering data from Sweden. This paper reviewed a part of the Swedish project entitled “Design and simulation guidelines of energy efficient office building”. It has been observed that various kinds of

Fig. 2. Structural details and physical appearance of some novel multifunctional glazing products [25].

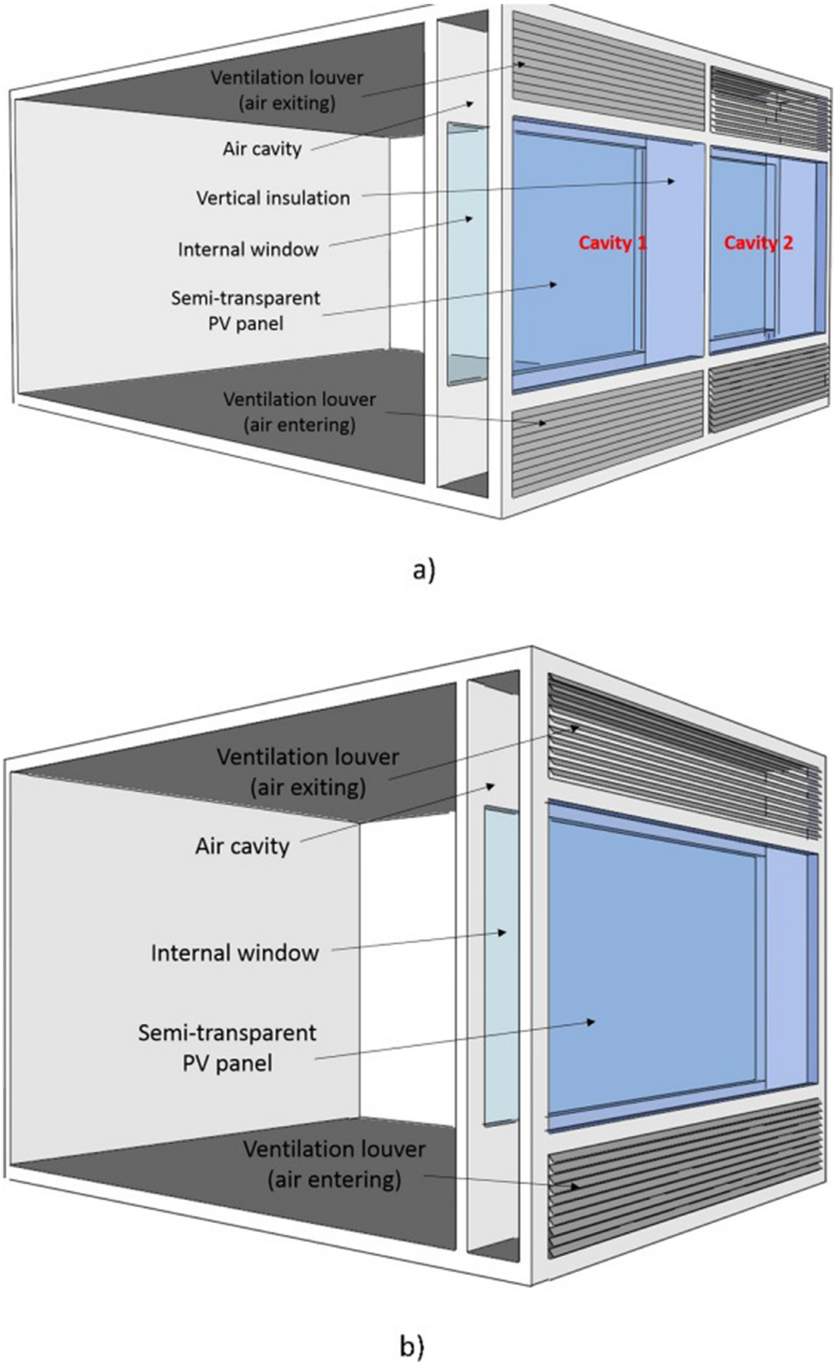


Fig. 3. Multifunctional ventilated building-integrated facade technologies [27].

Table 1
Overview of energy saving strategies by efficient lighting system [35].

Energy saving strategy	Relative saving potential
Improvement in lamp technology	10% (T12 to T8) 40%[a] (T12 to T5)
Improvement in ballast technology	4–8%
Improvement in luminaire technology	40%[b]
Use of task/ambient lighting	22–25%
Improvement in maintenance factor	5%[c]
Improvement in utilisation factor	Depends on application and context
Reduction of maintained illuminance levels	20% (500 to 400 lx)
Reduction of total switch-on time	6%[d]
Use of manual dimming	7–25%
Use of switch-off occupancy sensors	20–35%
Use of daylight dimming	25–60%[e]

[a] However, this number also includes improvements due to HF ballast and improvement in luminaire.

[b] However, this number also includes dimming (occupancy and daylight) and improved (HF) ballasts.

[c] About 5% of light output would be lost each year without a proper maintenance programme.

[d] By reducing average existing total switch-on time to only 2600 h/year.

[e] This number is highly dependent on the climate, the shading strategy and the base line for comparison (if compared to a case where lights are on 100% of the time, the savings appear to be much higher than a more realistic case with e.g. manual on/off switch at the door).

sources show about 45–65% energy savings depending on control strategy, current technologies and room type [35]. By specific calculations, it is obtained that 50% energy could be saved from installation tasks and lighting of building sector which is controlled to give luminance level when needed [36]. Higher energy saving could be achieved by using this simple calculation. With the effective use of electrical energy for lighting purposes, energy can be saved by minimising the using of heating and cooling requirements indirectly [37]. Schemes generally applied to minimise the energy requirements for office building lighting [35]. The energy efficient lighting schemes with energy saving potentials are briefly illustrated in Table 1.

2.4.1. Natural day lighting system

Comfort factor is one of the most important factors for visual comfort. Comfort of the human body is closely related to intensity level of surroundings luminance, where more solar intensity might be cause of discomfort to the inhabitants [38]. For the occupants, to make a visually comfortable environment artificial lighting is required for all types of buildings. However, the utilisation of artificial lighting generally consumes more energy. Lam et al. [39] investigated that the lighting instruments are liable for 20 to 35% of total electrical energy expenditure in buildings in tropical regions. For the purpose of power saving, sunlight can be used as an alternative lighting source for supplying sufficient luminance intensity levels in buildings. This can be done during office hours, i.e. from 8.30 am to 5.00 pm, during which the sunlight is capable of supplying the necessary luminance to the area such as the lift lobby [40]. Li and Tsang [41] reported that in the facade design of modern buildings, daylight utilisation can reduce more than 25% of total power consumption for lighting. Recently, more focus is given on the issue of blaze and sunlight heat energy gained from the common areas like glass windows that have large transmittance value and are commonly used by the houses in the tropical area. The study by Li et al. [42] revealed that use of window glass with solar film coating is capable of reducing energy requirement in both cooling and lighting equipment while maintaining apparent pleasure of residents. In another work [43], it was suggested that further researches about apparent pleasure in the interior of the buildings in tropical areas should be considered for the condition of glass transmittance of enclosures used and the opportunity of utilising shading.

An overview of building daylighting systems has been summarised in the literature in terms of different aspects [45]. A method of maintaining healthy indoor environment by using natural daylighting system has been investigated by Kim and Kim [46]. A typical natural daylighting system is shown in Fig. 4. It is clearly understood from the light intensity distribution that solar canopy system has a distinct potential for reducing lighting-orientated energy consumption in the built environment. Solatube daylighting units can be effectively utilised in commercial, residential and industrial buildings in smart cities. A solatube system consists of three main parts called capture zone, transfer zone and delivery zone. Their roof type applications are highly preferable in modern architecture and desirable in terms of aesthetic features. These systems are able to welcome about 60% of outdoor illuminance to the indoor environment [47] as shown in Fig. 5, and they are considered as a key energy saving tool in all types of buildings.

2.5. Energy saving by using heat reflective coating

The effect of energy saving is not so efficient by the normal insulation. Nowadays, the use of reflective coating for building insulation is one effective method to improve buildings energy efficiency. By reflecting more lights, the reflective coating can minimise the heat gained by the building through solar radiation, hence can effectively lower the load required for air conditioning especially during the hot season. This method has been studied and used in Japan, America, and Europe, etc. Givoni and Hoffman [48] found that by having a white colour coating on the walls, buildings of small size and without ventilation were about 3 °C cooler than a grey colour building of same size in Israel during summer. The impact of exterior wall surface colour on the thermal characteristics and performances of buildings was investigated in several other works as well [49,50]. Karlessi et al. [51] conducted an investigation on the phase change nanomaterial (PCM) and its cooling performance as building coating. They concluded that all PCM painting yields lower wall surface temperatures compared to other general paintings, with the highest temperature deviation observed in the morning, i.e. 07–10am. Synnefa et al. [52] performed studies on 14 kinds of building coatings and their thermal performance, to reach the conclusion that the reflective coatings usage could minimize a white concrete tile's surface temperature by 4 °C during summer seasons and 2 °C during night-time. It could be only 2 °C hotter than the outside environmental temperature at the day period and at night time about 5.9 °C cooler than outside air temperature. Wang et al. [53] made a dynamic model of retail shed with solar reflective elements and analysed the performance of the heating and cooling energy per year. The investigation revealed that cooling load and overall electricity reduced by using reflective paintings in the outer walls and roofs. Shen et al. [54] presented an experimental investigation on the effect of reflective coatings on building energy usage and indoor climate. The results showed that about 2 to 4.7 °C (the range is 2–4.7 °C since it has stated the mean radiant temperature was 2.3 °C to 3.7 °C) by using various coatings from external and internal wall surface respectively depending on orientation, location and season. Santamouris et al. [55] studied the present development on secondary cooling method for modern technological progress to promote lifestyle in low-earning living houses. Synnefa et al. [56] carried out a study about the improvement, optical characteristics and thermal efficiency of colour paintings for cooling purposes in town area. Levinsona et al. [57] used the near-infrared (NIR)-reflective coating by finishing roof tiles to produce considerable minimisation in the roof surface temperature, unconditioned internal air temperature, heat flux in ceiling and air temperature in garret. The coatings yielded a 5 to14 K temperature reduction followed by ceiling heat reduction by 13–21%. Comparative experiments on heat reflective insulation were carried out by Guo et al. [50]. Indoor as well as outdoor condition in Hangzhou, was tested during both winter and summer. The building's exterior wall surface temperature can be minimised by using heat reflective insulation coating which makes maximum temperature difference between indoor and outdoor environment of about 8–10 °C. In Hangzhou, it is too obvious that building energy consumption can be reduced by using heat

Fig. 4. Workplace illuminated by typical daylighting through (a) the window only and (b) the solar canopy system with window [44].

