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Review

A Review of Roofing Methods: Construction Features, Heat Reduction, Payback Period and Climatic Responsiveness

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Received: 30 September 2018; Accepted: 15 November 2018; Published: 18 November 2018

Abstract: The roofs of buildings play an essential role in energy efficiency because a significant amount of solar radiation is absorbed by roofs in hot weather and a significant amount of heat is lost through roofs in cold weather. This paper is a systematic literature review about roofing methods for flat roofs. Ten roofing methods are reviewed in this paper. They are concrete roof, cool roof, insulated roof, roof garden, photovoltaic panels' roof, biosolar roof, double-skin roof, roof ponds, skylight roof, and wind catcher. The review covers each roof's main features, heat flux reductions, payback periods, and the appropriate climate for its implementation. Furthermore, the basic principles for selecting appropriate roofing methods are discussed and future studies for integrating these roofing methods are suggested. Some of these methods can eliminate the need of installing HVAC (Heating Ventilation and Air-conditioning) systems and others can achieve a high percentage of heat reduction if they are the right choice and they are implemented in the right circumstances. An incorrect selection could result in mild to severe energy penalties. The review contributes to the increasing knowledge about sustainable roofing and helps designers to increase building energy efficiency by selecting the appropriate roofing method.

Keywords: roof types; energy efficiency; passive cooling; literature review; climate responsive

1. Introduction

Building shape, location, materials, and elements of design, all play significant roles in energy performance inside a building [1], and consequently, the role of architects is to integrate them to produce a sustainable building and save energy usage. When designing a building, unfortunately roofs have not received much attention, yet the roof of building plays an essential role in building sustainability, as it absorbs thermal energy significantly in hot climates [2]. On the other hand, a significant amount of thermal energy is lost in cold days from roofs. The difference between internal and external temperature, roof area, building type, and different roofing construction materials are important factors influencing energy loss and gain; for instance, the rate of heat transfer by natural convection between a roof of a shed with an area of 400 m^2, a surface temperature of 27 °C, and ambient air temperature of −3 °C, with an average of 10 w/m^2k of convection heat transfer coefficient is −120,000 W [3]. To illustrate further, the average of heat lost through the roof for a typical uninsulated timber-framed house in New Zealand is 30–35% [4], about 25% for an uninsulated home in United Kingdom [5], and about 40% in Canberra, Australia [6].

In past years, much research has been conducted regarding different ways to deal with building roofs in order to improve thermal comfort, improve energy performance in buildings, and to reduce the negative impact on the environment. Many researchers have addressed different sustainable methods and treatments for building roofs to improve the energy performance in buildings. Some of these methods are traditional, while others have only been introduced in the past few years. Many experiments, simulations, and case studies can be found in this area. Based on a review of available roof construction techniques, ten roofing methods have been identified. These roofing methods are (1) Concrete roof; conventional roof slab; (2) Cool roof; adding reflective material on roof slab; (3) Insulated roof; adding insulation material on a roof slab; (4) Roof garden; adding a garden on a roof slab, which could include different layers such as plantation, soil, waterproofing, and drainage; (5) Photovoltaic panels roof; adding photovoltaic panels onto a roof slab; (6) biosolar; a combination of roof garden and photovoltaic panels on a roof slab; (7) Double-skin roof; adding a secondary slab over the main roof to cover it; (8) Roof ponds; adding water or wet materials on a roof slab to improve passive cooling; (9) Skylight roof; part of or whole roof containing a skylight; and (10) Wind catcher; adding an element over a roof to trap air and direct it inside a building. Each one of these roofs has some advantages accompanied with disadvantages, and they compete with each other in many aspects such as construction features, heat flux reduction, cost, maintenance, suitability to climate, and preferred building types. This paper reviews the ten roofing methods and conducts comparisons of their performance and features to help decision makers to select suitable methods for their buildings. Methodology in Section 2 introduces how the literature review has been conducted; the main feature of each of the ten roofing methods is reviewed in Section 3; they are further compared in terms of heat reduction related to a conventional roof, the payback period, and climatic responsiveness in Section 4. The principles of selecting the ten methods and possible integration are discussed in Section 5 followed by the conclusion where future studies are implied.

2. Methodology

The first stage is a literature search using the Web of Science data base. Using the targeted key words for the selected roofing methods, 574 peer reviewed articles were identified. Studies were conducted in different climate conditions (Figure 1). The majority of the studies were conducted in hot or warm conditions, specifically in Arid and Tropical climates, and even the studies in Temperate and Mediterranean climates focused on hot days in these climates. Only 35 papers described studies conducted in polar climates. Past research in this field was conducted in 64 different countries. The top five countries were: The United States, China, India, Italy, and Greece. Thirty-one countries published one–two studies. The gradient green coloured map in Figure 2 gives a visual view of the countries where roofing methods have been studied.

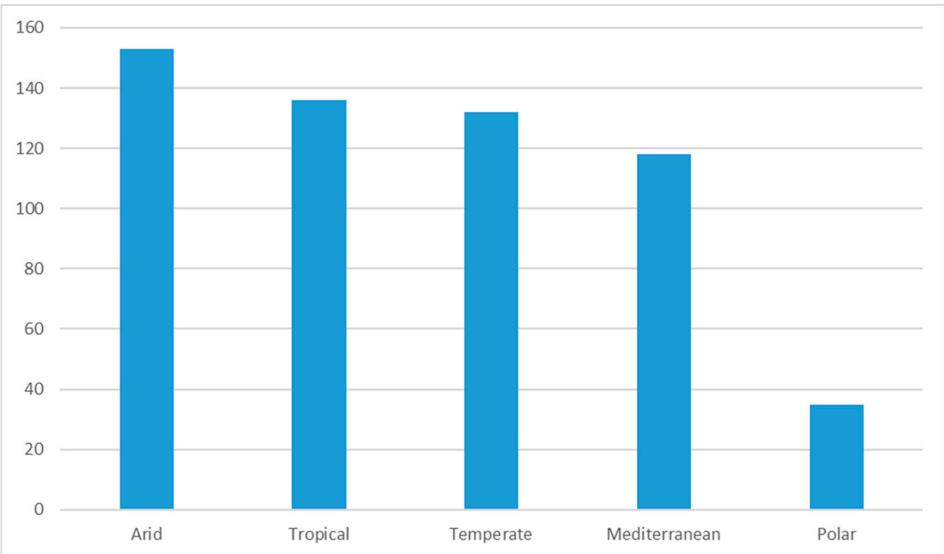

Figure 1. Number of papers from each climate.

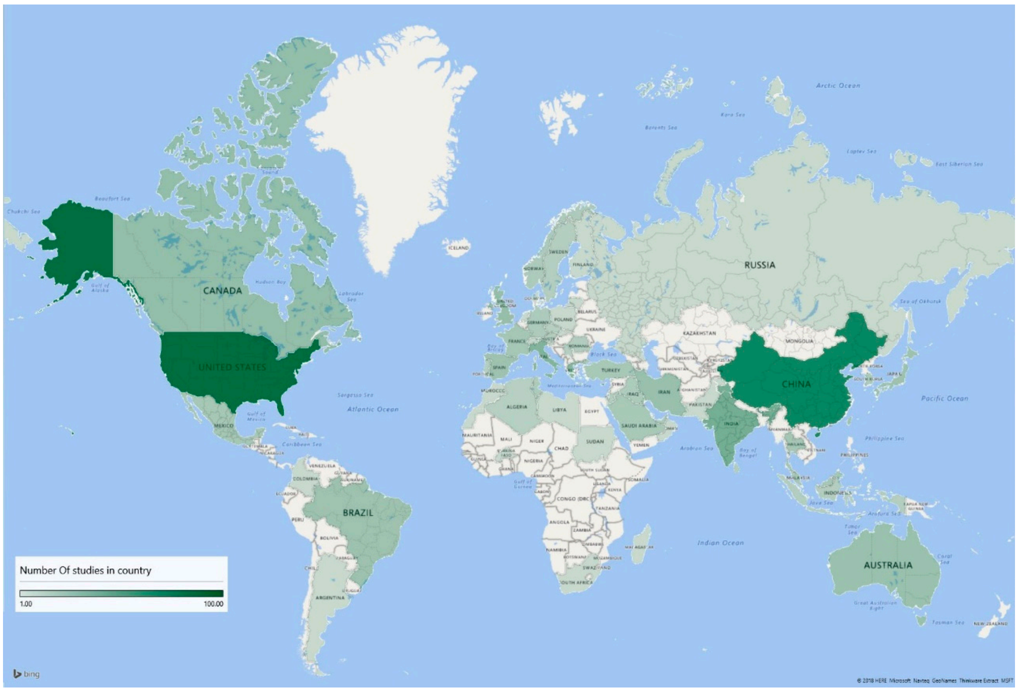

Figure 2. Number of papers from each country.

The earliest published record was for cool roof in 1930, followed by an insulated roof in 1970; the first paper about a wind catcher design was published in 1985; while skylight, roof garden, double skin roofs, and biosolar roofs started to be investigated in 2001, 2001, 2002, and 2007, respectively. All roofing methods have been mentioned in published papers during 2018, except concrete roofs which was published in 2017; this means that these methods are still receiving attention from researchers and there is still on-going investigation into them (Figure 3). Roof gardens, which was a trend in this last decade, have received the most attention from researchers, with 129 papers, followed by cool roofs, and photovoltaic roofs, with 117, and 95 papers respectively. Double-skin, skylight, and concrete roofs have the lowest number of published papers with 13, 22, and 24, respectively; while the others have around 50 publications (Figure 4). Energy and Buildings has been most active in this field by publishing 93 papers, followed by Building and Environment which published 38, while Renewable Energy, Applied Energy, and Energy Journals published slightly less than 20. Figure 5 shows the top 11 journals which published no less than six papers on this topic.

