GREEN ROOFS AND FAÇADES AGRICULTURE (GRF) FOR SUPPORTING BUILDING ENERGY EFFICIENCY

Campiotti C.*, Bibbiani C.**, Alonzo G.***, Giagnacovo G.*, Ragona R.*, Viola C.*
*Italian National Agency for New Technologies, Energy and Sustainable Economic Development
**University of Pisa
***University of Palermo
campiotti@enea.it

Abstract - Green roofs and façades agriculture (GRF) represents a sustainable technology for improving the energy efficiency of buildings, specifically to improve the energy consumption for conditioning in summer and the thermal insulation in winter. Worldwide, it is reported a surface of 234 ha of GRF, with the Germany leader in Europe (229194 m^2), followed from the North America (1272940 m^2) and the city of Singapore (127656 m^2). Furthermore, GRF contribute to mitigate impacts in cities, e.g.: the storm water runoff, the "heat island phenomenon", the CO_2 emissions and the unaesthetic vision of strongly urbanized areas. Recently, a number of municipalities started to adopt regulations and constructive benefits for renovated and new buildings which incorporate GRF. This paper deals with a general description of the GRF plant technology, the technical characteristics, the existing certification framework, the plants species and the hydroponics typologies. In addition, it is reported the description of a mathematical model to quantify heat fluxes and energy balance of the GRF associated with buildings.

Key words: energy efficiency, urban ecology, green roofs and façades, eco-buildings.

1. INTRODUCTION

Today, establishing vegetation on rooftops and façades of buildings attract more and more attention in many cities of the world. This plant techniques, commonly known as Green Roofs and Façades (GRF) were regarded as an important solution for providing insulation to building and thus contributing to save energy consumption by reducing energy demand on space conditioning. In addition, GRF offers a number of other benefits e.g.: minimizes contaminants from rainwater, increases the life span of typical roof/walls by protecting the building components from extreme temperatures, reduce potential damages from water-storms [9]. If widely adopted in the cities, GRF can reduce the Urban Heat Island Effect (an elevation of temperature due to the high concentration of heat absorbed and re-irradiated by walls, rooftops and pavements) and hence greenhouse gas (GHG) emissions [2, 17].

The plants can also remove airborne pollutants and improve the air quality in the urban areas, and provide a more aesthetically pleasing environment to live and work. Due to contribution which GRF give to the general topic of decreasing the CO_2 in the air, a widespread use of "green roofs", "living roofs", green façade and "eco roofs" can become a part of the solution and an action response to the Kyoto Protocol. Worldwide, it is reported a surface of 234 ha of GRF, with the Germany leader in Europe (229194 m^2), followed from the North America (1272940 m^2) and Singapore (127656 m^2). In Italy there are about 1000 m^2 implemented with Green Roofs (Fig. 1 and Fig. 2).

Because the building sector in Europe is responsible of 40% of the total end-energy consumed, there is increasing interest in using this "green option" to improve the *envelope thermal transfer value*, and therefore the energy efficiency of the buildings [11, 12, 13, 14]. As such, the green roofing and facades technology is being to become common especially in the buildings of new construction industry. GRF as natural cover of building's outside surface has a direct correspondence with the energy fluxes which determine the thermal balance of the buildings. Researches and studies have put in evidence that the shading effect of green-roof can effectively reduce the energy cooling load by 8% in annual energy consumption. Furthermore, it was reported that vertical greenery systems can reduce energy air conditioning load by reducing of about 5.5 °C the outside air temperature in the immediate outdoor, with corresponding energy reduction of 50-70% [1, 2, 3]. However, there is still a lack of quantifiable data to definitely account either the materials and techniques or the benefits that GRF can really provide to energy efficiency of buildings, its occupants, and the civil society. Although data are available for some areas (mainly Germany, North America and Singapore), most of them are not transferable to specific climatic conditions of other countries. Recently, ENEA started a project using some experimental facilities available at the Casaccia ENEA Centre, located in the north of Rome (latitude: 42°02'36", longitude: 12°18'28"). The priority established by the project team was to start developing a feasibility study to define materials, energetic parameters, plant species, technological options, and existing scientific information. This paper is also part of a research activity in progress at ENEA to explore the potential of GRF systems as sustainable and innovative

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tools for "green insulation" of buildings, and their contribute to aesthetic and eco-urban life in the cities.