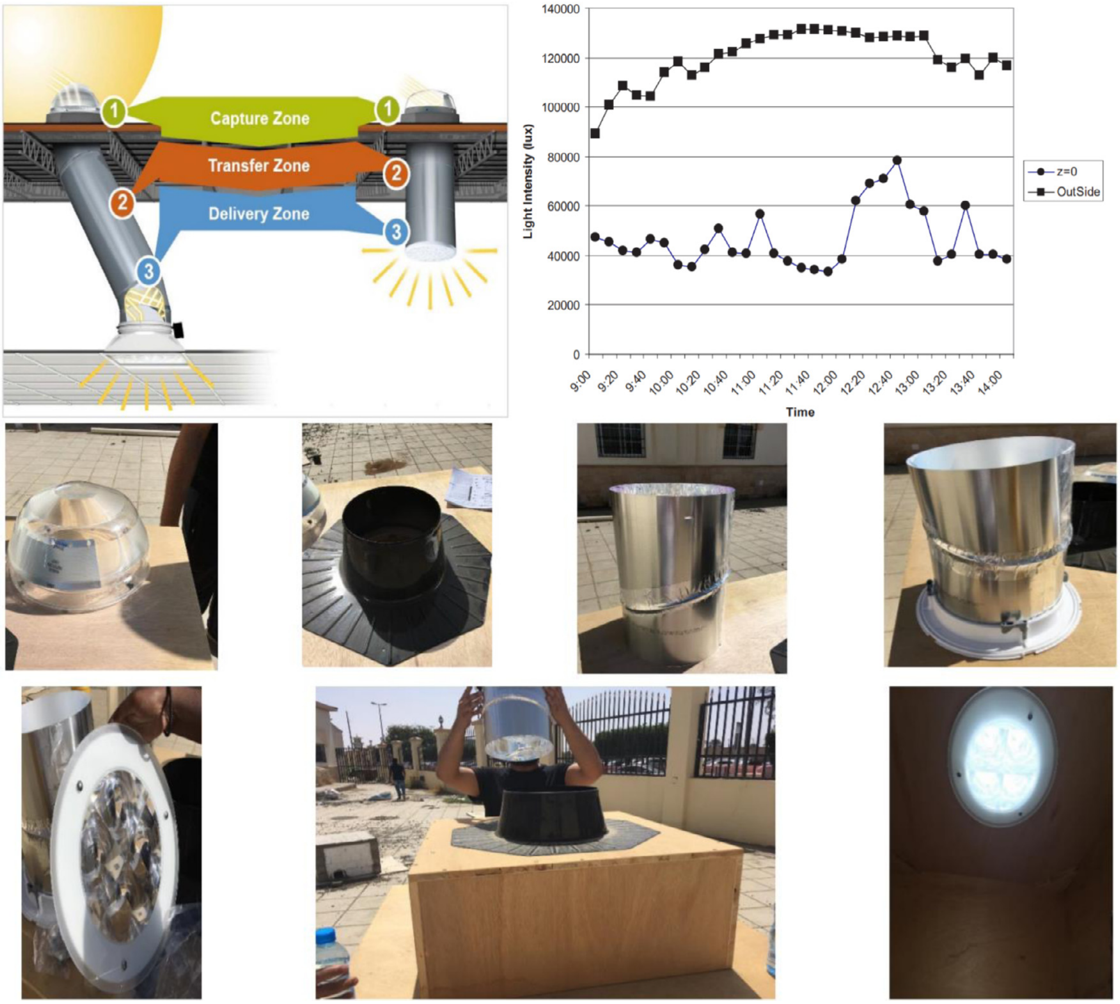


Fig. 5. Energy saving potential of solatube system in buildings [47].

reflecting insulation coating on the exterior wall surface where it has been measured that annual air-conditioning electricity saving by using the coating is about 5.8 kWh/(m^2 month) [50]. A building wall with heat reflective coating in exterior side is shown in Fig. 6.

Solar radiation reflective coatings are evaluated in several works in terms of their potential influence on energy saving in the built environment. Intensive analyses are done both numerically and experimentally as shown in Fig. 7 for accurate determination the impact of such reflective coatings on cooling energy saving in summer. According to the results, building box with the reflective coating material has 2.4 °C lower indoor temperature than the reference building box without coating. Moreover, the cooling load is found to reduce by about 9.1 W/m^2 with the reflective coating. When the whole summer season is taken into consideration, energy saving in electricity consumption is determined to be 15.2%.

2.6. Energy savings in buildings with passive climate control methods

In buildings, energy saving is mainly influenced by the architectural design of building, economic condition of the residents, energy systems and weather. In architectural design, most of the countries attempt to develop the energy efficiency of buildings by improving the building

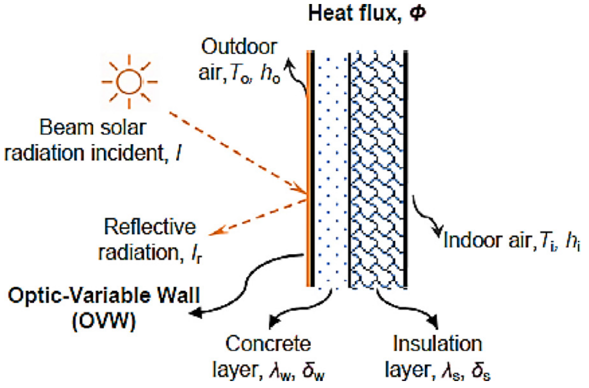


Fig. 6. A typical building wall integrated with thermally responsive coating on the exterior side [58].

standard and developing advanced technologies. The possible technology can be in the form of building technology, such as potential effects of thermal bridges on energy usage as presented by Theodosiou and Papadopoulos [59], advanced design tools as like as movable ventilation model [60] or performance of alternative design parameter with energy saving control technology [61]. A building design considering climate conditions such as bioclimatic design is one of the best attempts for improving energy saving and cost-effectiveness in buildings. The technique of design on the basis of climate condition promotes an efficient and important savings of energy which required for mechanical cooling and heating [62]. Recently, it has been stated that relative humidity of indoor environment as one of the control parameters in new HVAC system which supply comfort air within required levels, has a key potential to lower the energy used [63]. Many researches have been involved in laboratory, practical field or numerically to understand the effect of using hygroscopic components modest humidity level in indoor condition. The results showed that the thermal comfort can be improved by proper observation of air quality and using comfortable amount of energy in buildings. The performance of using hygroscopic components is influenced by many parameters such as the type and amount of materials given, the outside climatic conditions, the rate of moisture production and ventilation, which is related to the relative humidity and interior temperature of building [63]. The techniques of air condition quality and indoor thermal comfort are comprehensively analysed by other investigators. For the first hour working period, permeable elements reveal a good indoor air condition perception compared to the impermeable coverings [64]. This perception was observed that there is about 15% difference in case of satisfaction or dissatisfaction of interior air quality between the impenetrable and penetrable coverings. Orosa and Oliveira [65] proved that penetrable coverings provide optimum comfort air conditions, which are influenced by outside average temperature. They also analyse that the utilisation of penetrable coverings is a suitable comfort technology that is typically for temporally outdoor and indoor air conditioning with the minimisation of energy consumption. However, it provides a larger energy saving potential for the case of extreme outdoor climate, whereas in calm ambiance, mechanical air conditioning can be replaced as an alternative system. Recently, Djongyang et al. [66] also presented a review on thermal comfort, by using rational and adaptive approaches which have their own potentialities and limits. Rational approaches adopt the data that support its theory, while adaptive approaches use the data from building field studies of people. The study also revealed the mathematical modelling of heat exchange between human body and environment in awaked and sleeping conditions as well as human body thermoregulatory system for energy saving.

2.7. Energy saving by shading

Apart from the aforementioned methods, shading system is an efficient energy saving process for buildings as well. Nevertheless, such method is usually only beneficial for some specific time period of the year and for the other portion of the year it would be counterproductive [67]. Self-shading is one of the crucial shading systems which can be shown by Fig. 8. Shading control is essential for ensuring the thermal and ocular comfort for building interior. The passive shading method is efficient for curtailing heat acquired by building wall, particularly when cooling system of the building is not working properly. One obvious disadvantage of passive shading is that it acts as a barrier which limits the availability of sunlight [68]. This limits the use of natural

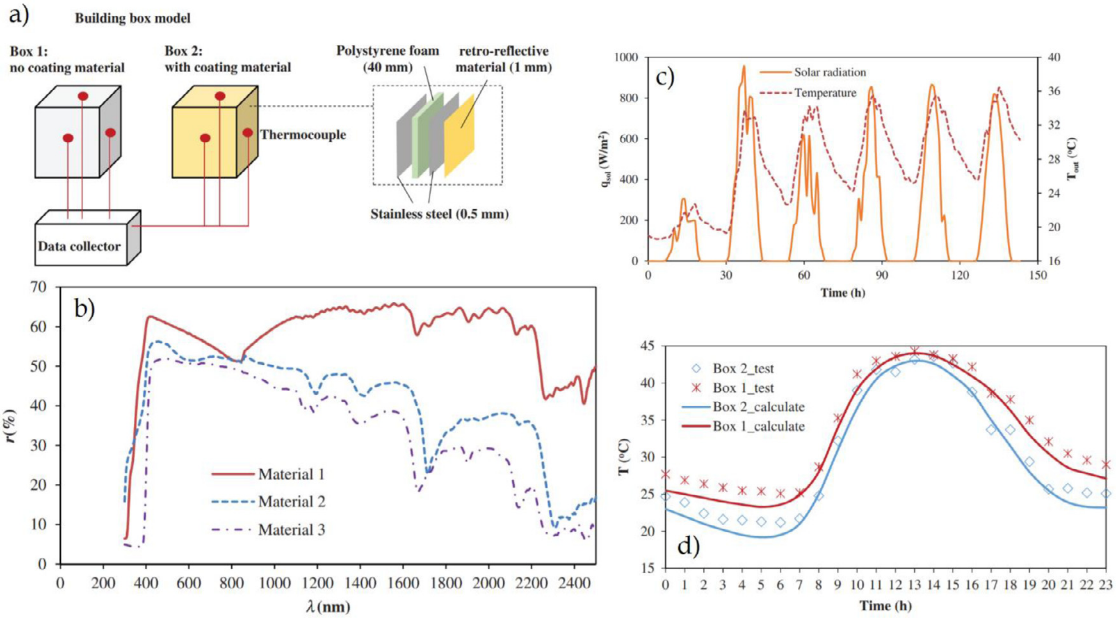


Fig. 7. Impact of reflective coating materials on building energy performance: (a) Coated and reference building box with the measurement details, (b) solar reflectivity of three coating samples with respect to wavelength, (c) typical outdoor characteristics in summer for the region, (d) reduction in indoor air temperature by using reflective coating materials [58].