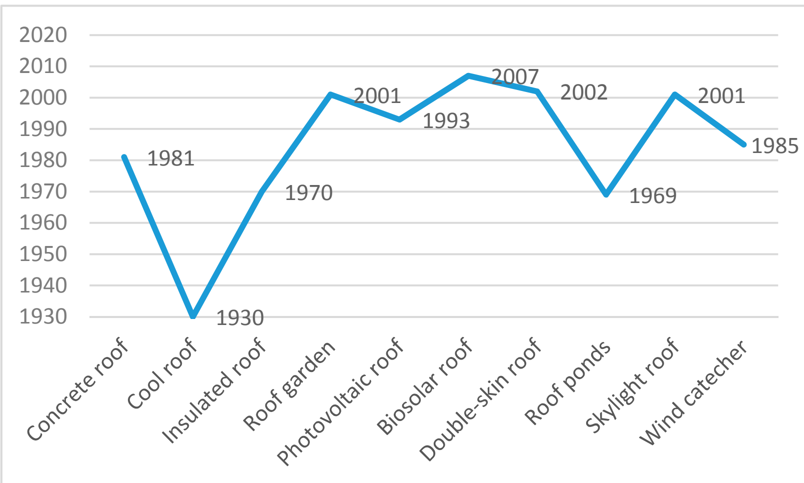

Figure 3. First paper published for each roof method.

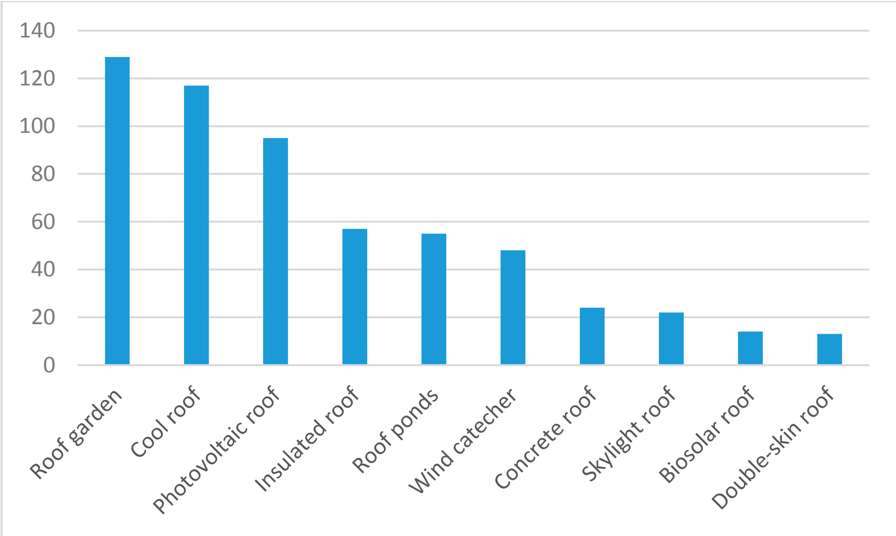

Figure 4. Number of papers published for each roofing method.

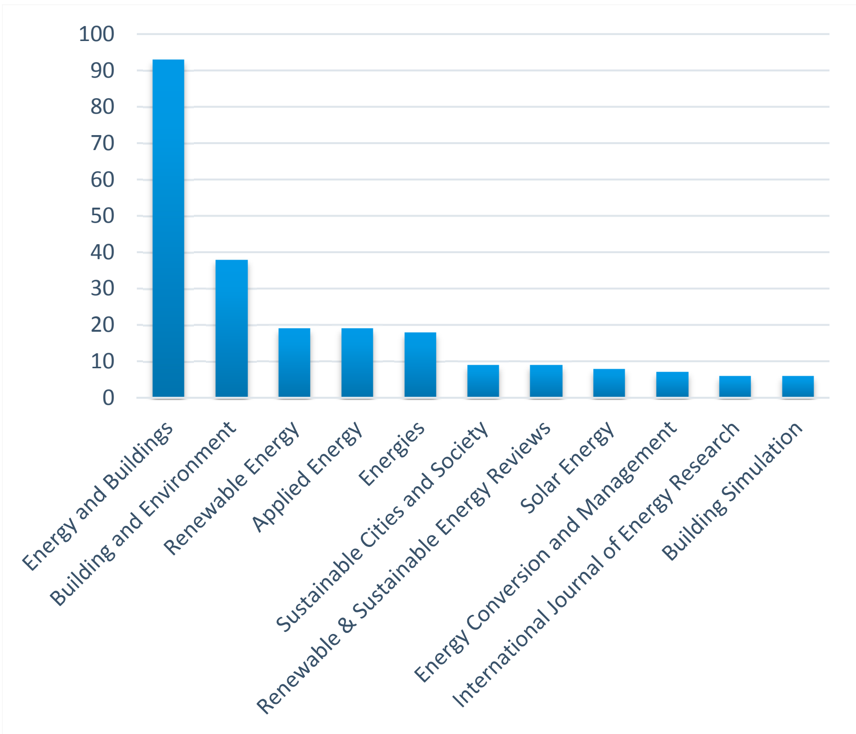

Figure 5. Number of papers published in relevant journals.

Although the majority of the papers provided case study, experimental, or simulation data, few papers conducted a comparison between two–four different roofing systems or a mix of two of them. Also, it was noted that researchers tended to conduct their experiments in a specific period such as summer time, while few studied the overall period during a year. These papers were further evaluated regarding data and results, climates, times cited, and the journal impact. Finally, the 87 most relevant papers are selected for the review. The following stage of this article reviews and deeply analyses data and results of the selected papers to find and evaluate the features of roofing methods, heat flux reduction, cost, maintenance, appropriate climate, and preferred buildings types. The final stage uses the outcome data from the second stage to conduct comparisons from different aspects, investigate their climatic applicability, and explore the possibility to introduce new methods.

3. Roofing Methods

Figure 6 illustrates these roofing methods, except for roof ponds, which are further divided into several sub-types in Figure 7. The following sections elaborate on them one by one.

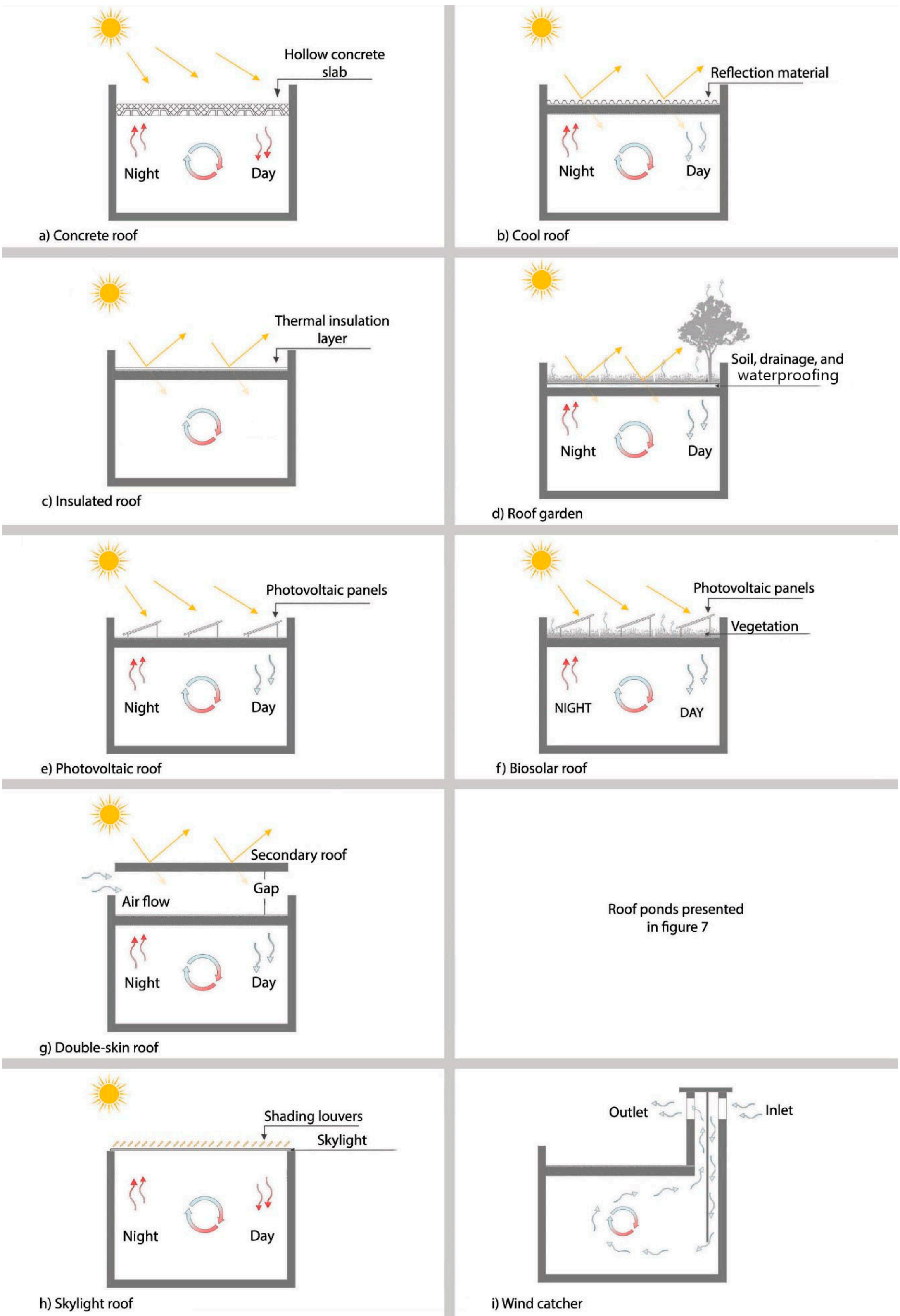

Figure 6. Main features of the reviewed roofing methods.