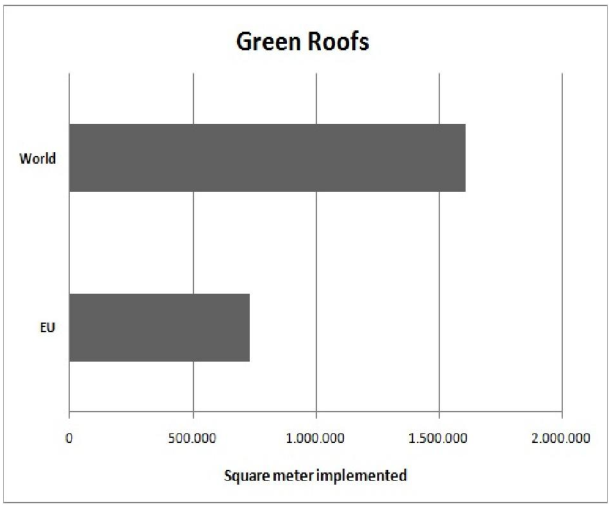

Fig. 1. Surface of green roofs in the world

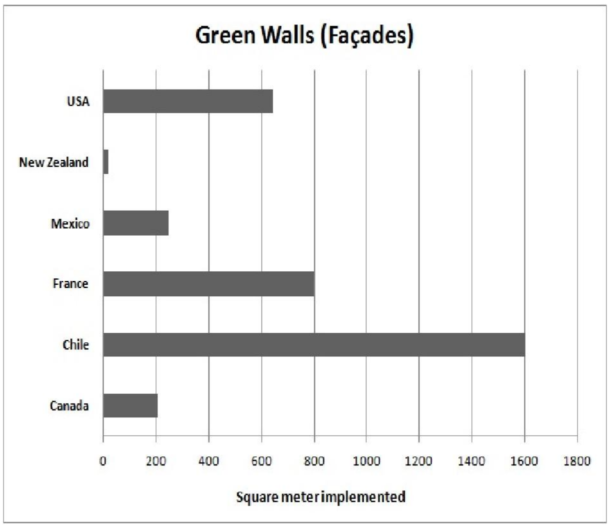

Fig. 2. Surface of green walls in the world

2. MATHEMATICAL MODEL FOR MEASUREMENTS OF GREEN ROOFS AND FAÇADES (GRF)

A mathematical model was developed in order to quantify the heat fluxes between the green wall (greenroof/façade) and the building according to an assumption of stationary conditions [4, 5, 11].

a) ***Heat transfer by convention***

Newton's Law states that convection heat transfer is ruled by the following equation

$$q_c = h_c\, A\, (T_s - T_{air}) \qquad (1)$$

where q_c has units of Watts.
The rate of heat q_c transferred to the surrounding air is proportional to the exposed area A, and to the difference between the surface temperature T_s and the air temperature T_{air}.

The constant of proportionality h_c is termed the convection heat transfer coefficient [$Wm^{-2}°K^{-1}$].

b) ***Heat transfer by radiation***

The heat emitted by a blackbody (per unit of time) at an absolute temperature T is given by the Stefan-Boltzmann Law of thermal radiation. Gray bodies emit less thermal radiation than a blackbody having the same surface, owing to an emissivity coefficient ε less than 1. The net heat transfer from a small gray body at absolute temperature T_s with surface A and emissivity ε to a much larger enclosing body at absolute temperature T_{surr} is given by

$$q_{rad} = \sigma\, \varepsilon\, A\, (T_s^4 - T_{surr}^4) \qquad (2)$$

where σ is the Stefan-Boltzmann constant, and T_{surr} the surrounding environment temperature.
The above equation is commonly written in a linearized form similar to the convection equation

$$q_{rad} = h_r\, A\, (T_s - T_{surr}) \qquad (3)$$

where h_r = linearized radiation heat transfer coefficient.
In fact if the temperature difference $\Delta T = T_s - T_{surr}$ is small, then one can write

$$(T_s^4 - T_{surr}^4) \cong 4T_{surr}^3\, (T_s - T_{surr}),$$

obtaining by comparison with (3)

$$h_r = 4\sigma\, \varepsilon\, T_{surr}^3 \qquad (4)$$

Generally, one assumes $T_{surr} = T_s$ when dealing with vertical façades, while $T_{surr} = T_s - 4$ °K when we refer to roofs (horizontal walls).