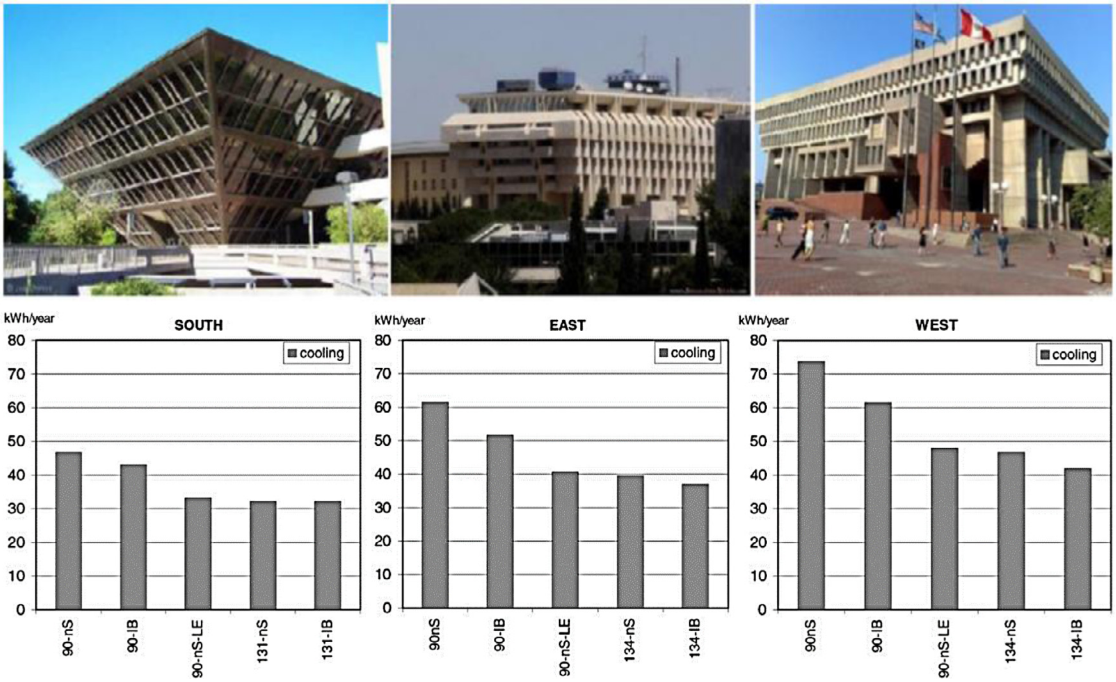


Fig. 8. Different types of self-shading buildings: The impact of facade inclination, glazing type, and shading on the energy consumption of a typical office building in Israel [70].

daylight by the building which can provide energy saving. Aside from conventional shading systems, nowadays solar panels can be used as a standard method for shading as well. Ultimately the energy gained from the shading is influenced by the climatic conditions of desired building area. Most recent technological advancement in the field of facade engineering has been critically reviewed by Marzban et al. [69] where solar radiation based smart morphing shadings get more attention. During installing solar shading, the specific focus has been given on both the building total energy consumption and performance of daylight in internal spaces.

2.8. Energy saving by using double skin facade system in buildings

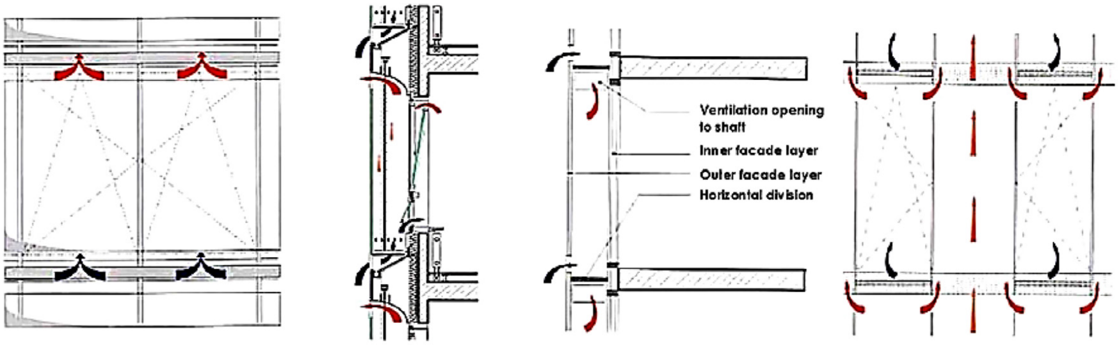
Double skin facade systems (DSF) are generally applied to gain better energy efficiency from the building facade by using high value of its glazing fractions. Different configurations of double skin facade system are shown in Fig. 9. It is constructed by an offset of exterior glazing which comes from interior glazing attached to the curtain wall. Actually, it is a controllable shading system positioned between the cavity of external and internal glazing systems [71]. Plants are also used in DSF configurations in modern architecture. The configuration of double skin facade with plants is shown in Fig. 10. It has achieved reputation in present time due to its capability of reducing solar thermal heat loss or gain by buildings [72]. This idea is slowly gaining importance in cool climate area, particularly for newly constructed buildings. Architecturally, DSF achieved more acceptances because of its transparent properties which allow deep connection with buildings' surroundings. It also admits entering a huge amount of sunlight inside the building boundary without any glitter. The heat transfer and air flow characteristics of PV-DSF and naturally ventilated DSF systems are shown in Fig. 11. Ultimately it has a fine high artistic value desired by owners, developers and architects [73]. Nevertheless, the DSF system has several drawbacks. Firstly, the construction of the DSF system requires much higher capital investment compared to classical single facade system. Another disadvantage is that the DSF system may create overheating which needs more cooling in hot sunny days [74,75]. The design factors of DSF includes selection of geometric parameters of glass, shading, cost expectations for cleaning, ventilation, shading, maintenance cost and wind loads [76].

2.8.1. Daylighting and DSF

The light treatment generally influences the space experience and inner psychological and biological clock of mankind. As a matter of fact, one of the crucial criteria which needs to be taken into account in architectural design is the sunlight effect on the human body [79]. Hien et al. [80], and Gratia and De Herde [72] suggested that the use of DSF system can curtail energy utilisation for lighting purposes. In another similar investigation, Kim et al. [81] evaluated the performance of controlling sunlight tarnishing systems by applying double skin envelop (DSE) technique at different daylight conditions. However, Hoseggen et al. [82], reported that the extra layer of glass lessens the daylight intensity level of indoor environment. Poirazis [83] reported that the daylight characteristics of DSF system are very close to another glazed facade type such as facade of single skin. So, floor space area should be considered in case of building design for receiving daylight if the incidental sunlight is about 300 lux for more than half working day in a year. On the basis of previous research works, it has been found that there is so lagging regarding the DSF system performance and the outcomes did not give any instruction about building structure and how the cavity of building should be developed to meet the minimal energy efficiency of using lighting energy in DSF system. These papers explained the general performance of light but till now no perfect research work or studies has been carried out at all related to this subject.

2.8.2. DSF ventilation

There are different objectives of using ventilation in a building. The main objective is to interchange polluted indoor air with fresh outdoor air. It is used to create fresh indoor environment without draught system and exchange of some temperature changes within occupied area [83]. DSF can be classified on the basis of its action. There are three types of ventilation which are the hybrid, the mechanical and the natural. For supplying clean air during or before the working period, various kinds of DFS ventilation can be used in various locations, orientations, climates



DSF – box window configuration, Source [14]

DSF – shaft box configuration, Source [14]

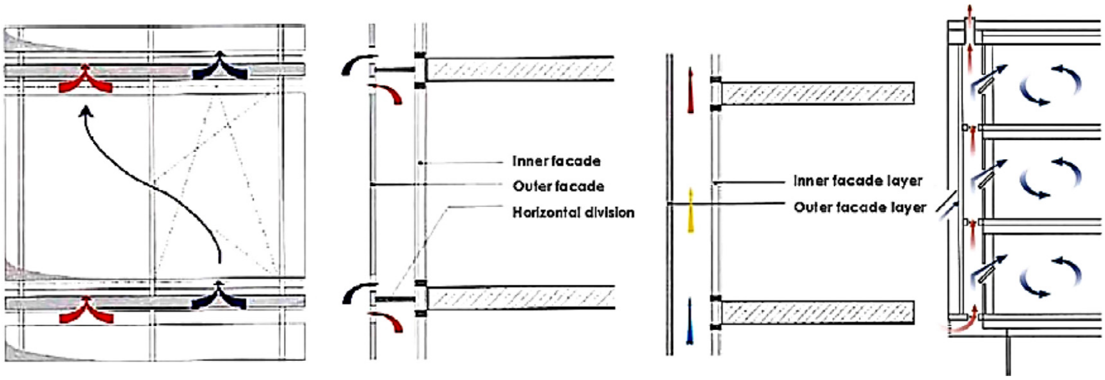


Fig. 9. Different configurations of double skin facade system [77].