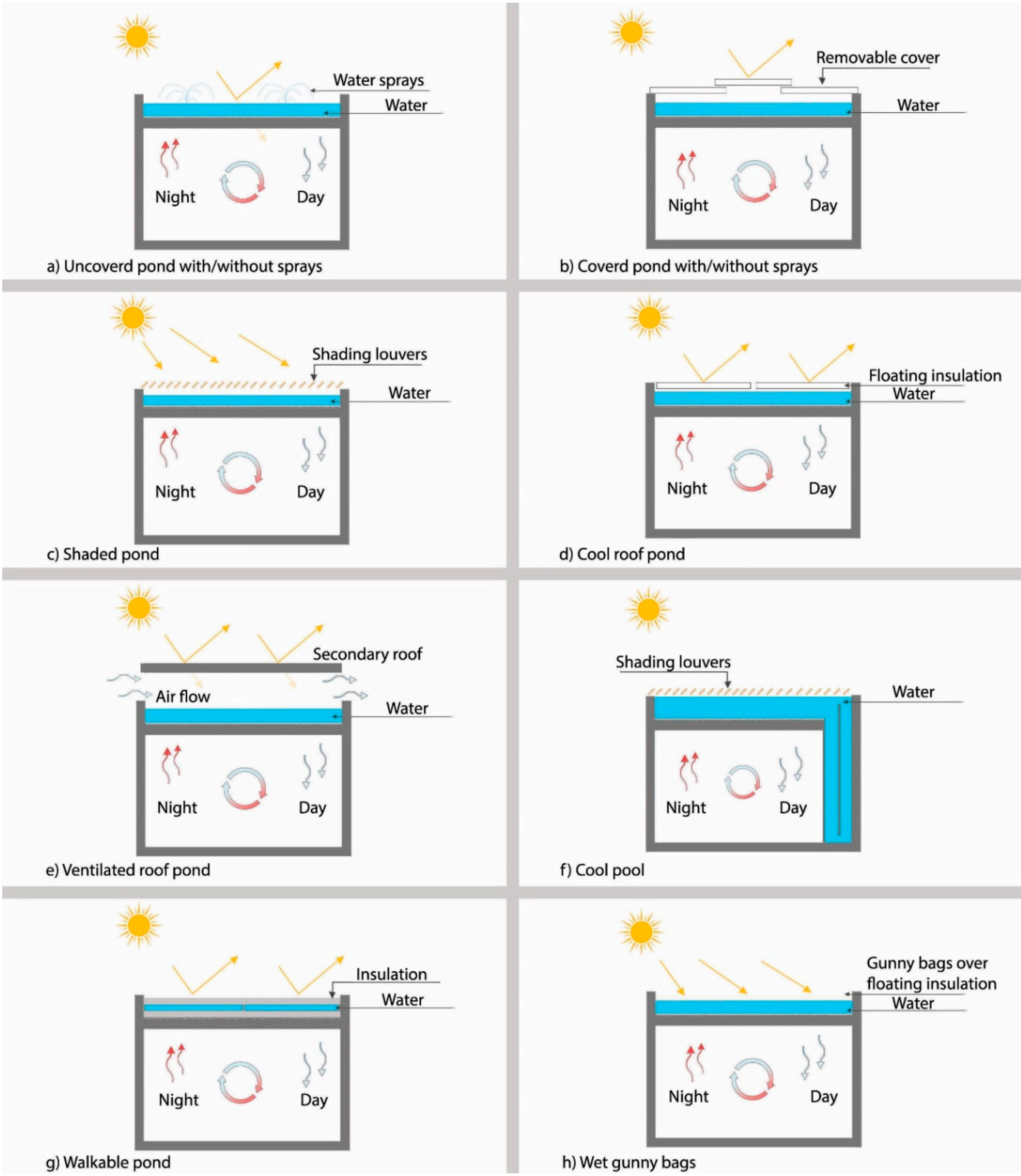

Figure 7. Roof ponds.

3.1. Concrete Roofs

Concrete slabs are one of the most important roofing methods. There are different structures, but the majority have high thermal conductivity. They absorb external heat in summer while thermal losses may occur in winter, which makes occupancy under these roofs thermally unstable and unbearable. Researchers have been trying to improve the concrete slabs by applying different treatments to these structures. Adding plastic waste and tires in the concrete mixture can reduce concrete heat gain by 10–19% without affecting its performance [7]. Rubberized concrete which can reduce the dead-load of roofs is also important [8]. Hollow concrete roofs can reduce thermal conductivity by 13.65–40.42% [9]. In addition, adding reflective coating and insulation layers to these slabs can reduce their thermal conductivity significantly [10], these two methods are discussed in more details in Sections 3.2 and 3.3. Some researchers have introduced the use of phase change material (PCM) which can absorb heating by a melting process before reaching internal spaces, thus reducing heat up to 40% [11]. Research conducted upon different climates and specifications of PCM have produced different outcomes; for instance, Alqallaf and Alawadhi [12] estimated that it reduced heat flux by 15.9–17.3%, and in Alexander and Gaurav's study and it could be reduced up to 100% in a Mediterranean climate [13].

3.2. Cool Roofs

By applying a reflective layer/coating over a roof slab, solar radiation can be reflected. Usually, this layer is white. When colours become darker, the reflectance decreases, and the superficial temperature becomes higher [14]. However, researchers have discussed the fact that dark colours can still be effective if they have a high reflectivity performance. This treatment is usually used for passive cooling, and it works well in hot climates such as arid and tropical climates. On the other hand this method has an energy penalty in cold days or the winter season, because it blocks passive heating at the building's roof and is not able to block heat loss from internal spaces though the roof slab, unless it is combined with thermal insulation. This method can reduce heat flux up to 33% [15]. The cool roof payback period is short compared with other methods which can be in two months [16]. In other climates, as mentioned before, it has an energy penalty towards heating loads, which was recorded in a Mediterranean climate, of about 12%, and 30% reduction in cooling [17]. Cool roofs, compared with photovoltaic panel roofs and roof gardens, maintains a lower surface temperature, which can improve the passive cooling during night time [18]. Careful selection of this method is needed when heating is highly required in a building, in order to evaluate its efficiency before applying it on the roofs of a building, and avoiding its negative impact on heating loads.

3.3. Insulated Roofs

Insulation is the most frequently used roofing method, and in many countries insulation is mandatory. However, in some cases the other passive cooling/heating methods can be more effective. Insulation performance depends on the material's thermal conductivity (k) and insulation layer thickness. Much research had been conducted to evaluate and test different materials and their thermal conductivity. In one such experience, Kumar and Suman [19] conducted an experimental evaluation of several materials, and they addressed their R-value. These values were used in Table 1 (In the columns headed with Kumar and Suman [19] values). In addition, calculation for total *R*-value, *U*-vale, and heat flux reduction effect was added. Calculation was conducted according to the assumption: basic roof section: 150 mm RCC (k = 1.26, R-value = 0.267 m^2k/W) + 50 mm mud phuska (k = 0.519) + 50 mm burnt clay brick tile (k = 0.798, R-value = 0.435 m^2k/W). R-value for insulation was calculated for 50 mm thickness.

Nandapala and Halwatura [20] introduced a system that can achieve a closer result by using the half thickness of insulation layer; in their system they used a 2.5 cm thickness of insulation layer over a slab, and then they placed a screed layer over the insulation with discontinuous concrete strips to support the system and to insure its stability. This insulation system can reach a heat reduction of up to 75% in a tropical climate. In Mediterranean climates another three materials were tested, which were polystyrene, rock wool, and fine white sand, and their results in heat reduction were 58.5%, 38.01% and 62% respectively [21,22]. They were tested during hot days, which means that they have similar effects in hot climates. If insulation is integrated with other techniques such as ventilation or a reflective layer, it could increase its efficiency up to 84% and 88% respectively [23,24]. Researchers have introduced vacuum panels as insulation layers, but experiments have concluded that they are less effective than traditional insulation and the payback period is about 17 years [25]. The environmental payback period is shorter than its economic payback period for insulation [26]. In addition, the economic payback varied regarding insulation material and its thickness, which can be 3.11–5.55 years [22,26].

Table 1. Reductions in Heat flux of different insulation materials.

Insulation Materials	R-Value 1 Insulation Materials	R-Value 2 RCC	R-Value 3 Mud Phuska	R-Value 4 Brick Tile	Resistance of the Inside Surface	Resistance of the Outside Surface	R-Total with Insulation	R-Total without Insulation	U-Value Total with Insulation	U-Value Total without Insulation	Reduce in Heat Flux %
	Kumar and Suman [19] values				Fixed values		Values calculated for this paper				
EPS (K = 0.035)	1.429	0.119	0.096	0.063	0.140	0.060	1.907	0.478	0.524	2.092	74.930
PUF (K = 0.027)	1.852	0.119	0.096	0.063	0.140	0.060	2.330	0.478	0.429	2.092	79.480
Foam concrete (K = 0.070)	0.714	0.119	0.096	0.063	0.140	0.060	1.192	0.478	0.839	2.092	59.910
Fiberglass (K = 0.040)	1.250	0.119	0.096	0.063	0.140	0.060	1.728	0.478	0.579	2.092	72.340
Styropor (K = 0.032)	1.558	0.119	0.096	0.063	0.140	0.060	2.036	0.478	0.491	2.092	76.520
Peripor (K = 0.028)	1.786	0.119	0.096	0.063	0.140	0.060	2.264	0.478	0.442	2.092	78.880
Neopor (K = 0.033)	1.511	0.119	0.096	0.063	0.140	0.060	1.989	0.478	0.503	2.092	75.960

3.4. Roof Gardens

Engaging vegetation in building roofs provides the building with several benefits such as fair insulation, passive cooling in summer and passive heating in winter, absorbing CO_2 from the surrounding environment during day time, improving air quality by producing O_2 and air filtration, improving space usage and storm water management. In addition, it provides urban heat island mitigation, and edible landscapes [27]. If the roof gardens are compared with other insulation materials, these insulation materials would excel in terms of price and efficiency. For hot climates roof gardens work well and can reduce heat flux by 31–37% [28–30]. The effect of passive cooling diminishes when the temperature rises, especially in arid climates where a 24–35% drop has been reported [31]. By adding insulation layer, reflective material, and ventilation to a roof garden, the heat flux can be reduced by up to 80% [32,33]. It has been proven that roof gardens can enhance the ventilation performance by 20% [34], and can be easily retrofitted if the building structure could host it. In the first zero energy building in Singapore, which was retrofitted from an existing building with a gross floor area of 4502 m^2, the estimated energy saving from adding a roof garden by using energy simulation was 70.2 (kWh/m^2/year) [35]. Moreover, the ambient air temperature reduced by 7 °C due to green roofs, and the surface temperature of the roof reduced by 24.5 °C compared with the existing case [36]. A roof garden's payback time is related to its components. If it is just a simple layer of waterproofing, soil and grass in a wet area, the payback would be about 10 years [37]. However, it would increase if it becomes intensively planted and needs a special structure and components; in this case it would reach 25–57 years [38]. The payback period in this method would be unfair if it is compared with others just from the energy saving perspective, due to many other benefits it can bring to the building and its value. Decision makers should take the multi-benefits into consideration. Passive heating of a roof garden during winter in tropical climates is reasonable [39], but in cold climates it may not be efficient enough to stand alone for this purpose, because it still can lose thermal energy in cold days [28]. In this case, integrating the roof garden with insulation can limit the loss of thermal energy and acquire more energy efficiency.