c) Combined heat transfer

Combining the convection and radiation effects, the thermal behavior between the external surfaces of a building and the environment could be arranged as:

$$q = q_c + q_{rad} = h_c\, A\, (T_s - T_{air}) + h_r\, A\, (T_s - T_{surr}) =$$
$$= h_e\, A\, (T_s - T_{air}) + A\, \Delta q \qquad (5)$$

where
$h_e = h_c + h_r$ is the combined heat transfer coefficient,
$\Delta q = h_r\, (T_{air} - T_{surr})$.
If $T_{surr} \neq T_{air}$ then the last term in (5) is needed to product a correct balance. Typical values of the h_e coefficient are [$Wm^{-2}°K^{-1}$]: 8.3 for heat transfer between vertical walls and indoor environment, 8.3 between horizontal walls like roofs and the sky, 25.0 for heat transfer between vertical walls and outdoor environment [4, 7, 8].

d) Sol-Air Temperature

If we take into account also the solar radiation effect in eq. (5), we obtain:

$$q_{tot} = h_e A (T_s - T_{air}) + A \Delta q - \alpha AG \qquad (6)$$

where α is the absorption coefficient of the exposed surface A, and G is the solar radiation intensity [Wm^{-2}].
Let us define a new equivalent $T_{sol\text{-}air}$ temperature, such as:

$$q_{tot} = h_e A (T_s - T_{sol\text{-}air}) \qquad (7)$$

Combining eq. (6) and (7), it follows that:

$$T_{sol\text{-}air} = T_{air} + \alpha G/h_e - \Delta q/h_e \qquad (8)$$

$T_{sol\text{-}air}$ can be defined as that fictitious temperature causing the same level of heat exchange related to the combined convection-radiation heat transfer and solar radiation effect.

e) The Green Wall performances: the "Green Factor" model [3, 6, 9, 12, 15]

In order to evaluate the performance of green walls in terms of cooling load demand variation, a model was developed to describe the dynamic thermal behavior of different green walls realized with various plant species. Thus, the "Green Factor" (K_g) was defined as [8]:

$$K_g = \frac{T_s - T_{gw}}{T_s - T_{air}} = 1 - \tau_g \frac{h_e}{h_e^*} \qquad (9)$$

where
τ_g = solar transmission coefficient of the green layer
h_e , h_e^* = surface heat transfer coefficient without and with the green layer
T_{gw} = external surface temperature of the green wall
T_s = external surface temperature of the bare wall
T_{air} = external air temperature

The K_g factor varies between 0 and 1, the former when no temperature decrease is obtained by the green wall, the latter when T_{gw} is equal to T_{air}.

Tab. 2. Plants species grown for green roofs

GREEN ROOFS		
Species	*Family*	
Sedum sp	Crassulaceae	Evergreen (5-7cm in height). Flowering in summer. Mild climate, sun exposure, drought tolerance
Dianthus sp	Caryophylla -ceae	Herbaceous plant. Red and white flowers. Tropical and temperate climate.
Allium	Alliaceae	Annual / perennial bulbous plants. White, rose, violet inflorescence. Temperate climate.
Achillea	Ateraceae	Perennial herbaceous. White and rose flower. Sun exposition.
Arabis	Cruciferae	Perennial herbaceous plant. White flower. Temperate and cold climate.
Aster	Asteraceae	Perennial herbaceous plant. Inflorescence of different colors. Temperate and cold climate.

The τ_g , h_e^* coefficients come from test values and therefore the K_g factor can be easily calculated from eq. (9). It is clear that a green wall reduces the solar transmission coefficient, and at the same time affects the transfer coefficient h_e^*.

