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Building climate control by means of passive systems

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Abstract

Nowadays the growth of the cities increased built and paved areas, energy use and heat generation. The phenomenon of urban warming, called urban heat island, influences negatively outdoor comfort conditions, pollutants concentration, energy demand for air conditioning, as well as increases environmental impact due to the demand of energy generation. Indoor air temperature depends on a combination of several different parameters related to the climate of the region, the building itself and its use. The main parameters influencing the microclimate are: external air temperature and relative humidity, incident solar radiation, long wave radiation exchange between the structure and its surroundings, incidence and speed of the wind, air exchanges, physical and thermal properties of the building's envelope materials, design variables such as building dimensions and orientation, presence of artificial light, and electrical equipment. In the Mediterranean region the main problem is to control the solar heat gain that increases building's temperature during the hot season. Solar heat is transferred to the internal air through the envelope by the heat transfer mechanisms as conduction, convection and radiation. Solar heat can be reduced by increasing the insulation between the exterior and interior of the building, shading the building surface from direct sun exposure, by using an adequate building's envelope materials or by using green roofs and walls. The use of green roofs and walls can contribute to mitigate the phenomenon of heat island, the emissions of greenhouse gases, and the storm water runoff affecting human thermal comfort, air quality and energy use of the buildings. Aim of this paper is to describe the benefits, the design requirements and plants, and the heat transfer mechanism of green roofs and walls. Green roofs and green vertical systems can be used as passive energy savings systems because they intercept solar radiation by the vegetation, provide thermal insulation by the vegetation and substrate, occur evaporative cooling by evapotranspiration from the plants and the substrate, and influence the effect of the wind on the building.

Keywords: air-conditioning, energy savings, green roofs, green walls, microclimate, urban heat island

1 Introduction

Nowadays, cities are characterized by higher urban air temperature in comparison to the air temperatures of the surrounding suburban and rural areas, with a difference that can be up to 5.6°C (Rowe, 2011; Santamouris, 2012; Kanechi, et al., 2014). This phenomenon, known as “Urban Heat Island” (UHI), is mainly due to city surfaces, made with non-reflective and water-resistant construction materials, that absorb a high percentage of the incident solar radiation, which is released as heat. Other additional causes of the UHI effect are: the decrease of urban vegetated areas with a reduction of shades and radiation interception, the reduced ability of the emitted infrared radiation to escape in the atmosphere, the scattered and emitted radiation from atmospheric pollutants to the urban area, the non-circulation of air in urban canyons, incidence and speed of the wind, and the production of waste heat from cooling systems, from industrial processes and motorized vehicular traffic (Santamouris, 2012).

UHI influences negatively outdoor comfort conditions, pollutants concentration, as well as induces a more use of air conditioning systems with an increasing of energy consumption for cooling and a raise of peak electricity demand (Karlessi et al., 2009; Karlessi et al., 2011). A sustainable technology for improving the energy efficiency of buildings is the use of green roofs and green walls in order to reduce the energy consumption for air conditioning in summer and to increase the thermal insulation in winter (Cheng et al., 2010; Jim and Tsang, 2011; Köhler and Poll, 2010; Perini et al., 2011; Pérez et al., 2011).

Nowadays a worldwide growing interest in urban green is encouraging the application of the greening technology for more sustainable buildings (Berardi et al., 2014; Fernandez-Caňero et al., 2013; Santamouris, 2012). Green roofs and green vertical systems can be used as passive energy savings systems because they intercept solar radiation by the vegetation, provide thermal insulation by means of the vegetation and substrate, occur evaporative cooling by evapotranspiration from the plants and the substrate, and influence the effect of the wind on the building (Perez at al., 2011). It is reported a worldwide surface of 234 ha of green roofs and walls, in Italy there are about 1000 m2 of green roofs while in Germany about 13.5 km2 of roofs are vegetated, equal to 14% of all flat roofs (Castleton et al., 2010). In the Mediterranean region, where the climate is characterized by limited water, the diffusion of green technology is limited due to a lack of knowledge of its benefits and characteristics, and by the lack of governmental incentives (Fernandez-Caňero et al., 2013).