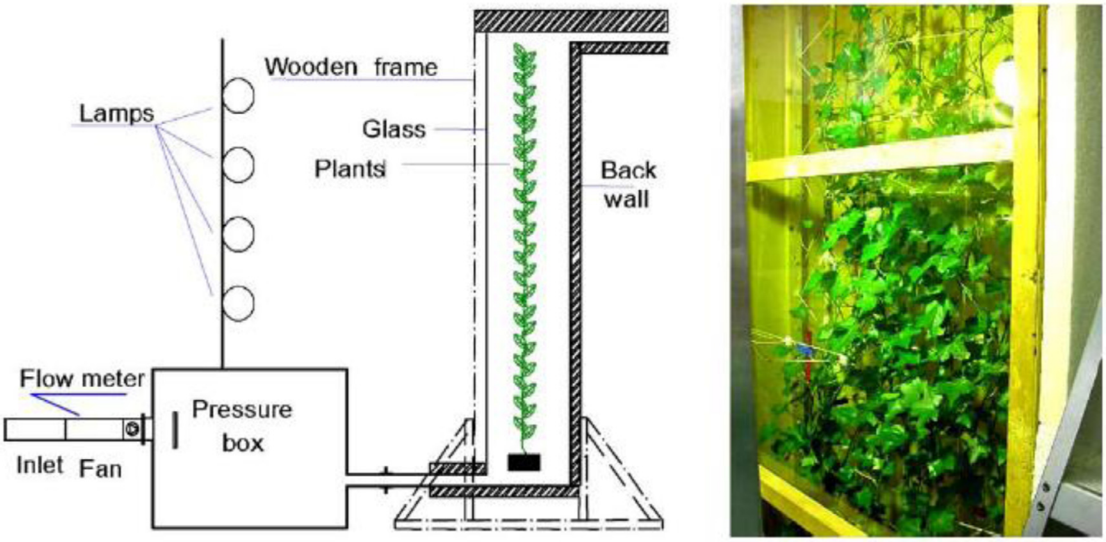


Fig. 10. Double skin facade with plants [78].

and types of building to optimise the energy expenditure and increase the pleasure of residents [84].

Control of ventilation in DSF systems is also of vital importance in terms of indoor air quality (IAQ) and thermal comfort in the built environment [84]. The aforesaid control mechanisms are created to adjust the position of motorised dampers, the position of the motorised glazing units of the test cell, and run the supply fan in case of demand. It is also understood from the findings in Fig. 12 that control systems in DSF ventilation helps to model building performance in form of a hierarchical structure to dynamically adapt the control system to environmental changes.

3. Vertical greenery systems

Generally, a vertical greenery system (VGS) is defined as plants grown on vertical surfaces [85]. In other words, this is the way by which different types of plants can grow on vertical surfaces whether made by humans or naturally either outside the building or inside [86]. The VGS may be standing in front of the wall or attached to the buildings wall surface [87]. In a nutshell, the VGSs can be described as any types of plant growing on any types of building vertical surfaces [88]. According to the requirements of implementation and maintenance cost, the VGSs can be classified as extensive and intensive systems [89,90]. Accord-

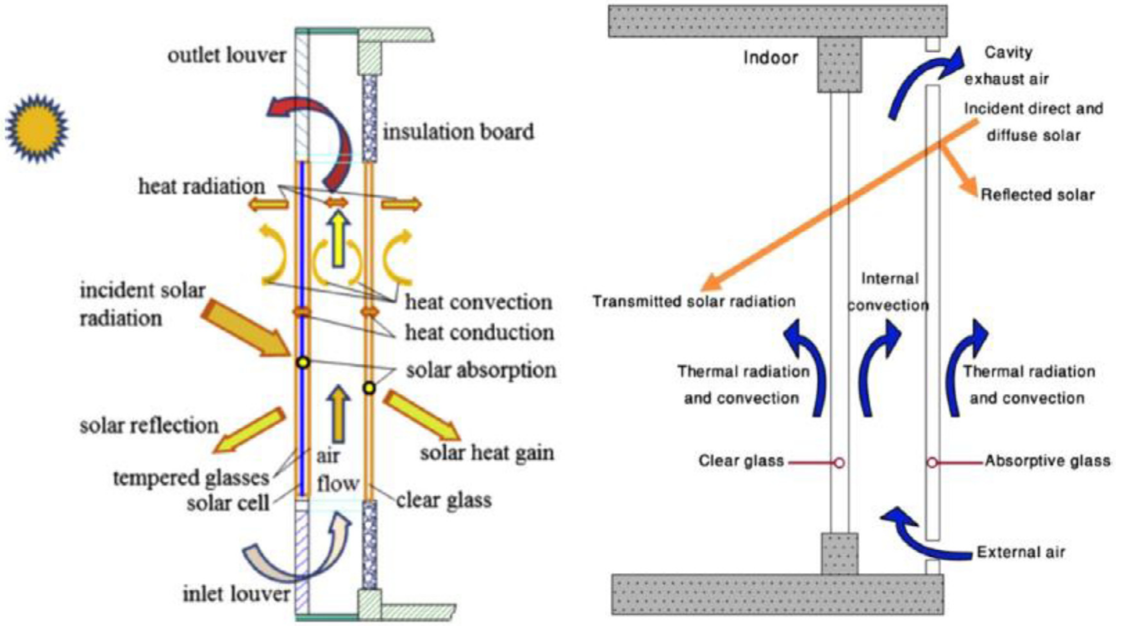


Fig. 11. (a) Heat transfer and energy flow in the ventilated PV-DSF system and (b) Heat transfer and air flow within a naturally ventilated DSF system [77].

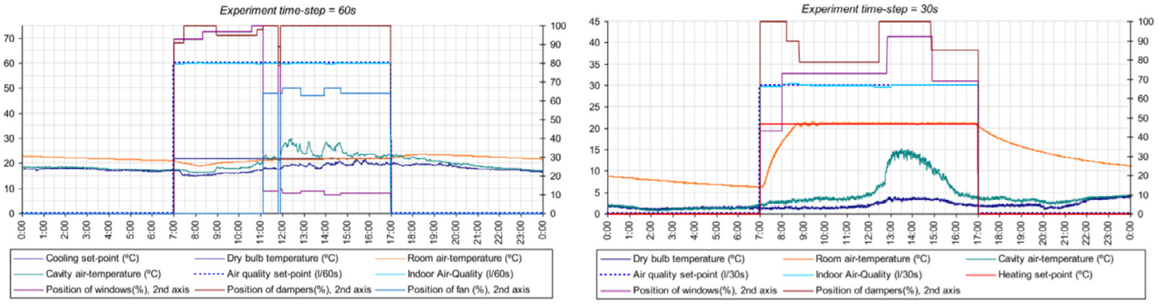


Fig. 12. Control of the ventilation process in summer (left) and winter (right) [84].

ing to existing literature, VGSs are broadly split into two groups, which are the Living Walls and the Green Facades [91]. Based on plant species, construction methods and growing media, there is another classification of VGSs [92]. According to this study, vertical greenery systems (VGSs) are classified into four categories, which are wall-climbing type, module type, hanging-down type and tree-against-wall type. The aforesaid types of VGS are shown in Fig. 13.

The performance of tree-against-wall type is the same as the vertical greenery system but, its working principle is different. In traditional architecture, wall-climbing types commonly use plants which cover the wall surfaces directly or with the help of the trellises to climb. Using this type of VGS is easy, but it takes more time to cover whole surface greenery. On top of the buildings or on the balconies with long pedicel, hanging-down type VGSs are usually used. Hanging-down type makes the building green within very short time. In VGSs, it may be necessary to make building colourful and visually attractive besides using different types of plants. The module type VGS is a new technique which advantages are being colourful, attractive, diverse, fast growing, easy to replace as well as enabling different types of withered plants to be used [92].

From the beginning of the 20th century, the research on VGSs has been substantially increased in urban areas [93]. A huge number of research has already proven the significance of VGSs in urban environment [94]. Due to the environmental effect of buildings on the outer as well as the inner climate becomes more and more apparent, thus the consideration on the utilisation of VGSs and green roofs has progressively increased [93]. Nowadays, VGSs are designed to offer sustainable solutions and provide great impact on society, environment and economy [95]. Recently, in the construction of green buildings, only the use of sustainable materials is insufficient. Besides using sustainable materials it is necessary to consider VGSs, insulation capacities of green roofs, shading effect of trees, or mitigation of urban heat due to evapotranspiration [93]. Due to recent research strongly focusing on “greening process” such as using plants to create building envelopes green, VGSs play an important role in this regard.