To highlight the energy performances of green walls in cooling and heating seasons, in terms of energy savings, energy balance can be calculated as:

$$\frac{E_{\Delta t}}{A} = U(T_{sol-air} - T_i)\Delta t \qquad \text{(no green wall)} \quad (10)$$

$$\frac{E_{\Delta t}^*}{A} = U(T^*_{sol-air} - T_i)\Delta t \qquad \text{(green wall)} \quad (11)$$

$E_{\Delta t}$, $E_{\Delta t}$ *: Energy coming into the building through the envelope, as bare or as green wall in Δt.
$T_{sol\text{-}air}$, $T^*_{sol\text{-}air}$: sol-air temperature , as bare wall, or as green wall ;
T_i: temperature inside the building (the controlled temperature, equal in both cases);
U: thermal transmission coefficient (U-factor) of the envelope;
Δt: time interval when solar effects are present;
A: envelope aerea.

Thus, the cooling load demand decrease for unit of surface in the time interval Δt is:

$$\frac{E_{\Delta t} - E_{\Delta t}^*}{A} = U(T_{sol-air} - T^*_{sol-air})\Delta t =$$
$$= U(T_{air} + \alpha\frac{\overline{G}}{h_e} - T_{air} - \tau_g \alpha \frac{\overline{G}}{h_e^*})\Delta t = U\alpha\frac{\overline{G}}{h_e}(1 - \tau_g \frac{h_e}{h_e^*})\Delta t =$$
$$= U k_g \alpha \frac{\overline{G}}{h_e}\Delta t \qquad (12)$$

where $\overline{G}$: is the average solar radiation intensity in the time interval Δt.

3. PLANT SPECIES AND TECHNICAL CONSIDERATIONS

Growing plants either on the rooftop or on the outside walls of buildings implies that plants should be selected according to a number of technical considerations and parameters, e.g.: plants should not modify the structural parts of buildings, plant species should be chosen to establish green coverage in a short time, plants should have high drought tolerance and finally plants should not create conflicts with local or native species and environment. As result, appropriate evaluation should be done to choose what plant species are most suitable either for rooftop or for facades. Criteria for selecting plant material include design intent, aesthetic appeal, local environmental conditions, plant characteristics such as rate of establishment, longevity, and disease and pest resistance, and the substrate composition and depth available for planting. Table 2-3 report a selection of adapted plants species and their biological characteristics of interest for GRF [16, 17, 18].

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Tab. 3. Plants species grown for green walls

GREEN WALLS		
Species	*Family*	*Type or features*
Hedera sp	Araliaceae	Evergreen climbing shrub (to 20m h). Cold and mild climate.
Parthenocissus sp.	Vitaceae	Deciduous climbing shrub (to 20m h). Temperate climate.
Bignonia capreolata	Bignoniaceae	Evergreen climbing (to 12m h). Mild climate.
Clematis montana	Ranunculaceae	Deciduous vigorous climbing (to 10m h). Cold climate.
Wisteria sinensis	Fabaceae	Deciduous climbing shrub (to 20m h). Rapid growth. Temperate climate and mild.
Jasminus officinalis	Oleaceae	Deciduous resistant climbing (to 6-7m h). Temperate climate and sun exposure (no wind).
Actinidia colomikta	Actinidiaceae	Deciduous resistant shrub climbing (to 4m h). Cold and mild climate.
Ampelopsis	Vitaceae	Deciduous shrub climbing (to 8m h). Temperate climate (full to partial sunlight).
Rhyncospermum jasminoides	Apocynaceae	Evergreen resistant climbing (to 20m h). Temperate climate (more suitable above 10°C).
Adiantum sp	Pteridaceae	Perennial herb. Tropical - temperate climate (shady - wetlands).
Rododendron obtusum	Ericaceae	Perennial sub shrubs. Temperature above 5°C.
Vriesea splenden	Bromeliaceae	Succulent plant. Tropical climate.
Dieffenbachia picta	Araceae	Perennial evergreen ornamental plant. Tropical climate.
Dracena godseffiana	Liliaceae	Evergreen ornamental plant (to 2m h). Tropical climate.