The aim of this research is to develop a feasibility study in order to define materials, energetic parameters, suitable plant species and options for the green roofs and green walls, and to collect existing performance data and scientific information on construction, maintenance, costs and plant systems. The research carried out is part of a research activity in progress at the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) to explore the potential of green technology as sustainable and innovative tools for improving energy efficiency by the use of “green insulation” of buildings, and their contribute to aesthetic and eco-urban life in the cities.

2 Benefits

Rooftop and wall gardening offer several benefits both on the roof/facade itself, on the building and on its surrounding urban environment, as well as social, environmental and aesthetical benefits depending on the climatic conditions of the area, on the greening technology design, on the building characteristics and on the urban context (Fioretti et al., 2010; Castleton et al., 2010; Wong et al., 2003; Perini et al., 2011; Wong et al., 2010; Berardi et al., 2014; Santamouris, 2012; Benvenuti, 2014; Rowe, 2011; Kohler, 2008; Francis and Lorimer, 2011; Fernandez-Caňero et al., 2013). The benefits on the green roof/facade are: extension of roof/facade life, thermal insulation of the green roof/wall, reduction of solar absorbance, reduction of the noise. The benefits on the buildings are: reduction of energy consumption, improvement of the internal comfort due to a reduction of the surface temperature and the attenuation of temperature fluctuations, reduction of heat load, acoustic comfort enhancement, increase in property values, implementation of spaces for recreation and amenity. The benefits at a larger scale are: energy consumption reduction (decreasing cooling and heating loads); urban heat island effect decreasing; water management improving (enhancement of stormwater management, of water run-off quality, of urban hydrology, of the use of rainwater); air pollution mitigation (enhancing urban air quality, filtering airborne particles, reducing dust and heavy metal accumulation in air); sound absorption (sound insulation and noise