3.5. Photovoltaic Panel Roofs

Photovoltaic (PV) panels are a renewable energy source, and they are used in the roofs of buildings because of their ability to supply buildings with electricity and to reduce the reliance on fossil fuel energy consumption. They also have an indirect effect on a building's energy performance by providing shading under panels and absorbing solar radiation which contribute to the reduction of heat gains on roofs. The reduction of cooling loads due to photovoltaic panels shading differs depending on the type of roof insulation [40]. Heat flux can be reduced by 60–63% [40,41] compared with exposed roofs, while it has a lower effect if insulation is applied to the roof. The energy saving in some cases is around 6–7% in a tropical zone [42]. However, there would be an energy penalty if the building is in cold climates or in a cold winter season. In another experiment in a Mediterranean climate, when a conventional roof was compared with another roof with Photovoltaic Panels, 6.7% increase of heating loads has been recorded in winter; while in summer there were 17.8% decrease in cooling loads recorded [43]. Panels' materials, orientation, capacity, tilting degree, and roof finishing materials play direct roles in their efficiency and payback period, which can be 4–11 years [44–46]. Buildings location and orientation play an important role in PV production and energy efficiency in the buildings [47]. From the different climates, hot climates have more reward potential from investing in PV [48]. In addition, researchers have proven that electric and magnetic fields under photovoltaics are internationally accepted for public exposure [49].

3.6. Biosolar Roofs

The concept in this method is to combine a roof garden and PV panels which should be fixed over the plantation area. This is a new approach. Plants generated a slight improvement on PV performance [50] because the plants helped to lower the temperature under the PV which would improve its production by 1.2–5.3% [51–53]. The improvement becomes negligible if the temperature is higher than 25 °C [50], and it varies according to the type of planting and roof garden features. On the other hand, PV panels provide a comfortable environment for plants. One of the successful implementations for this method is Queen Elizabeth Olympic Park in London which improved the biodiversity of plants on the roof. Ninety-two species were recorded in this site [54]. This combination reduced the sensible heat flux up to 50% [18]. Careful selection and placement of plant species and ground cover are required to prevent their shading effect on PV panels.

3.7. Double-Skin Roofs

This method aims to reduce heat flux in building roofs by using double layers with a gap between them. The first layer works as a reflector/absorber for heat, and the second layer covers the internal spaces. The gap works as an insulation layer to prevent the heat transfer between the addressed layers. The thermal resistance for a double-skin roof is dynamic, due to the dynamic nature of air in the gap [55]. Researchers have suggested applying a reflective material on the first layer and adding more efficient insulation materials between the layers to improve its efficiency. A double-skin roof can be defined as a passive cooling method and it is suitable for hot climates. This method can reduce heat gains up to 71% as recorded in tropical climates [56]; it may be less efficient if the upper layer has less ability to absorb or reflect heat and its efficiency in this situation would drop to 25% [57]. The efficiency can be increased by up to 85% if a reflective layer is used in the upper slab [2,56,58]. No paper discussed the payback period for this method; however, it is likely to take a long time depending on the construction features of the secondary roof.

3.8. Roof Ponds

From different passive cooling techniques, evaporation has been classified the most efficient way to reduce temperature in internal spaces [59]. The process is to use the evaporation of water in order to reduce air stream temperature. Water naturally tends to absorb heat from ambient surroundings and converts it into vapour. This process allows the opportunity for the surrounding air temperature to be reduced [60]. This technique leads to the introduction of roof ponds which uses the same procedure and benefit from the heat exchange with a building's roof and walls, contributing in a reduction of their temperature and cooling down the temperature of the internal spaces. The concept of this method was firstly introduced by Hay and Yellot in 1978 [61]. There are several types of roof ponds. Figure 7 illustrates these ponds, and the following subsections elaborate on each of them.

3.8.1. Uncovered Ponds with/without Sprays

An uncovered pond is the easiest to install and simplest method in roof ponds. It is a pond over a roof exposed to ambient conditions; the recommended depth for this method is 30 cm. It can cool down the temperature by exchanging the heat with the roof slab and using the natural physics for water to cool down the ambient temperature and evaporation. The disadvantage of this method is that water inside it gains heat from solar radiation, because it is exposed. It causes a fluctuation in water temperature of about 5 °C. If sprays are added to this method, they can increase its efficiency, and in this way it could reduce heat flux up to 55% in a tropical climate by using 10 cm water layer over a slab and compared with a conventional slab, both of which had 10 cm roofing construction [62]. In another experiment it was up to 40% in an arid climate by using sprays with shallow water compared with a conventional roof in Saudi Arabia which usually had 30 cm roof thickness [63].

3.8.2. Covered Ponds with/without Sprays

This method is simply a pond over a roof slab with a movable cover. The cover caps the pond during the day time to prevent water from being heated by solar radiation, and the cover is removed during the night time to help water to cool down from ambient temperature and evaporation.

This system's performance in cooling can be improved if spray sprinklers have been added [64]. The performance for this system with sprays is able to reduce heat flux up to 66% with water filling 10–15 cm [61].

3.8.3. Shaded Ponds

Providing a shading device over a roof pond would reduce or cut off solar radiation from heating the water. The shading device should allow water to be exposed to wind. The shading device could be similar to a horizontal curtain, or it can be an elevated metal or concrete roof. This system can maintain the internal temperature below 30 °C when the ambient temperature is over 40 °C [65]. This method is applied on concrete slabs; if it is applied over a metal slab, it is called a Skytherm roof, which has almost the same performance [65].

3.8.4. Cool Roof Ponds

A cool roof pond is a roof pond with a floating insulation. It is made by adding water over a roof slab which should be treated to be water proof, then adding an insulation layer over the water, and supplying this system with sprinklers and a pump. It is operated at night time, to spread water over the insulation panels which can cool down ambient temperature and evaporation, and it is returned to the pond through the insulation joint [66]. To improve exchange with internal spaces the cool water may be sent through large fan coils in the internal spaces. When the temperature exceeded 37 °C this system was able to keep the internal temperature at about 26 °C [66].

3.8.5. Ventilated Roof Ponds

This method integrates the double-skin roof and a roof pond, which prevents solar radiation from heating the water in the pond and improves the evaporation by ventilation process [66]. This roof can maintain the internal temperature at 24 °C, even if the ambient temperature exceeds 40 °C [66].

3.8.6. Cool Pools

A cool pool is a shaded roof pond on a roof connected with storage pipes in a building. The cool water which has been cooled in the pool from the ambient environment and evaporation flows in these pipes downward inside the building and it exchanges the thermal energy with air in internal spaces by evaporation and radiation. Then the heated water from the building flows again towards the pool to be re-cooled and complete the cycle [67]. This technique can provide passive cooling to spaces underneath floors. The efficiency of this method is higher than that a shaded pond. If it is used in well insulated spaces it can keep temperatures between 20–25 °C in a hot ambience; even though the temperature exceeds 38 °C, it can reduce cooling loads by 100%. Also it can be used as passive heating, but its running cost is not convenient compared with the other techniques available [67].

3.8.7. Walkable Ponds

A walkable bond is a sandwich method with two layers of insulation and between them a layer of water with a depth of around 3 cm, allowing a thermosyphonic, passive heat exchange circulation [65]. In this process the roof is still usable and there is no water to prevent use of the roof. The average indoor temperature in this method can be 28 °C when the ambient temperature fluctuates between 30–42 °C [65].

3.8.8. Wet Gunny Bags

This method uses gunny bags, which are placed over a floatable material. The gunny bags are used in this method as mediators between ambient temperature and a roof slab. It reduces or prevents solar radiation and disposes of the heat gained from internal spaces, and it can be used with a shallow depth on a concrete roof of approximately 5 cm. The efficiency of this method is slightly greater than the covered pond [68].

3.9. Skylight Roofs

The purpose of this roof is to provide indoor spaces with lighting to improve their internal comfort, to reduce lighting energy consumption, and to improve interaction between internal and external spaces. Usually it is used in buildings when the lighting from side windows is not enough in the day time. Using skylights has a direct effect on thermal loads inside a building. Therefore, special treatment is needed when selecting this roof to ensure that it does not affect the building in a negative way and increase the total energy consumption. Skylight performance differs by different glass treatment or shading devices. Some experiments have been conducted to decrease the thermal conductivity of skylights. For instance, integrating roof evaporative cooling with a skylight was highly efficient [69], and injecting PCM materials into the gap in double glazed glass can reduce heat flux up to 47.5% and the payback for PCM material can be about 3.3 years [70]. Although increasing PCM layer thickness can improve its thermal efficiency, it reduces its light transmission, so a balance of benefits is needed when selecting this method. There are vast choices of glass types and treatments. However, the limited literature available has included the effect of these different types and treatments using a skylight. Rezaei et al. [71] had conducted a review of different glazing types, technologies, and materials, which can be a start point for further studies to evaluate their impacts on the HVAC system and lighting energy loads by using them in skylights. A case study by Nasersharifi and Assadi [72] for arid climates showed that skylights can save 20% of lighting energy loads, and the payback period can be 19.75 years [73]. Li et al. conducted research in a subtropical climate by applying semi-transparent PV over the glass to improve its efficiency, but this increased its payback period to 23 years [74]. Motamed and Liedl [75] conducted a study on a small office in a Mediterranean climate in order to study the skylight areas on roofs and evaluate their benefits. They concluded that in order to achieve energy efficiency the ratio of a skylight should be 3–14% of the roof area, while 10%–14% is the optimal ratio to achieve energy efficiency and acquire adequate lighting.