For urban environment, plants as well as VGSs have various benefits [96]. Plants can be used as a natural tool for their various advantages such as shading effects, reflection and absorption capabilities for controlling microclimatic conditions in urban environment [97]. Small green areas are practically able to cool surroundings [98], and it has been experimentally determined and claimed that there is a direct connection between temperature as well as green areas [99]. On unused building surfaces applying VGSs would be a good way to integrate urban areas with different types of plants [100]. Applying green roofs as well as VGSs would be an exact solution to use greenery systems in buildings. Temperature controlling by using green roofs is a common technique which has been done previously [101]. On the other hand, vertical greenery system is a new idea to control temperature which requires more consideration for research [102]. Attractive VGS can improve the urban environment [103], increase biodiversity [104], mitigate pollution [105] also results economic benefit of the buildings as like as energy savings and decreasing surface temperature [106]. The

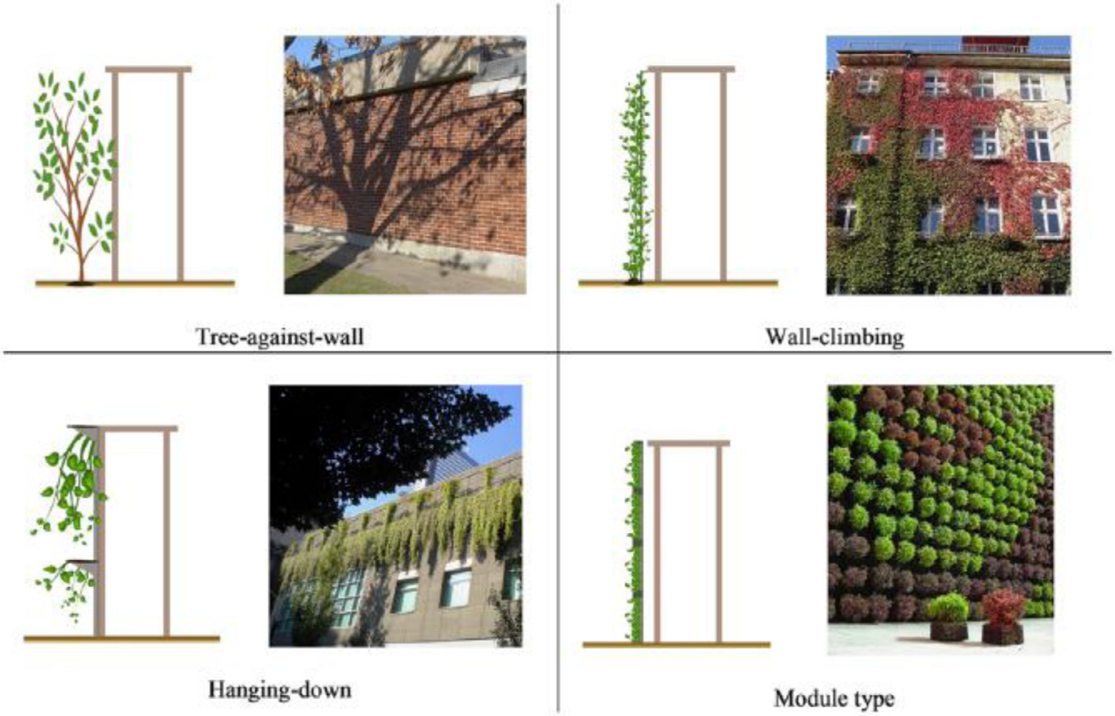


Fig. 13. Various types of vertical greenery systems [109].

most important advantage of VGS is various types of plants with different characteristics can be used in this system [107].

3.1. Energy savings

In the earth, the main source of energy is the sun. Solar energy can influence both the inside and outside environment of buildings [108]. The temperature of the environment and buildings can be reduced by planting trees on the building surface in the form of VGSs. All over the world, climates are different according to the region. Therefore, researchers carry out their work on VGS depending on various factors such as thermal performance of building, ventilation, orientation and buildings architectural features [109]. Four fundamental energy saving methods are used in VGS which are considered as passive energy saving mechanism. Firstly, interception of solar radiation due to the shadow risen by the vegetation; secondly, vegetation also provides thermal insulation; thirdly, plants evapotranspiration helps for evaporative cooling of building; finally, building blockage makes a variation of wind effect on building [89]. In 1980s, the first studies for solar control by using different types of plants were accomplished. To study the control of solar radiation, improve the indoor and outdoor thermal environment and reduce the cooling demand, different types of plants were chosen [110]. According to Akbari et al. [111] the daily average energy savings of two monitored houses were 3.6 and 4.8 kWh/day by using the shading of trees which is 30% of seasonal cooling energy savings. Peak demand savings for the same houses were 0.6 and 0.8 kW. In the area shaded by trees the amount of solar radiation is 100 W/m^2 which is very much smaller compared to the area without shading 600 W/m^2 [112]. With the help of the green wall space i.e. the space between the green screen and building wall, the ambient condition of the building such as humidity or temperature or both can be changed. The layer of air in green wall space produces an interesting insulation effect. The openings of the facade and the density of the foliage are the main factors which affect the renewal of air in green wall space. The insulating capacity of the green wall depends on the thickness of the substrate [113]. The cooling effect and heat flux distribution of a west-facing two-storey building covered with thick ivy has been investigated experimentally. The peak cooling load of ivy coated green building wall has been reduced by 28% [114]. The building facade absorbs thermal radiation, and it is blocked by the presence of trees which acts as a barrier of heat transfer [112]. If a concrete wall is externally coated with a layer of plants, then the heat transfer rate through the wall is significantly reduced. A green wall can minimise the heat transfer through the building wall by 0.24 kWh/m^2 reported by Hoyano [110]. A traditional facade covered by ivy and the insulation effect of the facade has been measured by Kohler (2007). About 5 °C of insulation impact has been observed in extreme winter conditions as well as desirable impacts in summer [115].

Energy is required for the evapotranspiration process of plants. The so-called “evaporative cooling” physical process represents 2450 J energy which is required for the evaporation of 1 g water. The type of plants affects the evaporative cooling of the leaves. The climatic condition also has a notable influence. The evapotranspiration of plants can be increased by the effect of wind and dry environments. Evaporative cooling of living wall substrate is another important parameter. Moisture content of the green wall substrate is significant for the evapotranspiration process. VGSs would have the twofold impact of minimising heat flow into the building through evaporative cooling and mitigating incoming solar energy into the interior through shading as well as improving energy savings [116]. Wind on the facades of the buildings is blocked by the VGSs which performs as a wind barrier. The wind blocking impact is affected by the orientation of the facade, density and penetrability of the foliage and the wind velocity with direction of flow. Because of vegetation, the impact of wind reduction as well as solar irradiation on the building energy performance has been simulated by McPherson et al. in four US cities representing four different climates. According to their study, winter winds are reduced by planting design for cold climates and deliver the access of solar energy to south and east walls. These rules and regulations are also important to avoid blocking summer winds. Low ground covers as well as trees with high-branching shade should be utilised to endorse both wind and shade in hot climates [117]. Blocking the wind would be a very important technique of improving energy efficiency of a building. Cold wind can play an important

Fig. 14. VGS and green roof integrated test room and reference room [92]).

role to reduce the temperature inside the buildings in winter. The efficiency of the regular insulation is reduced by the wind even in airtight buildings. If the building can be protected with vegetation then the heating demand is reduced by 25% which has been studied by McPherson et al. [117]. When vegetation is used in building as wind effect modifier then it should be very careful regarding the two facts which are not to favour the circulation of air in winter and not to obstruct the ventilation in summer [118]. During using the VGS as a passive energy saving technique, the types of plant is considered as another aspect. Different types of plants are used in different constructive systems. Generally, shrubs and herbaceous plants are more commonly utilised in green walls and climbing plants are usually chosen in green facades. Plants are basically evergreen in green walls but the plants in green facade are deciduous. Thermal behaviour of green walls greatly depends on the plant species. Perennial plants influence both the heating as well as cooling demand of a building. On the other hand, only the cooling period is influenced by deciduous plants because in heating period the solar radiation can pass through the plants [91]. Plants and shrubs grow along building facade or along trellises known as VGS which can reduce building surface temperature by shading [119]. Apart from, through wind speed attenuation, the VGS can reduce infiltration [120], and through evapotranspiration, it can cool the ambient air. Susorova et al. [121] revealed that an average of 0.7 °C exterior surface temperature can be minimised by ivy-covered walls. Different factors which reduce the buildings cooling loads such as the subsidence of urban heat island intensity and the improvement of the local micro-climate are the side benefits of the VGSs. During daytime, the facades with vegetation can serve to minimise surface temperature. On the other hand, at night time it can significantly release the heat into the canyon. During mitigation of urban heat island (UHI), VGS is often compared to cool paint. Cool paint reflect the radiation and increase their irradiance, but vegetated facade absorbs more solar radiation and dissipates more heat by evapotranspiration [122]. So, it can be said that vegetation is more efficient than cool paint for mitigating UHI [122]. Near the VGS, the ambient air temperature can drop by up to 3 °C showed by Wong et al. [116]. On the other contrary, Susorova et al. [121] reveal that the ivy-covered facade can reduce the ambient air temperature by 0.8–2.1 °C. Alexandra and Jones predicted the amount of energy savings in different cities after implementing VGS by CFD (computational fluid dynamics) simulation [123].

Xing et al. (2019) conduct a comprehensive experimental analysis on VGSs to evaluate the impact of greenery surfaces on indoor temperature regulation and energy saving in summer [124]. The tests are carried out on reference and greenery coated buildings as shown in Fig. 14. The results reveal that the indoor air temperature of the room with greenery coating is reduced by 0.4 °C on average and a maximum of 2.1 °C compared to the reference room without VGS. This can be also concluded from the surface temperature distributions for east, west, north, south and roof faces as depicted in Fig. 15. In conclusion, it can be said that the room furnished with VGS has a better thermal performance and significantly reduce the amount of energy consumption [124].

3.1.1. *Temperature reduction as well as cooling effects*

One of the most important properties of VGSs is temperature reduction. For temperature reduction, plants cooling effect is more efficient compared to the shading effect. Energy efficiency of a building is defined as the ability of a building to function as well as operate with minimum energy consumption [125]. Numerous studies have been accompanied to determine the thermal transfer value of VGSs, temperature variation, cooling effect, energy use and so on. These studies have been undertaken in various weather conditions. In Mediterranean region, a thermal comparison has been formed between a bare wall as well as covered wall with green facade which shows the thermal benefits of covered wall for both interior and exterior surfaces and reduced the effect of heat flow losses [119]. There was another study accomplished in Singapore to understand the effect of plants on walls of buildings and to determine energy consumption with temperature reduction of VGSs [126]. In California, an experiment has been conducted to test the ability of temperature reduction of VGSs which revealed the ability to reduce temperature of green facade is higher than the area without greenery [127]. By this study it can also be said that the living wall or green facade which has been installed shows more effectiveness to reduce indoor temperature and to improve the temperature reduction rate [127]. In another study, it has been shown that the living wall system without plant can reduce the temperature effect but the wall with plants and vegetation improve the reduction-ability of temperature [127].