Although some plants are able to grow directly on walls by taking root in the substance of the wall itself, it is advisable not to create conditions which could promote little deterioration in the building surface. Therefore, to grow plants on walls and buildings some kind of support structure is usually essential. Façade should incorporate structures where plants are planted or allowed to take roots by cables, rope or netting. Furthermore, wide-meshed grid structure to which plants can be attached and trained into place or special containers planted at different levels on the façade could be installed. Whenever possible it is advisable to leave a small gap between the façade of the building and the supporting structure in order to maximize the effects of summer cooling and winter insulation (chimney effect).
Particularly important aspects are:
● the load-bearing capacity of the structure;
● the design of waterproofing and irrigation systems (hydroponics system);
● methods of getting soil and other necessary materials onto the roof.

Many possibilities exist for constructing of greenroofs, depending on the characteristics of both buildings and local climate. Plants can be established directly upon the greenroof media via seed, plugs, or cuttings or pregrown at ground level on a blanket, mat, or tray and then placed on the roof. Both the facades and the green-roof use hydroponics systems to grow plants. Reasons of eco-sostenibility, ask for realizing hydroponics characterized with closed-loop hydraulic circuits, provided with a filtration and nutrient recycling systems, to allow to capture, reuse and treat nutrient solutions and water [17, 19, 20].

However, new building constructions can also include GRF systems which can use the grey-water from inside the building, with significant water saving of the building's potable water use. Finally, features should include also integration of photovoltaic technology to make fully energetically autonomous the vegetated area. Fig. 3 and Fig. 4, show the modular system under experimentation at ENEA.

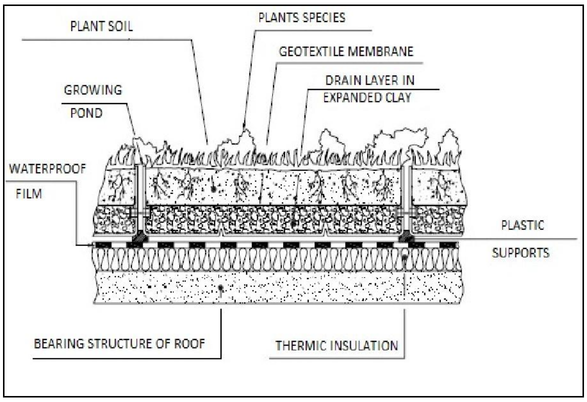

Fig. 3. Details of hydroponics substrate

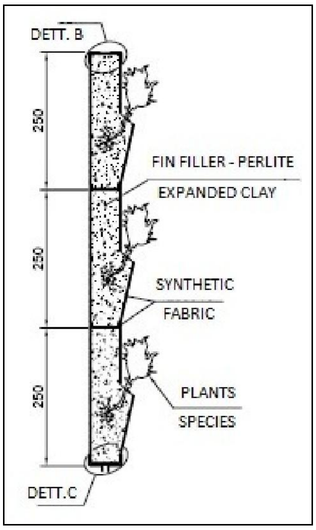

Fig. 4. Transversal section of ENEA modular system

4. STANDARD AND GUIDELINES FOR GRF SYSTEMS

Standards and building codes to regulate the construction of green roof and façades design need to be developed in order to standardize those information regarding materials, installations, hydroponics, selection and maintenance of plants, determination of dead loads and live loads, standard test methods and analysis, water capture and media retention, saturated water permeability of substrate drainage media.
However, in many countries a number of regulations were established to define standards and guidelines for designing and constructing buildings incorporating GRF systems (Tab. 4).