3.10. Wind Catchers

Wind catchers were developed many decades ago as a part of a traditional architecture in arid climates in the Middle East in order to improve the internal thermal environment by allowing the natural flow of air. They have been improved and are currently useful in modern architecture. The mechanism depends on the natural movement of air between the different pressures in the internal and external spaces. Air and cold breeze are trapped from the roof and diverted through a channel down to the building's interiors. It is usually combined with a spray system or wet porous layer to adjust the air temperature by evaporation and to filter the air as well. This method differs from the others, and it is not related to heat flux through the roof, but it can be combined with other methods to improve the internal comfort and reduce cooling loads naturally. Usually, it is used for passive cooling, however; researchers have introduced concepts to integrate it with other systems, so that it can be used in passive heating if required [76]. Wind speed has an essential impact on its efficiency. It improves until wind speed reaches 3 m/s; more than this will decrease its efficiency. Researchers suggested controlling air speed to achieve better performance [77]. In hot-humid climates regardless of the temperature fluctuation ranging from 24.7 °C to 40 °C, the internal temperature could stay comfortable [78]. Wind capture can reduce energy consumption in cooling loads by 16–27% in the hottest hours [79], and it was recorded in Iran in a hot and dry climate that it can reduce the internal temperature by 10–20 °C [80]. The cost of adding this method is not high and the payback can be in 1.3 years [81].

3.11. Other Roofing Methods

There are other roofing methods which can provide passive cooling/heating and some of these methods have a similar features to the reviewed methods. As an example, for porous roof tiles, which absorb water from rainfalls or other sources, the same principles of water evaporation will lead to heat reduction under this roofing method [82]. This method can reduce the external surface temperature by up to 11.3 °C in a subtropical climate [82], and in another experiment the temperature can be decreased 6.4 °C and 3.2 °C, for external and internal roof surfaces respectively. Besides this, the cooling loads reduces up to 14.8% [83]. In addition, other methods and effects can be acquired by integrating two or more of the reviewed methods. Some of these integrations and their energy efficiency will be presented in the next section.

4. Comparison

4.1. Suitability of Roofing Methods for Different Climates

Climate conditions play an essential role in selecting the roofing method and any selected method should respect a building's needs to adapt to weather conditions. Table 2 summarises the climatic applicability of the roofing methods in terms of six climate zones. In hot climates especially tropical, sub-tropical, and arid climates, passive cooling performance should be prioritize over insulation [84], due to its ability to prevent heating from solar radiation during the day and enable passive cooling during the day and night and; while insulation helps to reduce heat gain into slabs and it does not allow cooling during the night time. However, if a building is exposed to cold days the energy of heating should be evaluated; under this circumstance, the building may have an energy penalty from the passive cooling techniques [17]. In tropical and arid climates, the benefit from passive cooling is significant; while roof insulation is more applicable in cold climates to improve thermal stability inside buildings and to reduce energy consumption needed to heat internal spaces. Akyuz et al. [26] concluded that applying thermal insulation on a roof can decrease heat loss by up to 56% in a Mediterranean climate compared to a conventional roof. Over all, hot climates such as arid, topical, and sub-tropical need more cooling, so passive cooling methods are more applicable. Mediterranean and Temperate climates have changeable needs for cooling and heating due to the fluctuating weather; under this circumstance a passive cooling/heating methods have a slight impact on the total building energy during the whole year period; hence, methods with insulation or insulation combined with passive methods, have positive impact on buildings in these zones. Mountains and polar climates have very cold days throughout the year. For these climates, insulation is the optimal solution. These roofing methods can be constructed during the construction process of the project or they can be retrofitted. In order to exploit and evaluate the benefits of the retrofit, there are three key steps which should be taken into consideration: energy auditing, building simulation and measurement, and verification [85].

Table 2. A roofing method's impact on different Climates (P = positive, N = negative and F = fair).

Roofing Methods	Arid	Mediterranean	Mountains	Polar	Temperate	Tropical
Concrete roof	N	N	N	N	N	N
Cool roof	P	F	N	N	N	P
Insulated roof	F	P	P	P	P	F
Roof garden	P	P	N	F	F	P
Photovoltaic roof	P	P	N	N	N	P
Biosolar roof	P	P	N	F	F	P
Double-skin roof	P	P	N	N	N	P
Roof ponds	P	F	N	N	N	P
Skylight roof	N	N	N	N	N	N
Wind catcher	P	P	N	N	N	P

4.2. Comparing the Impact on Heat Gain Reduction

The investigated roofing methods differ in their performance and ability of heat gain reduction, which has a direct impact on cooling loads inside buildings. Reduction of heat flux from roofs has the same value of reduction of cooling energy. Some of the investigated methods exceed the benefit of just reducing the heat flux, and they deliver full adaptation for internal spaces without using mechanical systems in hot climates such as a cool pool, and wind catcher. The garden roof with reflective materials, insulated roofs with ventilation, double-skin with cool roof, insulated roof with reflective layer, and cool pool have great rates of heat flux reduction, which has been addressed in many studies. Ventilated roof ponds and walkable ponds create a good reduction in internal temperature compared with outdoor ambient temperature, which means they have high reduction of heat flux as well. If sky lights have a low U-value and are supported with a shading device or reflective layer, they will lead to better heat flux reduction. Their effects on thermal energy gained compared with conventional roofs are summarised in Table 3.

4.3. Comparing Payback Periods

Few papers addressed the payback period of each roofing method, and some of them differed in the predicted payback periods due to materials used and other factors such as project type, size, location, and climate. While every method can have a special period to payback its cost, Figure 8 shows the average economic payback period for these methods. The addressed period could be longer according to factors mentioned above. Although the roof ponds payback periods are not available, it can be concluded that the payback period for simple systems is short due to their simplicity. Usually, the payback period refers to the economic benefit, and most of the papers mentioning the payback period discussed the financial saving from using these roofing methods. On the other hand, the environmental payback period (which starts from manufacturing until the fitting in a building) is very important in achieving sustainability however unfortunately, few papers mentioned it. This needs further investigation.

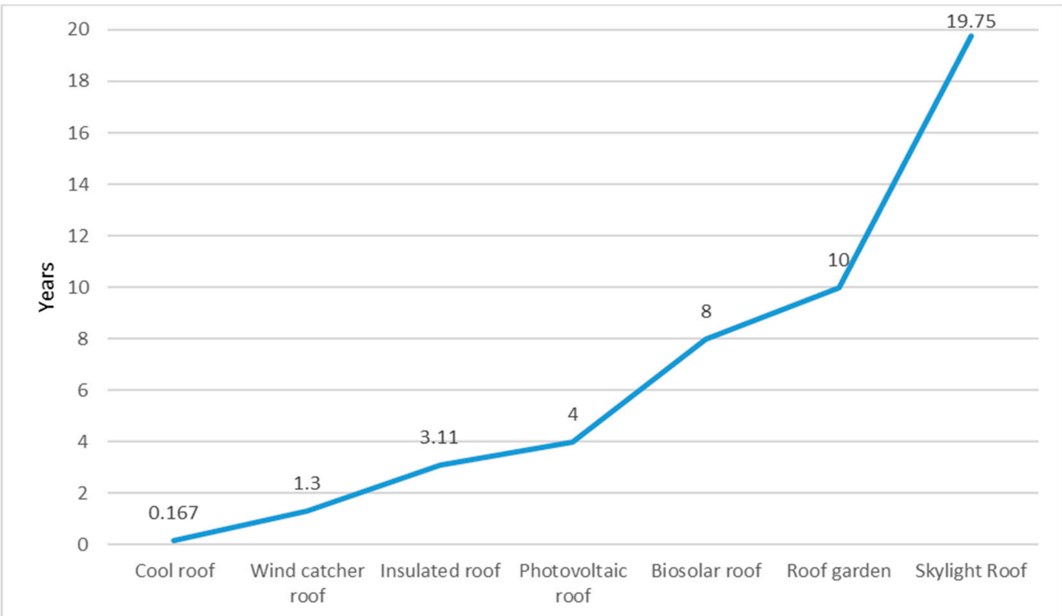

Figure 8. Payback periods in years for roofing methods.

Table 3. Comparison between the different roofing methods, the percentage of heat gain reduction, and the reduced temperature inside the building (N/A = not available).

Roofing Methods	Heat Gained Reductions %	Temperature Reduction Under Roof °C	References	Climates	Methods	Details
Skylight roof	N/A	N/A	N/A	-	-	-
Wind catcher	-	20	[80]	Arid	Simulation	Two-storey building with/without wind catcher
Ventilated roof pond	N/A	16	[66]	Arid	Physical experiment	Large room, 3 × 4 m, with well insulated walls and concrete roof
Walkable pond	N/A	14	[66]	Arid	-	-
Cool roof pond	N/A	11	[66]	Tropical	Physical experiment	3 × 3 m pond, with a depth of 60 cm.
Shaded pond	N/A	10	[65]	Tropical	-	
Cool pool	100	N/A	[67]	Hot summer of a Mediterranean climate	Physical experiment	Well insulated room
Insulated with reflective layer	88	N/A	[24]	Laboratory	Laboratory experiment	Using a halogen lamp as a heating source
Double-skin with cool roof	85	N/A	[2]	Tropical	Simulation	Standard house in Djibouti
Insulated with ventilation	84	N/A	[23]	Tropical	Physical experiment	Twelve-storey residential building
Roof garden with reflective material	80	N/A	[32]	Tropical	Physical experiment	5 m^2 lawn on top of a four-storey building
Roof garden with ventilation	79	N/A	[33]	Three different hot climates	Physical experiment	Two cells with dimensions of 1.3 m × 1.0 m × 0.9 m
Insulated roof	75	N/A	[20]	Tropical	Simulation and Physical experiment	Physical model
Double-skin roof	71	N/A	[56]	Tropical	Physical experiment	Twelve-storey naturally ventilated residential building
Covered pond with/without sprays	66	N/A	[61]	Hot and humid climates	Physical experiment	Two cells with dimensions of 3.0 m × 3.0 m × 2.45 m
Wet gunny bags	66	N/A	[68]	Arid	Physical experiment	Shallow ponds measuring internally 117 × 117 × 22 cm over a roof of a building in campus
Photovoltaic roof	63	N/A	[40]	Hot summer of a Mediterranean climate	Measurements	Building partially covered by PV
Uncovered pond with/without sprays	55	N/A	[62]	Tropical	Physical experiment	Two-storey building using 1.2 m × 1.2 m × 0.2 m reservoir
Biosolar	50	N/A	[18]	Hot summer of a Mediterranean climate	Simulation	US Department of Energy benchmark buildings
Hollow concrete	40	N/A	[9]	Hot climates in China	Simulation and Physical experiment	Physical model
Concrete with PCM	40	N/A	[11]	Arid	Simulation	Common building roof
Roof garden	37	N/A	[29]	Tropical	Simulation	Institutional building model
Cool roof	33	N/A	[15]	Hot summer of different climates	Simulation	Global climate model
Concrete with waste plastic and tires	19	N/A	[7]	Laboratory	Laboratory experiment	Using hot-box