A long side VGS has the ability to reduce buildings indoor temperature besides minimising the ambient as well as surface temperature of building wall. Price et al. investigated the cooling effect of green facades which has showed that the exterior surface temperature, ambient temperature, heat flux as well as interior air temperature can be minimised through the VGS [129]. The physical structure of the buildings, dimensions as well as materials, covering facade with plants minimise indoor temperature especially after sunset and provides residence relief [88]. In all climates, VGSs act better compared to the green roofs in canyons to reduce temperature. But, the performance of temperature reduction has been found better when the VGS is used with green roof [123]. Every type of VGSs as like as green facade or living wall has specific effect on temperature minimisation. The temperature of VGS such as green facade is reduced by the flow of air through the foliage. But, based on the substrate cover as well as materials used the living walls

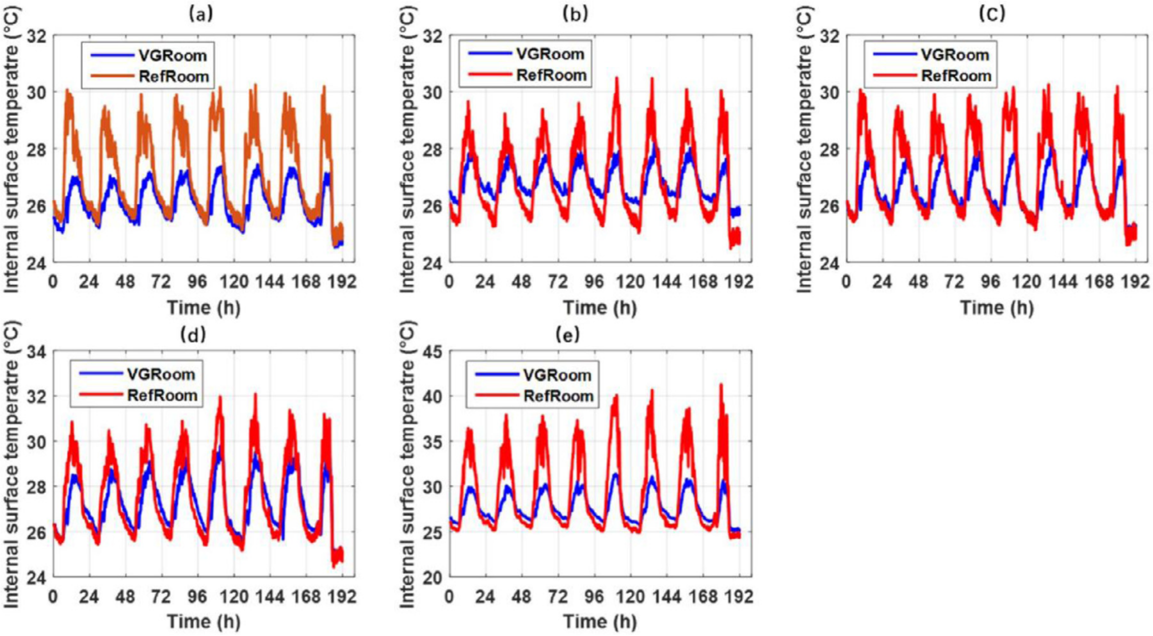


Fig. 15. Internal surface temperature for the VGS and green roof integrated test room and reference room for the (a) east, (b) south, (c) west, (d) north and (e) roof [92].

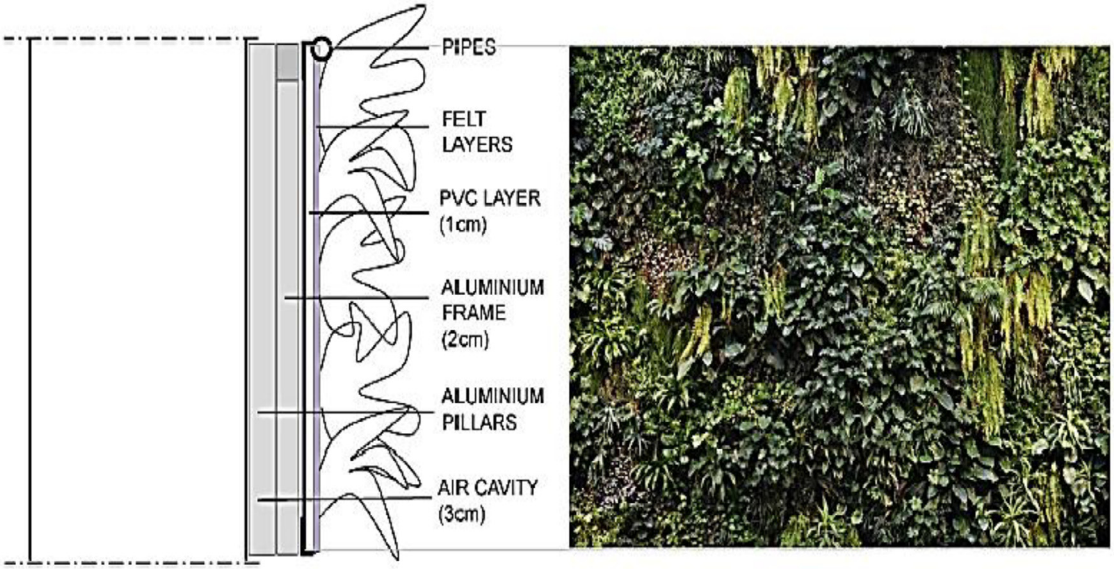


Fig. 16. Side view and front view of a living wall system [128].

provide good shading. The side and front view of a living wall is shown by Fig. 16. In Singapore, an experiment with eight different VGSs of different substrates and plants has been conducted and it has been found that the living wall with organic substrate showed the best performance in temperature reduction [116].

3.1.2. Building orientation effect on thermal performances of VGSs

The VGSs can be installed in each building orientation but it is needed to choose the appropriate orientation for achieving highest energy efficiency of buildings. Some factors such as latitude, climate and geographical properties are different from one region to another region thus much study is required on these factors for choosing appropriate orientation to install VGS. A study shows that in Mediterranean climate, the best orientations to install VGS are on west, east, south and north respectively for having better temperature reduction effect [130]. If a VGS is installed without windows and building facing on west, east, south and north correspondingly then the cooling load capacity reduction of the building is up to 20%, 18%, 8% and 5%, respectively [130]. In dry Mediterranean region, the temperature reduction capacity of green facade in different orientation such as north-west, south-west and south-east have been measured and shown that the ability to reduce temperature is up to 5.5 °C [131]. But, temperature reduction peaks to 15.2 °C when it is orientated on south-west. Then, the crucial way to face the challenge of maintaining temperature in hot summer and cold winter is to provide a microclimate between green plants or vegetation and wall surface during installing VGSs. Each climatic condition needs to be tested separately to decide the best orientation for installing VGSs to have maximum energy efficiency [109].

3.1.3. The effects of building ventilation on thermal performances of VGSs

By correct design of building, ventilation is capable to improve the efficiency of VGSs. But, the number of experiments studied on the effect of ventilation on thermal performance of VGSs are very limited. The velocity of air around the VGSs is measured in some experiments to mention the importance of ventilation. It is necessary to do more research and focus new ideas to combine ventilation with VGSs to improve the thermal performance of VGSs [109].

3.1.4. Improving the performance of VGSs by adding architectural features

It is not necessary to install VGSs in front of vertical surfaces to have their better thermal benefits. The thermal performance of entire VGSs can be improved by installing with appropriate architectural features. Double skin facades are a successful example of combination of vertical greenery systems. Double skin facades have some exceptional benefits such as thermal benefits, moisture, acoustic, fire safety as well as visual comfort [132]. Sometimes two layers of facades are used which are segregated by an air gap to improve the insulation of wall [133]. Inside the air gap blinds are located which save the building from solar radiation. This is the way through which blinds are used but they are not pleasant in warm duration. Natural benefits of plants are used in the double skin facade with vertical greenery system to improve the thermal performance, thus it is used instead of blinds [78]. For high density cities, due to the lack of adequate land vertical greenery is generally used as a substitute source of green shading. Highly populated urban cities such as Hong Kong and Singapore should pay attention to develop high rise environment by creating “Vertical City Garden” via the introduction of VGSs and rooftop gardens [134].

3.1.5. Thermal calculation

In VGSs, thermal performance can be measured with the help of the shading coefficient and leaf area index of plants used in vertical greenery system. The thermal performance is also influenced by the envelope thermal transfer value (ETTV). The formula for an entire building can be written as Eq. (2) [126]:

$$ETTV_i = 12(1 - WWR)U_w + 3.4(WWR)U_f + 211(WWR)(CF)(SC) \tag{4}$$

$$ETTV = \frac{\sum_{i=1}^{n} A_i ETTV_i}{\sum_{i=1}^{n} A_i} \tag{5}$$

Where, ETTV (W/m^2) is calculated over the whole building envelop while ETTV$_i$ (W/m^2) is applied for each wall of different orientations. The numerical constants can be obtained by simulation average of different solar angles in each year [126]. The envelope thermal transfer value can be determined with the help of the overall thermal transfer value (OTTV) by calculating average heat gain through building envelope. Apart from, it is necessary to calculate three basic components of heat transfer through the building facade to measure ETTV. One of them is heat conduction through opaque walls which can be determined by utilising the thermal transmittance of opaque wall U$_w$ (W/m^{2}K). Secondly, heat conduction through windows which can be determined by the thermal transmittance of fenestration U$_f$ (W/m^{2}K). Lastly, the solar radiation through windows can be measured by using the correction factor (CF) for solar heat gain through fenestration and shading coefficient (SC) of fenestration. Here, window-to-wall ratio is also required to calculate. The maximum allowable ETTV to conserve energy in Singapore is 50 W/m^2 [135]. Xing et al. utilised the subsequent equations to determine the total heat losses through the walls and roof (Q in Wh), averaged heat fluxes (q in W/m^2) and the total electric energy consumptions (E in Wh) of the two rooms of his experiment [124].

$$Q = \int_{\Delta t} q(t) F dt \tag{6}$$

$$\bar{q} = \frac{\int_{\Delta t} q(t) dt}{\Delta t} \tag{7}$$

$$E = \int_{\Delta t} P(t) dt \tag{8}$$

Where, P(t) is known as power consumption in W which can be calculated by utilising power metre. The heat flux q(t) (W/m^2) which is determined by using HF (heat factor) self-recording metre; Δt (h) is the four-day period of the energy saving experiment; and F is the total area of roofs and wall in m^2. However, the total heat losses through the walls and roof (Q) were measured from the heat fluxes which was a little bit less than the total electric energy use. This difference was created because of including the heat loss for cold air infiltration into the total heat loss of experimental room [124]. The vertical greenery system energy saving rate (ESR) can be measured by utilising the following equation [124]:

$$ESR = \frac{E_{Ref\,Room} - E_{VG\,Room}}{E_{Ref\,Room}} \tag{9}$$

Where, RefRoom and VGRoom were two reference rooms used in this experiment. The electrical energy use of the RefRoom and VGRoom are $E_{RefRoom}$ and E_{VGRoom}. The energy saving rate of the VGS in the experiment is 18%, which is smaller than the former study (25%) [136]. The result of the experiment showed that, the temperature of VGRoom is about 1 °C higher than that of the RefRoom which indicates that more energy was required for RefRoom to maintain the temperature as same as VGRoom. Consequently, the energy savings of VGRoom is larger than the RefRoom [124].