absorption). Moreover roof greenery and vertical planting contribute to ecological preservation due to their capacity to help urban biodiversity acting as habitat for colonizing species such as spontaneous plant species, weeds, spiders, beetles, ants, bees and birds and so on.
The lifetime of green roofs can be approximately beyond 50 years (Berardi et al., 2014; Getter et al., 2009; Rowe, 2011), because the roofs are protected by the growing substrate and plant canopy from ultraviolet radiation and from the temperature fluctuations between night and day (Rowe, 2011). Vertical gardens could damage the wall they are covering but, at the same time, they protect the exterior finishes and masonry from ultra violet radiation, rain, extreme temperature fluctuations and presence of moisture.
Roof greenery and vertical planting are useful to provide thermal insulation, keeping buildings cool during the warm season and warm during the cold season, thus resulting in energy savings for air-conditioning (Fernandez-Caňero et al., 2013; Berardi et al., 2014; Santamouris, 2012; Benvenuti, 2014; Kanechi, et al., 2014; Blanusa et al., 2013). Green roofs and green walls can reduce the indoor air temperature in function of the climatic conditions, the green technology used, the type of plants, and the building and materials characteristics (Santamouris, 2012; Berardi et al., 2014). Green technology will play an insulating role in non-insulated buildings rather than in insulated ones; the better the insulation of the building, the lower the contribution of the vegetated roof and wall (Berardi et al., 2014; Santamouris, 2012; Blanusa et al., 2013). If the energy load is due to the heat transfer through opaque surfaces of the buildings, vegetative technology may reduce significantly heating and cooling loads (Santamouris, 2012), with an expected reduction of the annual energy load varying between 1% and 40% (Santamouris, 2012). Vegetation can contribute to insulate buildings due to the depth of the substrate, to transpiration of water through plant stomata, and to shading (Blanusa et al., 2013).
Green roofs and vertical gardens provide stormwater attenuation and delay runoff in order to mitigate the problem of peak flows helping the water to flow toward the drains (Kohler and Poll, 2010; Cameron et al., 2012; Rowe, 2011). Vegetation intercept intense precipitation holding water temporarily within their canopy: water retained in the substrate will evaporate by plants or will be transpired back into the atmosphere (Rowe, 2011; IGRA, 2014). Runoff is reduced from 50% to 100% in function of the type of greening technology used, plant species, roof slope, substrate composition and depth, preexisting substrate moisture, and the intensity and duration of the rain event (Rowe, 2011; IGRA, 2014). Besides, the retained runoff contribute to microclimatic cooling and to the mitigation of the urban heat island effect (Kohler and Poll, 2010). The greening of buildings can have a positive effect on water quality of runoff absorbing and filtering pollutants; water quality will be influenced by the substrate composition and depth, plant type, characteristics and age of the roof, fertilization and maintenance practices, the magnitude of the rain event, local pollution sources, and the physical and chemical properties of the pollutants (Rowe, 2011).
Greening technology can reduce air pollution directly and indirectly (Berardi et al., 2014; Fernandez-Caňero et al., 2013; Rowe, 2011). Lowering surface temperatures will contribute to a reduction of building energy consumption and of the urban heat island effect that would indirectly result in air pollution mitigation (Berardi et al., 2014; Rowe, 2011). Vegetated building roofs and surfaces act as biofilters, absorbing some contaminant, removing pollutants and retaining particles suspended in the air (Fernandez-Caňero et al., 2013). Plants remove gaseous air pollutants through leaf stomates, intercept particular matter with their leaves, and break down organic compounds such as poly-aromatic hydrocarbons in the plant tissues or in the soil (Rowe, 2011). One square meter of vegetated area can absorb the particulate matter emissions of one car emitted during one year (Rowe, 2011). The greatest quantity of pollutants are removed when plants are actively growing and in-leaf while the lowest rate of removal occurred when plants are dormant (Rowe, 2011).
The greening of buildings can contribute to sound absorption and noise insulation (Berardi et al., 2014; Rowe, 2011), reducing sound reflection by up to 3 dB and improving sound insulation by up to 8 dB (IGRA, 2014). Roof greenery and vertical planting considerably decrease the noises due to the high absorption coefficient of the vegetation layer. Vegetation in combination with the growing substrates will absorb sound and electromagnetic waves better than a hard surface (Rowe, 2011; IGRA, 2014).

Green roofs and vertical gardens can promote and increase biodiversity in the area acting as a natural habitat for invertebrates, birds, weeds and plants (Fernandez-Caňero et al., 2013).

3 Classification and design of greening technology

The greening of building can be achieved with green roofs and/or green vertical systems. The design of green roofs and walls depends on the characteristics of the buildings and on the climatic conditions of the area.

Green roofs are classified as intensive, semi-intensive and extensive green roof based on vegetation type, on the thickness of substrate layer, on the maximum load bearing capacity of the roof, on the walkability use of the roof, on the type of irrigation system used, and on the initial and maintenance costs required (Fioretti et al., 2010; Castleton et al., 2010; Spala et al., 2008; Berardi et al, 2014; Fernandez-Caňero et al., 2013;Santamouris, 2012; IGRA, 2014).

Intensive green roofs, designed as recreation space with small trees, shrubs and hard-scapes, generally require both substrate depths greater than 15 cm and regularly maintenance (Rowe, 2011). Intensive green roofs require a reinforced structure due to their heavy weight (200-500 kg/m^2) (Fernandez-Caňero et al., 2013); drainage and irrigation systems must generally be utilized increasing the technical complexity and costs (Berardi et al., 2014).

Extensive green roofs are used for roofs with little load bearing capacity as ecological protection layer. Plants as grasses, herbaceous perennials, annuals, and drought tolerant succulents can be used (Rowe, 2011). The extensive green roofs, with a substrate layer up to 20 cm, are characterized by a weight up to 150 kg/m^2 (Fernandez-Caňero et al., 2013); they require low level of maintenance, low initial costs, no irrigation systems.