5. Discussion

There are many features of these roofing methods which should be known during the selection process; for instance: whether the method provides passive cooling/heating and whether it needs mechanical operation. Table 4 summarises the main features for each roofing method. The investigated methods differ in their energy performance. Some can increase thermal resistance of the roof slab to improve its insulation and reduce the heat flux; some can reflect solar radiation to protect the slab from acquiring heat; and others can cool the slab by exchanging heat with water through evaporation.

Each one of the reviewed methods can acquire a sustainable effect in a specific circumstance, while in other situations, they may generate a negative impact and reduce energy efficiency. For instance, the different passive cooling roofing methods can achieve significant heat reduction results in hot climates, which save energy. However, using passive cooling roofing methods in cold climates have negative impacts and generate an energy penalty. Some buildings can achieve the targeted sustainability from using more than one method, however, there is usually one method that is most ideal for a specific building. Hence, before applying the selected roofing method on a building, some factors should be taken into consideration. One of the most important factors is the building type and function, while other factors also play an important role in the selection process, such as the owner's need, the project's budget, and the architectural approach. For instance, in the case of industrial buildings, warehouses, and sheds which have a light roof structure with no need to use their roofs, a cool roof or a light weight roof pond is highly recommended. Roof gardens or biosolar roofs have a great potential to increase the value of buildings and deliver more spaces for people to spend more time with nature, so buildings which can provide accessibility to the roof, such as residential, public, commercial, and some governmental buildings, have a great potential for these methods. With buildings that consume large amounts of electricity, and have a free area on their rooftop which is unusable or inaccessible, such as educational or governmental buildings, a photovoltaic panel roof is a highly recommended option. With buildings which need a stable indoor temperature without fluctuation, such as a laboratory or chemical storage buildings, insulation is highly recommended. Buildings with large spans need more lighting, because the lighting provided from facades is not enough to achieve passive lighting. With these types of buildings or with buildings that require solid walls, the use of skylights is highly recommended. Some roof ponds can reduce building cooling loads up to 100%, which classifies them as good selections for different types of buildings, if these buildings can host them on their roofs. A wind catcher is an adjustable method which can be turned off when it is not needed, and it provides effective cooling, which makes it a recommended method for different types of buildings. Finally, meeting a balance of all the addressed factors and evaluating the short and long terms benefits during the selection process are essential factors in selecting the right choice.

In addition, a wide implementation of roofing methods such as, roof garden in city can lead to a significant enhancement in mitigating urban heat, making this an excellent strategy in managing the extreme heat [86]. Moreover, cool roofs can be a viable and cost-effective strategy for mitigating the city-scale urban heat island effect if it is applied on city-wide scale [87]. This kind of implementations may enhance the probability of precipitation toward the outskirt of the city [88]. Furthermore, both green and cool roofs may reduce horizontal and vertical wind speeds, as well as vertical mixing during day time and lower atmosphere dynamics, which lead to a stagnation of air near the surface, potentially causing air quality issues [89]. The implementation of above strategies are dependent on political will and commitment [90], and should carefully consider the potential negative impacts [89].

Table 4. The roofing methods' main features (P = positive, N = negative, H = high and L = low).

Roofing Methods	Passive Cooling	Passive Heating	Impact on Hot Days	Impact on Cold Days	Cost	Maintenance	Easy to Construct or Retrofit	Cool More than One Floor	Impact on Ambient
Biosolar	Yes	Yes	P	P	H	H	Yes	No	P
Photovoltaic roof	Yes	No	P	N	H	L	Yes	No	P
Photovoltaic roof with ventilation	Yes	No	P	N	H	L	Yes	No	P
Photovoltaic roof with cool roof	Yes	No	P	N	H	L	Yes	No	P
Concrete with waste plastic and tires	No	No	P	P	L	-	No	No	-
Hollow concrete	No	No	P	P	L	-	Yes	No	-
Concrete with PCM	No	No	P	-	H	-	No	No	-
Cool roof	Yes	No	P	N	L	L	Yes	No	P
Double-skin roof	Yes	No	P	N	H	L	No	No	-
Double-skin with cool roof	Yes	No	P	N	H	L	No	No	P
Roof garden	Yes	Yes	P	P	H	H	Yes	No	P
Roof garden with reflective material	Yes	No	P	-	H	H	Yes	No	P
Roof garden with ventilation	Yes	Yes	P	P	H	H	Yes	No	P
Insulated roof	No	No	P	P	L	-	Yes	No	-
Insulated roof with ventilation	Yes	No	P	P	L	L	Yes	No	P
Insulated roof with reflective layer	Yes	No	P	P	L	-	Yes	No	P
Skylight roof	No	Yes	N	N	H	L	No	No	-
Cool pool	Yes	No	P	N	H	L	No	Yes	P
Cool roof pond	Yes	No	P	N	L	L	Yes	No	P
Covered pond with/without sprays	Yes	No	P	N	L	L	Yes	No	P
Shaded pond	Yes	No	P	N	H	-	Yes	No	P
Uncovered pond with/without sprays	Yes	No	P	N	L	L/-	Yes	No	P
Ventilated roof pond	Yes	No	P	N	H	-	No	No	P
Walkable pond	Yes	No	P	N	L	-	No	No	P
Wet gunny bags	Yes	No	P	N	L	-	Yes	No	P
Wind catcher	Yes	No	P	-	L	-	Yes	Yes	-

6. Conclusions

This paper has reviewed 10 roofing methods, which can be applied on flat roofs during the construction stage or as a retrofit. Their principles are explained, and their main features are summarized in tables, to give designers and decision makers a better understanding of each method. These systems' performances in reducing heat flux, and payback periods in hot climates have been discussed. In hot climates, designers should use passive cooling methods with low R-value due to their ability to provide higher energy performance; in Temperate and Mediterranean climates, insulation or insulation combined with passive cooling methods are preferred; in Polar and Mountain climates, insulation is the ideal selection. Moreover, cool pool, ventilated roof pond, and wind catcher can help stabilize a building's indoor temperature on hot days and they can reduce cooling loads up to 100%; roof gardens have the highest positive impact on the environment with passive heating on cold days and passive cooling on hot days; it can reduce the cooling loads up to 37%, and the reduction can be up to 80% if it is integrated with reflective material and ventilation; cool roof and uncovered pond have a reasonable heat gain reduction, which can be up to 33% and 55% respectively, with a short payback period; photovoltaic panels' roof is a sensible solution to reduce the fossil fuel energy consumption for a building and it also has a valuable heat reduction, which can be up to 63%. Finally, a skylight with thermal treatment is an ideal selection if the building has a deficit of natural light.

The possibility of integration of these roofing methods should be explored. For example, combining a roof garden with roof ponds can generate a new roofing method, such as a water garden roof, which would be worthy of further investigation; photovoltaic panels can be used as a secondary slab for double-skin roofs; in dry climates, dry gardens can be used to replace wet gardens to reduce the reliance on irrigation. These suggested methods need further studies to investigate their performance and benefits.

Author Contributions: Methodology; formal analysis; investigation; data curation; writing—original draft preparation; visualization; and project administration; were done by M.A. In addition, conceptualization; writing—review; and editing were done by M.A. and Z.G. Moreover, validation; and supervision; was done by Z.G. Finally, resources were provided by Griffith University.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

R-value	thermal resistance
U-value	thermal transmittance
K	thermal conductivity
R-total	sum of all R-values in the different layers of a construction component, in this case, a roof slab
RCC	reinforced cement concrete
PV	photovoltaic
PCM	phase change material