3.2. Pollution reduction

There are numerous environmental benefits of VGSs. Such as, the VGSs work as natural air filtration by absorbing the dust and cleaning the air [137]. On the other hand, plants consume CO_2 by photosynthesis and release oxygen [138]. This reduces the CO_2 emission and makes the air fresh. Gradually, the earth’s temperature is increasing day by day due to CO_2 covers the earth’s atmosphere as like as blanket [139]. Apart from, in the atmosphere greenhouse gas (GHG) expansion takes place due to CO_2 emission [140]. There are some other important benefits of VGSs such as noise control and acting as a barrier for noise abeyance [141]. VGSs are also able to reduce noise disturbance and reduce sound reflection [85]. It has been estimated that, the VGSs can save energy 2651 × 10^6 kWh per annum which can significantly reduce the emission of CO_2 to the atmosphere. According to the sustainability report of China Light and Power Group in 2009, from the electric power generation the amount of CO_2 emission was 0.83 kg/kWh [142,183]. It is estimated that Double-skin Green Facade (DSGF) is able to minimise 2200 × 10^6 kg of CO_2 per year. In 1999, U.S Department of Agriculture revealed that one medium size deciduous mature tree can sequestrate an average of 133.1 kg of CO_2 per year [143]. Vertical greenery system would be a significant strategy for climate change mitigation in the modern world due to it makes a great contribution through carbon sequestration. According to Nordbo et al. [144], it would be possible to effectively offset CO_2 from the atmosphere, if 80% urban area is covered by green plants. In China, 6.38% green urban areas can sequestrate 1.895-ton carbon. 0.33% carbon emission from the combustion of fossil fuel has been sequestrated by green spaces in total 35 cities in China [145]. Another study revealed that, 60% of cooling energy demand in Beijing, China was mitigated by consuming 3.33 × 10^{12} kJ heat energy by urban vegetation in summer. Subsequently, 243 thousand tons of CO_2 per summer is minimised by mitigating the simultaneous carbon emission [146]. VGSs also able to absorb different types of pollutants such as tiny particles and black carbon whose diameter is less than 10 μm or PM10 which contributes different harmful diseases such as cardiac as well as pulmonary diseases [147]. The application of VGSs in urban street is able to reduce PM10 and NO_2, up to 60% as well as 40%, respectively [148]. Nowadays, carbon sequestration by plants gained attention all over the world. But, in tropical region the number of studies regarding carbon sequestration by VGSs are very limited [105]. The amount of carbon sequestration depends upon the type of plants. An edible plant, winged bean could sequestrate about 0.94 kg CO_2/m^2 yearly, while Bread Flower and White Sky Vine can sequestrate more than 0.05 tCO_2e [149].

One of the most important benefits of VGSs is to improve air quality by filtering particulate materials in their leaves [150]. Kohler revealed that, the plants have ability to reduce CO_2 emissions which are produced by traffic or heating. Recently, in a study carbon sequestration modelling of green wall was carried out [105]. According to a study in 2017, the plants with higher woody stem are more preferable for VGSs because of higher capacity to carbon sequestration [150]. VGS is considered as natural carbon sequestration technology [151]. Pulselli et al. [152] revealed that VGS is capable to sequestrate about 90 kg CO_2 per year. While Pan and Chu [151] revealed that the range of yearly carbon sequestration is from 61 to 253 g/m^2. Numerous studies have shown that plant mass and productivity can be increased by high concentration of atmospheric CO_2 [153]. For mitigating Urban Heat Island (UHI) impact VGS plays an important role. According to scientific evidence, urban microclimate can be adjusted by proper integration of the vegetation with urban ecosystem [154].

3.3. Economic benefits

The vertical greenery system's economic benefit in modern life is expanding. Window shadings are one way of using VGSs [155]. The properties of appropriate shading systems provided by vertical greenery system are decreasing discomfort glare as well as increasing daylight which leads to reduce electricity demand [156]. Apart from, vertical greenery systems control the storm water and act as spongy surfaces [157]. VGSs are suitable for eco-retrofitting projects which is more economical than reconstruction or demolition [158]. Besides temperature reduction or energy savings, VGSs have different economic benefits [159]. Since plants are able to absorb shortwave radiation besides reduction of solar re-radiation from various hard surfaces, VGSs have vital impact on minimising urban heat island i.e. reducing the electricity demand for urban cooling [160]. Furthermore, by planting shading effect, transpiration and evaporation of plants, VGSs make the environment cool [155]. Since, vertical greenery systems can lessen temperature and suitable for minimising systems cooling energy load, thus this is the way through which it can develop the energy efficiency of buildings. Greenery systems are also of vital importance for reducing outdoor temperature up to 5 °C, thus minimising the cost of cooling the cities in urban areas [155]. The impact of greenery surfaces on outdoor temperature reduction is illustrated by a comprehensive experimental research shown in Fig. 17.

3.4. Building appearance

Babylon Hanging Garden is one of the well-known examples of the vertical greenery systems aesthetic application [161]. According to the aesthetic view of different personnel and because of plants growing is biologically innate, people can use living plants or greeneries in different forms in their buildings. Plants create different places on the earth for rest and recreation [112], which proved that natural contact with plants improve psychological phenomena of human health and wellbeing [162]. Furthermore, nearness to green areas reduce human stress and obesity [163]. A comparative study on one house between without any greenery and greenery with different positions has been done, where it found that house with green facade gives aesthetically good-looking for all respondents [164]. Fig. 18 reveals the building appearance with traditional green facade and double skin green facade. The plants compound by buildings and in urban areas draw the attention of people more than the plants in gardens [165]. Besides the other benefits of VGSs, it is necessary to make people aware regarding the aesthetic benefit of greenery systems.

3.5. Social benefits

By shading and evapotranspiration, vertical greenery systems have high potentiality to reduce urban heat island problems by reducing wall temperature [167]. Heat stress causes by urban heat island (UHI) which has serious environmental impact to human health [168]. Concerning heat stress as well as thermal sensation, the most important meteorological variables are wind velocity, relative humidity and temperature of air [169]. These are the factors through which different thermal indices like Predicted Mean Vote (PMV) as well as Universal Thermal Climate Index (UTCI) can be calculated [168]. Thermal wellbeing of human has been described by PMV. On the other hand, UTCI assessed the human behaviour with respect to heat stress in outdoor thermal environment [170]. Previous studies show that the VGSs have the ability to enhance noise attenuation by diffracting, absorbing and reflecting sound [171,213]. By minimising long-term sound pollution, the green wall can develop human subjective well-being. A standardised laboratory test was conducted by Azkorra et al. [172], and he interpreted that the VGSs have very high potential as sound insulation tool for residential as well as commercial buildings. Apart from, the green walls can act as an ideal tool to optimise landscape aesthetics [173]. Different scientific studies reported that it is required to provide pleasant visual quality for faster recovering of human stress. Also, it is scientifically proved that natural scenery helps people to survive with stress related psychological problems [162]. VGSs helps to block sunlight and to control light intensity, these are the way through which it can reduce glare and provide safety as well as visibility [174]. VGSs have potential to cover and shad of reflecting concrete surfaces. These are the social benefits which can be accomplished by the application of VGSs. Apart from, temperature as well as energy reduction, thermal pollution and aesthetic sense, vertical greenery system has other benefits such as noise reduction and the effectiveness of substrates. Urbanisation, growing population, transportations and vehicles, factories are the sources of noise in cities. In a survey questionnaire, it has been revealed that, 30–50% of respondent's problem is noise pollution [162]. Noise annoyance can be reduced at home in urban vicinity green areas [175]. The effect of vertical greenery system on noise annoyance was investigated in Singapore, and the result revealed that VGSs are capable to minimise noise annoyance [176]. Another experiment in the USA presented that VGS can absorb sound as well as minimise sound transmission [127]. The types of VGSs shown in Fig. 19, and kinds of plants affect the noise reduction results thus it is required to find out best system to maintain the level of noise annoyance by selecting appropriate plants and green walls. Outdoor vertical greenery system studies showed that both the living walls and green facades were able to increase acoustic insulation properties of buildings [176]. In urban areas, vertical green facade foster biodiversity in those regions that would otherwise be covered in hard walls [177]. Urban design through ecological engineering approach, vertical greenery system is able to restore ecosystem and ecosystem services that have been displaced by conventional urban architecture [178].