Tab. 4. National and international laws for GRF

LEGISLATION	DESCRIPTION
Dir. 2002/91/CE	EU Directive on the Energy performance of building (EPBD)
DLgs 192/2005	Dir. 91/2002/CE
DLgs 311/2006	Integration to DLgs 192/2005 – reports the building's certification of energy's performances
DPR 59/2009	Carry out some topics provided for art. 4 del DLgs. 192/2005. In art.2 there are the same definitions, reported in DLgs. 192/05 and in DLgs 311/06, and other three included green covering
DM 26/6/2009	National guidelines for energy certification of buildings
UNI 11235	Defines the rules of design, implementation, maintenance and control of green roofs
Dir. 2010/31/UE	Energy performance of buildings (Dir. 2002/91/CE)

The European Commission has launched in 2005 the GreenBuilding Programme [10] which promotes energy efficiency and renewable energy use in buildings. This programme may also complement and facilitate participation to other national classification which support financing of assessments, incentives or other decisions as subsidies, fiscal mechanisms, voluntary agreements. Table 5 reports a selection of the main certification programs available in Europe and in all the world. Participation in such programmes of certification improve the building's market value, decrease vacancy, reduce liability, and improve occupant performances.

Tab. 5. Certification programs in the World

CLASSIFICATION	COUNTRY
AQUA	Brazil
BERDE	Philippines
BREEAM	The Netherlands United Kingdom
Build It Green	USA
CASBEE	Japan
CEPHEUS	Germany
DCBA	The Netherland
DGNB	Germany
Energy Rating	Denmark
Estidama	United Arab Emirates
GBAS	China
GBI Malaysia	Malaysia
Green Building Council	Italy, Philippine India
Green Globes	Canada – USA
Green Mark	Singapore
Green Star	Australia New Zealand South Africa
GRIHA	India
HKBEAM	Hong Kong
HQE	France
Institute of Architecture Pakistan Green sustainable Architecture (IAPGSA)	Pakistan
International Green Construction Code (IGCC)	USA
KGBC	Korea
LEED	Brazil - Mexico USA
Lider A	Portugal
Living Building Challenge	USA
Minergie	Switzerland
Nabers	Australia
NAHB NGBS	USA
PromisE	Finland
Protocollo ITACA	Italy
TQ Building Assessment tool	Austria
VERDE	Spain

The main feature of Green Building Challenge Certification than the first generation - UK BREEAM, the American LEED and the Danish Energy Rating, applied since 1997 – is to have not structural limitations because it isn't tied to reality of geographical region of origin, but it is an evaluation method that can be adapted to different local conditions while maintaining the same terminology and basic structure.

5. RESULTS AND DISCUSSIONS

The ENEA activity with the methods, the hydroponics techniques, the engineering and biological parameters presented in this article, it has the main goal of defining a general feasibility study on the potential contribute of green-roof and façades on the energy efficiency of buildings. To make a successful use of the GRF solution (green-roof and/or green-wall) in terms of high visual appeal when associated to the buildings, it would be very important to develop adequate hydroponics systems. At this scope, technical information on the developing of specific hydroponics systems e.g.: hydroponics on the rooftop or on the wall, were also reported. A mathematical model was elaborated to fully explore the energy fluxes and the energy potential of GRF. In addition, the paper reported a survey of the main plant species (candidate plants) with suitable characteristics in terms of rate of plant establishment, speed of growing, disease and pest resistance. Activity is under progress to collect experimental data in order to evaluate both the crops and the plant techniques performances, and to define the *envelope thermal transfer value* of buildings with GRF plant technology.

6. CONCLUSIONS

Buildings in Europe consume about 40% of total energy use and not less than 65% of total electricity consumption. Green roofs and façades (GRF) plant technology represents a class of sustainable technology options still underexploited in conventional roof and walls of civil buildings but with a high potential to be used as innovative and ecological solution for improving energy efficiency and energy saving in the sector of construction industry. GRF can be used as insulation system either to reduce energy for conditioning in summer and/or to increase the thermal properties of building's roof and walls in winter. In addition, GRF have the potential to improve biodiversity since offer a suitable habitat for microorganisms, insects, and birds. Furthermore, realizing of GRF systems in cities requires a proper selection and analysis of potential candidate plants in order to allow optimum adaptation with the local microclimate and to avoid competition between native and new introduced species, and plant communities already growing in the constructed area. Finally, these natural insulating systems improve the quality of air and the aesthetical impact of buildings, reduce the "heat island" in city centers, and thus contribute to combat Climate Change and Global Warming. Further work of ENEA will pay attention also to the development of suitable hydroponics plant crop systems able to allow optimal aesthetical integration between the GRF and the constructive and structural characteristics of buildings.

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