References

1. Su, B.; Aynsley, R. Roof Thermal Design for Naturally Ventilated Houses in a Hot Humid Climate. *Int. J. Vent.* **2009**, *7*, 369–378. [CrossRef]
2. Omar, A.I.; Virgone, J.; Vergnault, E.; David, D.; Idriss, A.I. Energy Saving Potential with a Double-Skin Roof Ventilated by Natural Convection in Djibouti. *Energy Procedia* **2017**, *140*, 361–373. [CrossRef]
3. Kreith, F.; Manglik, R.M.; Bohn, M.S. *Principles of Heat Transfer*; Cengage Learning: Stamford, CT, USA, 2010.
4. Level. Passive Design. In *How Insulation Works*; BRANZ Ltd.: Porirua, New Zealand, 2017.
5. Heat Loss from Homes. Available online: https://www.haringey.gov.uk/environment-and-waste/going-green/green-home-improvements/heat-loss-homes (accessed on 10 December 2018).
6. Stay Warm. Available online: https://www.actsmart.act.gov.au/quick-tips/energy_saving/stay_warm (accessed on 10 December 2018).
7. Yesilata, B.; Isiker, Y.; Turgut, P. Thermal insulation enhancement in concretes by adding waste PET and rubber pieces. *Constr. Build. Mater.* **2009**, *23*, 1878–1882. [CrossRef]
8. Najim, K.B.; Fadhil, O.T. Assessing and improving the thermal performance of reinforced concrete-based roofing systems in Iraq. *Energy Build.* **2015**, *89*, 213–221. [CrossRef]
9. Shi, G.Z.; Li, L.P.; Song, C.F.; Cheng, S.M.; Tao, W.Q.; He, Y.L. 3D numerical thermal optimization of the roofs constructed with cast-in-situ hollow concrete floor system by finite volume method. *Energy Build.* **2016**, *131*, 142–152. [CrossRef]
10. Xaman, J.; Cisneros-Carreno, J.; Hernandez-Perez, I.; Hernandez-Lopez, I.; Aguilar-Castro, K.M.; Macias-Melo, E.V. Thermal performance of a hollow block with/without insulating and reflective materials for roofing in Mexico. *Appl. Therm. Eng.* **2017**, *123*, 243–255. [CrossRef]
11. Alawadhi, E.M.; Alqallaf, H.J. Building roof with conical holes containing PCM to reduce the cooling load: Numerical study. *Energy Convers. Manag.* **2011**, *52*, 2958–2964. [CrossRef]
12. Alqallaf, H.J.; Alawadhi, E.M. Concrete roof with cylindrical holes containing PCM to reduce the heat gain. *Energy Build.* **2013**, *61*, 73–80. [CrossRef]
13. Thiele, A.M.; Jamet, A.; Sant, G.; Pilon, L. Annual energy analysis of concrete containing phase change materials for building envelopes. *Energy Convers. Manag.* **2015**, *103*, 374–386. [CrossRef]
14. Han, J.; Lu, L.; Yang, H.X. Investigation on the thermal performance of different lightweight roofing structures and its effect on space cooling load. *Appl. Therm. Eng.* **2009**, *29*, 2491–2499. [CrossRef]
15. Oleson, K.W.; Bonan, G.B.; Feddema, J. Effects of white roofs on urban temperature in a global climate model. *Geophys. Res. Lett.* **2010**, *37*. [CrossRef]
16. Zhang, Z.J.; Tong, S.S.; Yu, H.B. Life Cycle Analysis of Cool Roof in Tropical Areas. *Procedia Eng.* **2016**, *169*, 392–399. [CrossRef]
17. Androutsopoulos, A.V.; Stavrakakis, G.M.; Damasiotis, M. Cool Roof Impacts on a School-Building Thermal and Energy Performance in Athens, Greece. *Procedia Environ. Sci.* **2017**, *38*, 178–186. [CrossRef]
18. Scherba, A.; Sailor, D.J.; Rosenstiel, T.N.; Wamser, C.C. Modeling impacts of roof reflectivity, integrated photovoltaic panels and green roof systems on sensible heat flux into the urban environment. *Build. Environ.* **2011**, *46*, 2542–2551. [CrossRef]
19. Kumar, A.; Suman, B.M. Experimental evaluation of insulation materials for walls and roofs and their impact on indoor thermal comfort under composite climate. *Build. Environ.* **2013**, *59*, 635–643. [CrossRef]
20. Nandapala, K.; Halwatura, R. Design of a durable roof slab insulation system for tropical climatic conditions. *Cogent Eng.* **2016**, *3*. [CrossRef]

21. Pisello, A.L.; Pignatta, G.; Castaldo, V.L.; Cotana, F. Experimental Analysis of Natural Gravel Covering as Cool Roofing and Cool Pavement. *Sustainability* **2014**, *6*, 4706–4722. [CrossRef]
22. Daouas, N.; Hassen, Z.; Aissia, H.B. Analytical periodic solution for the study of thermal performance and optimum insulation thickness of building walls in Tunisia. *Appl. Therm. Eng.* **2010**, *30*, 319–326. [CrossRef]
23. Tong, S.S.; Li, H.; Zingre, K.T.; Wan, M.P.; Chang, V.W.C.; Wong, S.K.; Toh, W.B.T.; Lee, I.Y.L. Thermal performance of concrete-based roofs in tropical climate. *Energy Build.* **2014**, *76*, 392–401. [CrossRef]
24. Alvarado, J.L.; Terrell, W.; Johnson, M.D. Passive cooling systems for cement-based roofs. *Build. Environ.* **2009**, *44*, 1869–1875. [CrossRef]
25. Alam, M.; Singh, H.; Suresh, S.; Redpath, D.A.G. Energy and economic analysis of Vacuum Insulation Panels (VIPs) usedin non-domestic buildings. *Appl. Energy* **2017**, *188*, 1–8. [CrossRef]
26. Akyuz, M.K.; Altuntas, O.; Sogut, M.Z. Economic and Environmental Optimization of an Airport Terminal Building's Wall and Roof Insulation. *Sustainability* **2017**, *9*, 1849. [CrossRef]
27. He, B.; Zhu, J. Constructing community gardens? Residents' attitude and behaviour towards edible landscapes in emerging urban communities of China. *Urban For. Urban Green* **2018**, *34*, 154–165. [CrossRef]
28. D'Orazio, M.; Di Perna, C.; Di Giuseppe, E. Green roof yearly performance: A case study in a highly insulated building under temperate climate. *Energy Build.* **2012**, *55*, 439–451. [CrossRef]
29. Yang, J.; Pyrgou, A.; Chong, A.; Santamouris, M.; Kolokotsa, D.; Lee, S.E. Green and cool roofs' urban heat island mitigation potential in tropical climate. *Sol. Energy* **2018**, *173*, 597–609. [CrossRef]
30. Bevilacqua, P.; Mazzeo, D.; Bruno, R.; Arcuri, N. Experimental investigation of the thermal performances of an extensive green roof in the Mediterranean area. *Energy Build.* **2016**, *122*, 63–79. [CrossRef]
31. Mahmoud, A.S.; Asif, M.; Hassanain, M.A.; Babsail, M.O.; Sanni-Anibire, M.O. Energy and Economic Evaluation of Green Roofs for Residential Buildings in Hot-Humid Climates. *Buildings* **2017**, *7*, 30. [CrossRef]
32. Liang, H.H.; Huang, K.T. Study on rooftop outdoor thermal environment and slab insulation performance of grass planted roof. *Int. J. Phys. Sci.* **2011**, *6*, 65–73.
33. Jiang, L.; Tang, M.F. Thermal analysis of extensive green roofs combined with night ventilation for space cooling. *Energy Build.* **2017**, *156*, 238–249. [CrossRef]
34. Ran, J.D.; Tang, M.F. Effect of Green Roofs Combined with Ventilation on Indoor Cooling and Energy Consumption. *Energy Procedia* **2017**, *141*, 260–266. [CrossRef]
35. Sun, X.; Gou, Z.; Lau, S.S.-Y. Cost-effectiveness of active and passive design strategies for existing building retrofits in tropical climate: Case study of a zero energy building. *J. Clean. Prod.* **2018**, *183*, 35–45. [CrossRef]
36. Wong, N.H.; Tan, E.; Seng, A.K.; Mok, S.; Goh, A. Performance of greenery systems in zero energy building of Singapore. In Proceedings of the International Conference on Sustainable Design and Construction (ICSDC), Kansas City, MI, USA, 23–25 March 2011.
37. Chan, A.L.S.; Chow, T.T. Energy and economic performance of green roof system under future climatic conditions in Hong Kong. *Energy Build.* **2013**, *64*, 182–198. [CrossRef]
38. Refahi, A.H.; Talkhabi, H. Investigating the effective factors on the reduction of energy consumption in residential buildings with green roofs. *Renew. Energy* **2015**, *80*, 595–603. [CrossRef]
39. Jim, C.Y. Passive warming of indoor space induced by tropical green roof in winter. *Energy* **2014**, *68*, 272–282. [CrossRef]
40. Dominguez, A.; Kleissl, J.; Luvall, J.C. Effects of solar photovoltaic panels on roof heat transfer. *Sol. Energy* **2011**, *85*, 2244–2255. [CrossRef]
41. Ban-Weiss, G.; Wray, C.; Delp, W.; Ly, P.; Akbari, H.; Levinson, R. Electricity production and cooling energy savings from installation of a building-integrated photovoltaic roof on an office building. *Energy Build.* **2013**, *56*, 210–220. [CrossRef]
42. Chenvidhya, T.; Seapan, M.; Parinya, P.; Wiengmoon, B.; Chenvidhya, D.; Songprakorp, R.; Limsakul, C.; Sangpongsanont, Y.; Tannil, N. Investigation of power values of PV rooftop systems based on heat gain reduction. In *Reliability of Photovoltaic Cells, Modules, Components, and Systems Viii*; International Society for Optics and Photonics: Bellingham, WA, USA, 2015.
43. Kapsalis, V.; Karamanis, D. On the effect of roof added photovoltaics on building's energy demand. *Energy Build.* **2015**, *108*, 195–204. [CrossRef]