The indoor vertical greenery system provides fresh indoor environment and comfort acoustic and thermal conditions to the building occupants [180]. Human psychological improvement can be provided by indoor vertical greenery system. A study was conducted on indoor vegetation system in a classroom which shows positive perception and induced psychological and physiological relaxation of students [181]. Compared to the indoor VGS illustrated in Fig. 20, the outdoor VGS has the same benefits. To develop medical and psychological status amongst heart and lung disease patients or surgery patients, it is highly appreciated to integrate both the indoor and outdoor VGS in rehabilitation centres and hospitals [182]. VGS protects building facades from extreme heat radiation as well as high precipitation besides creating an attractive visual presentation [183]. This is the way through which VGS reduces the

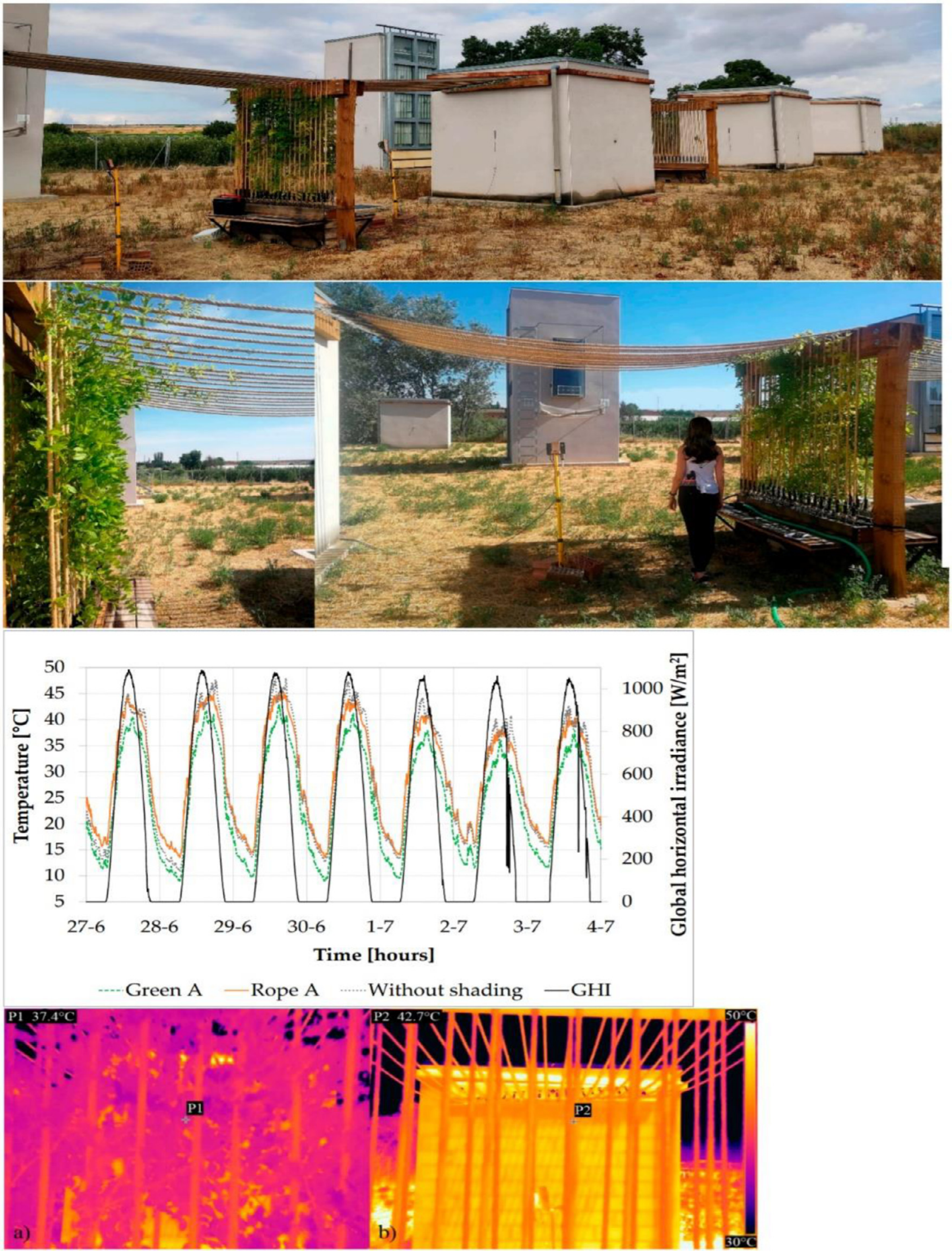


Fig. 17. Minimising outdoor temperature via greenery surfaces: Outdoor temperatures with and without shading systems and thermal imaging analyses [155].

building's maintenance cost and prolongs the lifespan [184]. Nowadays, VGS has been rapidly used in urban areas which increase awareness amongst city residents to become more environmentally friendly and to conserve and preserve natural bio-diversity [147].

3.6. Barriers to VGS

Although, vertical greenery system has many advantages, it has some delimiting factors such as installing costs, maintenance cost, and poor financial as well as energy payback period [186]. Most of the articles discussed the benefits of vertical greenery systems, but fewer articles discussed about the potential drawbacks. One of the most important factors is the irrigation cost which may increase the maintenance cost of VGS [187]. For tropical areas, a green maintainability structure was familiarised in a study in Singapore. In design stages, different important factors or parameters need to be considered to minimise the risk and costs throughout the life cycle of VGS [188]. Including abiotic and biotic, there are some other challenges like water stress as well as frost

Fig. 18. Comparison of building appearances of traditional green facade (left) versus double-skin green facade [166].

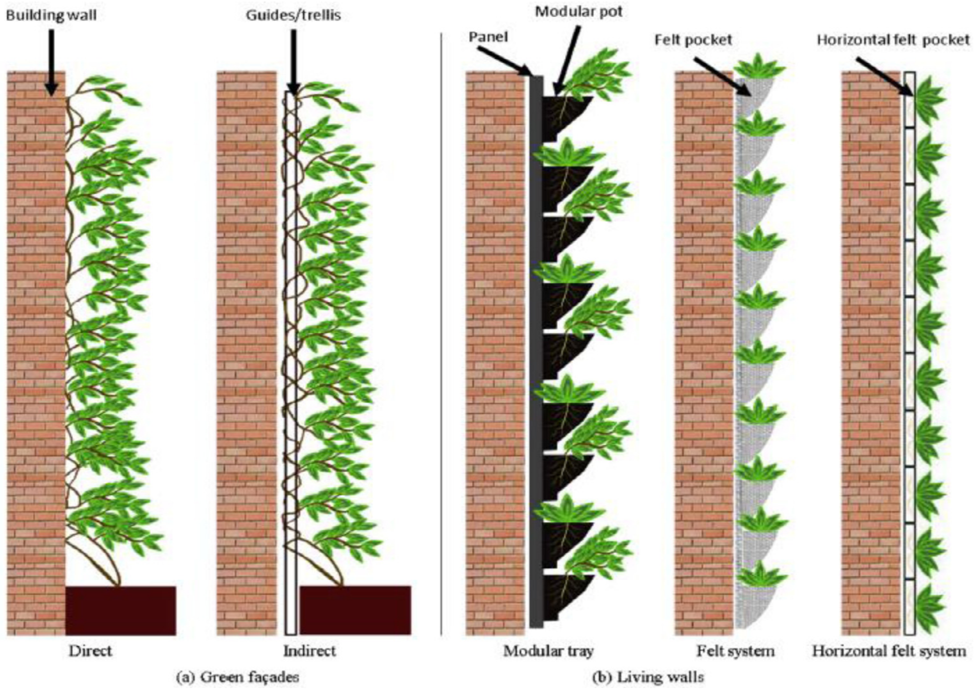


Fig. 19. Schematic diagram of different vertical greenery systems [179].

Fig. 20. Indoor vertical greenery system [185].

in different regional climate [189]. The selection of appropriate plants is another challenge to get better performance from VGS [190]. Apart from, different external factors like government initiatives, establishing new policies, subsidies and mandatory application of VGS also act as potential challenges to build green walls [186]. Since, the VGS is a relatively new system thus it is required to endure to be improved. It has been predicted by different researchers that, a complete standard guideline for vertical greenery system is still a decade away [191].

4. Conclusion

Buildings consume 40% of total energy worldwide. A global view of building sector energy consumption scenario as well as energy saving technologies has been presented in this study. Appropriate utilisation of building energy saving techniques has a great impact to make a building energy efficient and socio-economic development of our present civilisation. Numerous techniques which are used to save building energy have been discussed extensively. Replacing single-glazed windows with double-glazed windows or alternative novel glazing discovered that about 39 to 53% energy could be saved of commercial buildings in UK. Approximately 11% of total building energy could be saved per annum by proper maintenance of central heating equipment. Using advanced design and automatic control techniques of HVAC equipment could effectively save about 20% of total building heating load. Amongst the techniques, vertical greenery system (VGS) is most reliable and efficient one. VGSs would have the twofold impact of minimising heat flow into the building through evaporative cooling and mitigating incoming solar energy into the interior through shading as well as improving energy savings. A green wall can minimise the heat transfer through the building wall by 0.24 kWh/m^2. Thermal behaviour of green walls greatly depends on the plant species. Perennial plants influence both the heating as well as cooling demand of a building. On the other hand, only the cooling period is influenced by deciduous plants because in heating period the solar radiation can pass through the plants. The indoor air temperature of the room with greenery coating is reduced by 0.4 °C on average and a maximum of 2.1 °C compared to the room without VGS. Proper shading of trees able to reduce 25–30% of seasonal building cooling demand. If a VGS is installed without windows and building facing on west, east, south and north correspondingly then the cooling load capacity reduction of the building up to 20%, 18%, 8% and 5% respectively. Consequently, it can be said that the appropriate use of building energy saving techniques can save a huge amount of building energy which would be grateful to minimize the GHG and save environment from global warming. More critical thinking about individual building energy saving technologies such as double-glazing windows, DSF and VGS can be considered as future work. Integrating natural ventilation system with VGS would be a very good combination to reduce building energy consumption. In future experiment it is highly recommended to apply ventilation as well as vertical greenery system together. Alongside ventilation, to improve temperature reduction ability and efficiency of VGSs, combination of VGSs and different architectural features is recommended to find new techniques. To find the best material for improving the thermal performance of VGSs, it is recommended to make a deep study about different materials of green facades as well as living walls. It is also useful for readers to make an assessment regarding the initial investment and maintenance costs of green facades. However, green façade systems are still cost-effective when their multifunctional features are taken into consideration such as excellent heat and noise insulation, aesthetic appearance, eco-friendliness and health benefits (Eqs. (1), (3)–(6)).

Conflicts of interest

The authors declare that there is no conflicts of interest of the manuscript.

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