Semi-intensive solutions are middle way systems (IGRA, 2014).

The types of green roofs influence the energy performance and storm water management potentials: low for extensive green roofs and better for intensive roofs (Berardi et al., 2014).

Green roofs are designed as complex layered structure that includes plants, growing medium, a drainage layer, a filter membrane layer, a root barrier layer, and a waterproofing layer (Fioretti et al., 2010; Spala et al., 2008; Berardi et al., 2014; Kanechi et al., 2013; Rowe, 2011). A waterproofing membrane is located on the top of the roof deck in order to prevent the entering of the moisture inside the building (Fioretti et al., 2010; Spala et al., 2008). Above this membrane, a root barrier layer is set in order to protect the roof construction and the waterproofing membrane from being damaged by roots (Fioretti et al., 2010). A drainage layer, made of light-weight materials such as rubber, plastic, gravel, lava, expanded clay or clay tiles, is placed next in order to carry excess runoff to roof drains. Depending on the design and the material, the drainage layer can have additional functions such as water storage, enlargement of the root zone, and space for aeration of the system (IGRA, 2014). A filter fabric, preferably made of geo-textiles such as fleece or other woven materials, is installed to separate the plant and substrate layers from the drainage layer below in order to prevent soil from washing away (Fioretti et al., 2010). The growing medium, characterized by good physic-chemical properties that enhanced plant growth, high water holding capacity, high nutrient-retaining capacity, and lightweight, complete the green roof (Kanechi et al., 2013). Growing substrate can be realized with lava, pumice, expanded clay, expanded schist, and clay tiles (IGRA, 2014). Plants can be established directly upon the green roof media via seed, plugs, and cuttings or plants can be pre-grown at ground level on a blanket, mat, or tray and then placed on the roof. An irrigation system can be placed within or above the growing medium (Berardi et al., 2014).

Green vertical systems are classified as green facades and living wall (Perez at al., 2011; Perini et al., 2011; Francis and Lorimer, 2011; Jim and He, 2011; Kontoleon and Eumorfopoulou, 2010); the green vertical systems, as green roofs, can be intensive, semi-intensive and extensive (Perez at al., 2011).

Green facades are made with climbing vegetation, rooted in the ground at the base of the building or in pots located at different heights of the façade, that is trained to grow directly on wall surfaces or to cover free-standing supporting structures (Perez at al., 2011; Francis and Lorimer, 2011; Kontoleon and Eumorfopoulou, 2010). The limits of this greening technology

are the limited space at the ground level and the potential for vertical growth of the plant species; 20 m is the maximum height of most climbing plants (Kohler, 2008). Green facades can be divided into: traditional green facades, where plants growth directly on the wall; double-skin green or green curtain, with the aim of creating a double-skin or green curtain separated from the wall; perimeter flowerpots, with plants planted around the building to constitute a green curtain (Perez at al., 2011).
The growth of climbing plants directly on walls can damage walls or create an obstacle during building renovation (Kontoleon and Eumorfopoulou, 2010). A technological solution to this problem can be the use of modular trellises, wired structures and mesh structures as support for climbing plants (Perez at al., 2011; Kontoleon and Eumorfopoulou, 2010). Trellis metal modules, made from a welded steel wire that supports plants with both a face grid and a panel depth, can be mounted on the wall or on independent structures with multiple supports that permits the maintenance and integrity of the building; they provide a restricted growing environment for plant foliage (Perez at al., 2011; Kontoleon and Eumorfopoulou, 2010). Wired structures are obtained both with high-tensile steel cables, anchorages, separators and other items and with a wire-rope net system, that being more flexible provides a greater degree of design applications than cables (Kontoleon and Eumorfopoulou, 2010). Cables are used to support faster growing climbing plants with a denser foliage while wire-nets are used to support plants that grow slower (Kontoleon and Eumorfopoulou, 2010). Mesh frames are made with steel mesh anchored to the building (Perez at al., 2011).
Living walls are made of modular panels, sometimes pre-cultivate, which are fixed to a vertical support or on the wall structure; each panel contains growing medium, such as soil, felt, perlite, etc, and a water delivery system (Perez at al., 2011; Perini et al., 2011; Francis and Lorimer, 2011; Kontoleon and Eumorfopoulou, 2010).
Green façades will be realized using hardy and robust plant species able to support their growth with minimal intervention needing a relatively simple irrigation system. Living wall systems, supporting a great variety of plant species characterized by different density, require more reliable irrigation, intensive maintenance and protection than green facades (Kontoleon and Eumorfopoulou, 2010).
Green walls can be realised or using modular trellises, wired structures or mesh structures as support for climbing plants or mounting an hanging structure or a frame onto any vertical surface such as a wall, fence or balcony of the building; there is a gap between the frame and the building. A PVC sheet and a waterproof membrane are installed and then felt is used as a rooting medium for the plants. Modular panels containing a lightweight soil-less growing media in which a variety of plants can grow. A hydroponic watering system is placed to ensure water and nutrients on a regular basis.