44. Hayat, M.; Shahnia, F.; Arefi, A.; Iu, H.; Fernando, T. Comparison of the Economic Benefits and the Payback Periods of Rooftop Solar Panels in Australia. In Proceedings of the 2017 3rd International Conference on Power Generation Systems and Renewable Energy Technologies (Pgsret), Johor Bahru, Malaysia, 4–6 April 2017; pp. 113–117.
45. Buker, M.S.; Mempouo, B.; Riffat, S.B. Performance evaluation and techno-economic analysis of a novel building integrated PV/T roof collector: An experimental validation. *Energy Build.* **2014**, *76*, 164–175. [CrossRef]
46. Mittelman, G.; Alshare, A.; Davidson, J.H. A model and heat transfer correlation for rooftop integrated photovoltaics with a passive air cooling channel. *Sol. Energy* **2009**, *83*, 1150–1160. [CrossRef]
47. Kylili, A.; Fokaides, P.A. Investigation of building integrated photovoltaics potential in achieving the zero energy building target. *Indoor Built Environ.* **2014**, *23*, 92–106. [CrossRef]
48. Emziane, M.; Al Ali, M. Performance assessment of rooftop PV systems in Abu Dhabi. *Energy Build.* **2015**, *108*, 101–105. [CrossRef]
49. Safigianni, A.S.; Tsimtsios, A.M. Electric and Magnetic Fields Due to the Operation of Roof Mounted Photovoltaic Systems. In Proceedings of the PIERS Proceedings, Stockholm, Sweden, 12–15 August 2013; pp. 1908–1911.
50. Nagengast, A.; Hendrickson, C.; Matthews, H.S. Variations in photovoltaic performance due to climate and low-slope roof choice. *Energy Build.* **2013**, *64*, 493–502. [CrossRef]
51. Chemisana, D.; Lamnatou, C. Photovoltaic-green roofs: An experimental evaluation of system performance. *Appl. Energy* **2014**, *119*, 246–256. [CrossRef]
52. Lamnatou, C.; Chemisana, D. Photovoltaic-green roofs: A life cycle assessment approach with emphasis on warm months of Mediterranean climate. *J. Clean. Prod.* **2014**, *72*, 57–75. [CrossRef]
53. Alshayeb, M.J.; Chang, J.D. Variations of PV Panel Performance Installed over a Vegetated Roof and a Conventional Black Roof. *Energies* **2018**, *11*, 1110. [CrossRef]
54. Nash, C.; Clough, J.; Gedge, D.; Lindsay, R.; Newport, D.; Ciupala, M.A.; Connop, S. Initial insights on the biodiversity potential of biosolar roofs: A London Olympic Park green roof case study. *Isr. J. Ecol. Evol.* **2016**, *62*, 74–87. [CrossRef]
55. Zingre, K.T.; Yang, E.H.; Wan, M.P. Dynamic thermal performance of inclined double-skin roof: Modeling and experimental investigation. *Energy* **2017**, *133*, 900–912. [CrossRef]
56. Zingre, K.T.; Wan, M.P.; Wong, S.K.; Toh, W.B.T.; Lee, I.Y.L. Modelling of cool roof performance for double-skin roofs in tropical climate. *Energy* **2015**, *82*, 813–826. [CrossRef]
57. Krarti, M. Roof Cover Impact on Cooling Energy Use of Office Buildings. In Proceedings of the Asme 8th International Conference on Energy Sustainability, Boston, MA, USA, 30 June–2 July 2014.
58. Lai, C.M.; Huang, J.Y.; Chiou, J.S. Optimal spacing for double-skin roofs. *Build. Environ.* **2008**, *43*, 1749–1754. [CrossRef]
59. Amer, E.H. Passive options for solar cooling of buildings in arid areas. *Energy* **2006**, *31*, 1332–1344. [CrossRef]
60. Chan, H.-Y.; Riffat, S.B.; Zhu, J. Review of passive solar heating and cooling technologies. *Renew. Sustain. Energy Rev.* **2010**, *14*, 781–789. [CrossRef]
61. Rincón, J.; Almao, N.; González, E. Experimental and numerical evaluation of a solar passive cooling system under hot and humid climatic conditions. *Sol. Energy* **2001**, *71*, 71–80. [CrossRef]
62. Yang, W.S.; Wang, Z.Y.; Zhao, X.D. Experimental investigation of the thermal isolation and evaporative cooling effects of an exposed shallow-water-reserved roof under the sub-tropical climatic condition. *Sustain. Cities Soc.* **2015**, *14*, 293–304. [CrossRef]
63. Al-Turki, A.M.; Zaki, G.M. Energy saving through intermittent evaporative roof cooling. *Energy Build.* **1991**, *17*, 35–42. [CrossRef]
64. Tiwari, G.N.; Kumar, A.; Sodha, M.S. Cooling by Water Evaporation over Roof–Review. *Energy Convers. Manag.* **1982**, *22*, 143–153. [CrossRef]
65. Spanaki, A.; Tsoutsos, T.; Kolokotsa, D. On the selection and design of the proper roof pond variant for passive cooling purposes. *Renew. Sustain. Energy Rev.* **2011**, *15*, 3523–3533. [CrossRef]
66. Givoni, B. Indoor temperature reduction by passive cooling systems. *Sol. Energy* **2011**, *85*, 1692–1726. [CrossRef]

67. Ponni, M.M.; Baskar, R. Comparative study of different types of roof and indoor temperatures in tropical climate. In Proceedings of the 2nd PALENC Conference and 28th AIVC Conference on Building Low Energy Cooling and Advanced Ventilation Technologies in the 21st Century, Crete, Greece, 27–29 September 2007; pp. 530–536.
68. Runsheng, T.; Etzion, Y.; Erell, E. Experimental studies on a novel roof pond configuration for the cooling of buildings. *Renew. Energy* **2003**, *28*, 1513–1522. [CrossRef]
69. Pagliarini, G.; Rainieri, S. Dynamic thermal simulation of a glass-covered semi-outdoor space with roof evaporative cooling. *Energy Build.* **2011**, *43*, 592–598. [CrossRef]
70. Li, D.; Wu, Y.Y.; Zhang, G.J.; Arici, M.; Liu, C.Y.; Wang, F.Q. Influence of glazed roof containing phase change material on indoor thermal environment and energy consumption. *Appl. Energy* **2018**, *222*, 343–350. [CrossRef]
71. Rezaei, S.D.; Shannigrahi, S.; Ramakrishna, S. A review of conventional, advanced, and smart glazing technologies and materials for improving indoor environment. *Sol. Energy Mat. Sol. Cells* **2017**, *159*, 26–51. [CrossRef]
72. Nasersharifi, Y.; Assadi, M.K. Skylight Application for Natural Lighting in a Building; the University of Tehran Branch of Melli Bank Case Study. In Proceedings of the 4th International Conference on Production, Energy and Reliability, Kuala Lumpur, Malaysia, 3–5 June 2014.
73. Motamedi, S. Energy Analysis of Toplighting Strategies for Office Buildings in Austin. 2012. Available online: https://repositories.lib.utexas.edu/handle/2152/20030 (accessed on 11 September 2018).
74. Li, D.H.W.; Lam, T.N.T.; Cheung, K.L. Energy and cost studies of semi-trans parent photovoltaic skylight. *Energy Convers. Manag.* **2009**, *50*, 1981–1990. [CrossRef]
75. Motamedi, S.; Liedl, P. Integrative algorithm to optimize skylights considering fully impacts of daylight on energy. *Energy Build.* **2017**, *138*, 655–665. [CrossRef]
76. Suleiman, S.; Himmo, B. Direct comfort ventilation. Wisdom of the past and technology of the future (wind-catcher). *Sustain. Cities Soc.* **2012**, *5*, 8–15. [CrossRef]
77. Noroozi, A.; Veneris, Y.S. Thermal Assessment of a Novel Combine Evaporative Cooling Wind Catcher. *Energies* **2018**, *11*, 442. [CrossRef]
78. Priya, R.S.; Sundarraja, M.C.; Radhakrishnan, S. Experimental study on the thermal performance of a traditional house with one-sided wind catcher during summer and winter. *Energy Effic.* **2012**, *5*, 483–496. [CrossRef]
79. Hedayat, Z.; Belmans, B.; Ayatollahi, M.H.; Wouters, I.; Descamps, F. Performance assessment of ancient wind catchers—An experimental and analytical study. *Energy Procedia* **2015**, *78*, 2578–2583. [CrossRef]
80. Haghighi, A.P.; Pakdel, S.H.; Jafari, A. A study of a wind catcher assisted adsorption cooling channel for natural cooling of a 2-storey building. *Energy* **2016**, *102*, 118–138. [CrossRef]
81. Mostafaeipour, A.; Bardel, B.; Mohammadi, K.; Sedaghat, A.; Dinpashoh, Y. Economic evaluation for cooling and ventilation of medicine storage warehouses utilizing wind catchers. *Renew. Sustain. Energy Rev.* **2014**, *38*, 12–19. [CrossRef]
82. Zhang, L.; Zhang, R.; Zhang, Y.; Hong, T.; Meng, Q.; Feng, Y. The impact of evaporation from porous tile on roof thermal performance: A case study of Guangzhou's climatic conditions. *Energy Build.* **2017**, *136*, 161–172. [CrossRef]
83. Zhang, L.; Zhang, R.; Hong, T.; Zhang, Y.; Meng, Q. Impact of post-rainfall evaporation from porous roof tiles on building cooling load in subtropical China. *Appl. Therm. Eng.* **2018**, *142*, 391–400. [CrossRef]
84. Sodha, M.S.; Singh, S.P.; Kumar, A. Thermal performance of a cool-pool system for passive cooling of a non-conditioned building. *Build. Environ.* **1985**, *20*, 233–240. [CrossRef]
85. Sun, X.G.Z.; Lu, Y.; Tao, Y. Strengths andWeaknesses of Existing Building Green Retrofits: Case Study of a LEED EBOM Gold Project. *Energies* **2018**, *11*, 1936. [CrossRef]
86. Sharma, A.; Woodruff, S.; Budhathoki, M.; Hamlet, A.F.; Chen, F.; Fernando, H.J.S. Role of green roofs in reducing heat stress in vulnerable urban communities—A multidisciplinary approach. *Environ. Res. Lett.* **2018**, *13*, 094011. [CrossRef]
87. Li, D.; Bou-Zeid, E.; Oppenheimer, M. The effectiveness of cool and green roofs as urban heat island mitigation strategies. *Environ. Res. Lett.* **2014**, *9*, 055002. [CrossRef]
88. Song, J.; Wang, Z.H.; Wang, C. The Regional Impact of Urban Heat Mitigation Strategies on Planetary Boundary Layer Dynamics Over a Semiarid City. *J. Geophys. Res.* **2018**, *123*, 6410–6422. [CrossRef]

89. Sharma, A.; Conry, P.; Fernando, H.J.S.; Hamlet, A.F.; Hellmann, J.J.; Chen, F. Green and cool roofs to mitigate urban heat island effects in the Chicago metropolitan area: Evaluation with a regional climate model. *Environ. Res. Lett.* **2016**, *11*. [CrossRef]
90. He, B.-J.; Zhao, D.-X.; Zhu, J.; Darko, A.; Gou, Z.-H. Promoting and implementing urban sustainability in China: An integration of sustainable initiatives at different urban scales. *Habitat. Int.* **2018**. [CrossRef]