4 Energy fluxes in green roofs and walls

Aim of the green wall or roof is to reduce solar energy absorbed by the wall/roof by screening the exposed surface and to increase thermal insulation; this allows the reduction of the energy demand for air conditioning used to reduce high temperatures in the warm periods.
Figure 1 shows the energy fluxes occurring in the green roof/wall system, and the symbols used in this figure are shown in Table 1. Heat is exchanged by means of conduction (C), convection (A) and radiation (E in the solar range and R in the long wave infrared range); solar radiation (Es) increases energy of the whole system, thus a reduction of the solar transmissivity of the plant wall results in a decrease of the temperature inside the building. Solar transmissivity of the plant wall mainly depends on the percentage of building surface covered with the plants. When the plants wall strongly reduces solar transmissivity, heat transfer from the plant wall to the building surface mainly occurs by convection and by long wave infrared radiation. Heat transfer by convection depends on the air velocity in the gap. Radiation heat transfer in the long wave infrared range depends on the emissivity of the surfaces; a suitable choice of the building surface emissivity can increase the thermal insulation of the building. Natural ventilation occurring through the green wall/roof, if it is permeable to the air, influences the air gap temperature and consequently the building air temperature.

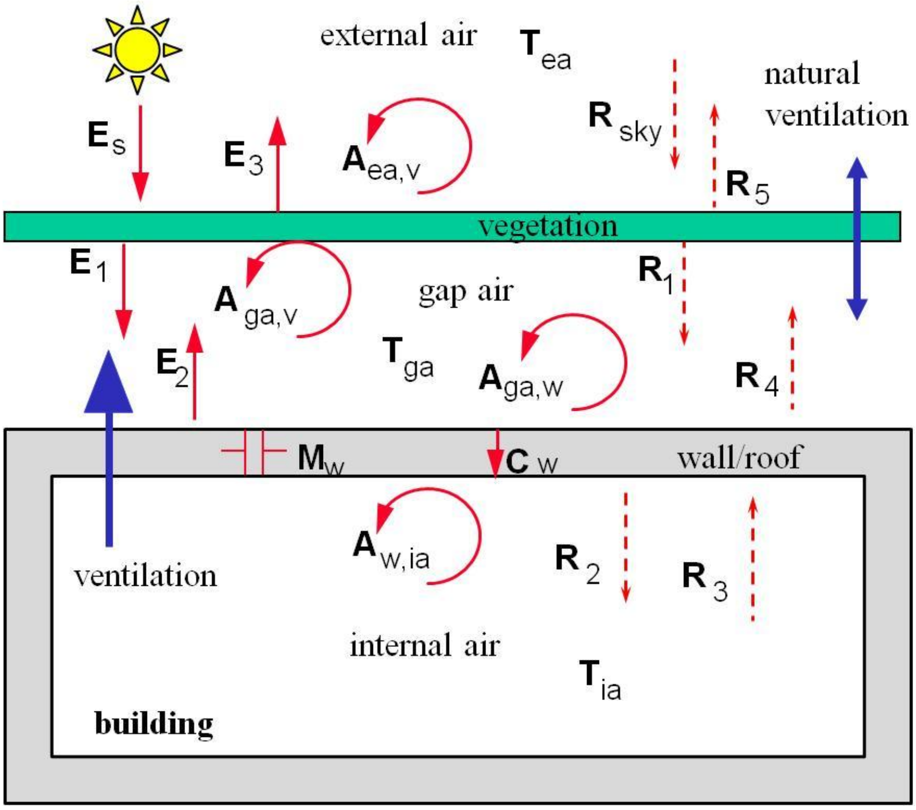

Figure 1: Energy fluxes in a green roof/wall system; symbols are described in Table 1.

Table 1: List of Symbols

A = heat transfer by convection[W]
C = heat transfer by conduction [W]
R = heat transfer by long wave infrared radiation [W]
H = heat transfer by ventilation[W]
E = incident solar radiation heat flux [W]
M = heat storage [W]
T = temperature [K]
Subscripts
ea=external air
ga=gap air
ia=external air
s=solar
v= vegetation
w= wall/roof

5 Plants

Solar radiation and the external air temperature and relative humidity are reduced as they pass through the vegetation covering a building. Plants with their biological functions, such as photosynthesis, respiration, transpiration and evaporation, absorb about 60% of the incident solar radiation reducing the amount of solar radiation that reaches the surfaces of the building (Wong et al., 2003; Spala et al., 2008; Jim and He, 2011; Fioretti et al., 2010; Perez at al., 2011; Bowler at al., 2010). The shadow produced by the vegetation is function of the kind of plants used, of the vegetative stage and of its conditions (Fioretti et al., 2010). Plants absorb part of the energy from solar radiation for the vital process of photosynthesis. Evapotranspiration, i.e. the loss of water from a plant as vapor into the atmosphere, uses thermal

energy and increases latent rather sensible heat, cooling the leaf and the temperature of the air surrounding the leaf (Bowler at al., 2010).
Plants, influencing the thermal insulation of the building, are selected for their final height, for their leaf area index, fractional coverage (i.e. the fraction of the roof surface that is directly covered by at least one leaf), albedo (i.e. the reflectivity of the surface to the incident solar energy over the vegetation layer) and stomatal resistance, for their flowering period as well as for the need of water and type of soil, according to the climatic conditions of the area, the plant impact on the ecosystems, and water availability (Kohler and Poll, 2010; Berardi et al., 2014; Spala et al., 2008; Kanechi et al., 2013; Kanechi et al., 2014; Blanusa et al., 2013).
Turf and Sedum are commonly used as vegetation for rooftop gardening for their high temperature tolerance and low fertility, for their abilities to survive with limited water, for their low maintenance costs regarding extensive cultivating management (Berardi et al., 2014; Kanechi, et al., 2014; Blanusa et al., 2013). Other plants that can be used for green roofs due their growth rate, photosynthetic ability, stomatal conductance are: Evolvulus pilosus, Fragaria x ananassa, Hedera helix, Lampranthus spectabilis, Ophiopogon japonicas, Pelargonium x hortorum, Petunia x hybrid, Thymus serphyllum, Verbena x hybrid, Vina majorm, and so on (Kanechi, et al., 2014; Kanechi et al., 2013).

6 Conclusions

Green roofs and vertical gardens systems represent a class of plant technology still absent from conventional roof and walls of buildings but with a high potential to be used as innovative solutions for improving energy efficiency and saving in the sector of construction industry. The greening technology can be used as a biological insulation system either for reducing energy for conditioning in summer or to increase the thermal properties of buildings in winter. In addition, these natural insulating systems can also improve the quality of air and the aesthetical impact of buildings in high constructed areas in cities, and have the potential to recreate natural ecosystem with trees, bushes and crops and thus contributing also to combat the global climatic changes by decreasing the urban heat island and the CO2 emissions in the city's centers.

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