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Roofs of the future: rooftop greenhouses to improve buildings metabolism

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Abstract

Ancient civilizations had agriculture production in their metropolis but modern urban planning separated agriculture from cities, such as Chandigarh by Le Corbusier. At present, FAO estimates that urban agriculture produces food for a quarter of world's population, reducing food transport, package and waste impact among others and improving food safety. Meanwhile, city governments and citizens are reinventing their roofs usage in order to take more advantage of them. Rooftop Greenhouses (RTGs) are an interesting option because they increase the scarce green area of the cities, create new agricultural spaces and promote food self-sufficiency in urban areas among other growing interests. RTGs are greenhouses located on the roof of the buildings that usually produce food using soil-less culture systems. These structures as well as the green façades called Vertical Farming (VF) are part of the “building-based Urban Agriculture (UA)”.

In this sense, this article presents the first results of the research project Fertilecity, which aims to analyze, from a technological and sustainability approach, a new agricultural production system for Mediterranean urban areas through the integration of greenhouses on the roof of buildings. This innovative system is an integrated RTG (i-RTG) that includes energy, water and CO₂ flows in the metabolism of the building. Multidisciplinary experts participate in Fertilecity Project using multiple methods such as

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Life Cycle Assessment and the Integrated Value Model for Sustainable Assessment (MIVES). Their first results are: a review of the main experiences in UA; an environmental and economic life cycle analysis of implementing Rooftop Greenhouses (RTGs) in Barcelona and the construction of the ICTA Rooftop Greenhouse Lab (RTG-Lab) near Barcelona. This project aims to demonstrate the potential of i-RTGs and quantify their environmental, economic and social benefits, as well as study how they can change the image of our cities.

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1. Introduction

Urban agriculture (UA) has been developed for centuries, for example in times of splendor of Egypt, Roman, Greek and Byzantine cultures. During these periods there were vegetables, herbs, palms and fruit trees in gardens and orchards within the urban area of major cities [1]. Also in Middle Age, there were gardens with herbs and vegetables to feed the city inhabitants in monasteries, palaces and houses [2]. From then on there have been several similar cases of UA. Some have been private orchards such as garden cities starting with Norman Shaw's Bedford Park (1877-1897) and Unwin's y Parker's Letchworth Garden City (1903) and Hampstead Garden Suburb (1907). On the other hand, there have also been community actions such as the North American Potato patches and Relief Gardens during the economic crisis of the 1893 and the 1929 respectively [3]. During the First World War UA was part of strategies to complement food rationing, such as the North American US School Garden Army [4]. In the Second World War UA had a political use in examples such as the English Dig for Victory in 1940 [3]. In the 70s, UA gardens were used as community and social support activities like the "City Farms and Community Gardens" movement in Netherlands and UK [5]. In the 90s there were similar interesting experiences, for example the London 2012 Capital Growth, 56St Blaiser in Paris Rosa Rose Garden in Berlin. In the 21st century UA moves forward to Sustainable green cities, Eco monumentality, zero emissions projects [6], energy production or Green design, like the gardens along Tokyo Highways.

However, at present, cities agriculture production is not self-sufficient but it relies on distant agriculture areas. Therefore, cities food safety depends on these distant foods cost, transport, distribution and its stability as well as its variety and quality. This issue has a high impact because, for example in Europe, about 75% of population live in cities and it is foreseen to be 80% in 2020 [7]; while in Latin America and the Caribbean cities population is the 79% [8]. In this sense FAO's definition of UA comes as part of the solution "small areas within cities, such as vacant lots, gardens, verges, balconies and containers, that are used for growing crops ... for own-consumption or sale in neighborhood markets." [9]. Producing food inside the city with UA increases agriculture performance because it minimizes costs and improves city areas, it permits changing the current lineal food production system for a circular agro-urban system that optimizes urban cycles [2] and moreover, it contributes to the food safety for vulnerable people with less resources among others.

In this case, Rooftop Greenhouses (RTGs) on urban buildings are a smart option that has been increasing in recent years, because they generate new agricultural spaces and increase the low green area of most cities. RTGs consist of a greenhouse built on the roof of a building that usually produces food through the use of soil-less culture systems [10]. They are private or public agriculture holdings that have the growing area in buildings roofs. Following traditional or high technologies cultivation methods they are used to grow from aromatic plants to vegetables and fruit trees. There are commercial, self-consumption and research RTGs which focus on environmental, nourishing, recreational and educational aspects among others [11].

Most RTGs are horticultural commercial activities that produce food through soil-less agriculture systems (i.e., hydroponic, substrate, aeroponics) and concentrated in urban areas of North America. For example in New York, the store The Vinegar Factory (Manhattan) produces its own vegetables and fruits in a 830 m²-RTG [12]. Lufa Farms in Montreal, Canada, [13] constructed a RTG of 2,900 m² on a commercial building to cultivate a broad variety of horticultural products such as lettuce, tomatoes and eggplants in different thermal zones. In Europe, the implementation of RTGs is still in the shape of some starting projects, such as the INFarming [14] in Germany. Most of the aforementioned RTGs use hydroponic and substrate agriculture systems. Controlled environment technologies

are commonly used when cultivating different vegetables in the same RTG like in Lufa Farms. Regarding commercialization options, some companies like The Vinegar Factory have their own market place, some sell their products in markets under a local production label while others like Lufa farms work with a Community Supported Agriculture (CSA) model.

RTGs promote local food production so that the transportation requirements and the consequent environmental impacts are reduced [10, 12]. More environmental advantages will come in the future because RTGs are expected to be implemented in already constructed roofs, most of which are unproductive spaces at present. In consequence, cities will be more multifunctional by integrating food production into edifices. Regarding agronomic issues, RTG agriculture follows the same rules of commercial agriculture, which are the principles of Good Agricultural Practices as recently defined by FAO (2013). These rules consider the integrated plant hygiene and pest management procedures, which include the use of living organisms for biological control to reduce the use of pesticides. Moreover, RTGs for food production avoid the most common food risk in urban agriculture: soil contamination and the consequent bioaccumulation of metals [15]. In terms of air pollution, although it can affect vegetation by accumulating trace metals, it depends on the location of the cultivation activity and on the distance to traffic hotspots [16]. Besides, this can be controlled more easily in RTGs than in open fields. These structures can be considered as part of the building-based UA movement and closely related to Vertical Farming (VF) [17], Skyfarming [18], and Zero-Acreage Farming [19] among others.

RTGs are the scope of the Fertilecity Project; the objectives, methods and present results of which are presented in this paper. As shown, Fertilecity aims to analyze, from a technological sustainability vision, a new agricultural production system for Mediterranean urban areas through RTGs integrated in buildings that improve their metabolism exchanging energy, water and CO₂ flows between RTGs and buildings.

2. The Fertilecity Project

This project carries out multidisciplinary assessments of RTGs using multiple tools and methods: Life Cycle Assessment; Life Cycle Costing; Geographic Information Systems; Rainwater Harvesting Software (PluGriSost); Sustainability Assessment; Building Energy Modeling software's (TAS) and the Integrated Value Model for Sustainable Assessment (MIVES). Fertilecity also works with a real prototype, The ICTA Rooftop Greenhouse Lab (RTG-Lab). This is an integrated RTG (i-RTG) located on the rooftop of the ICTA-ICP building (UAB campus, Bellaterra, Spain). As a novelty, the RTG-Lab integrates the energy, water and CO₂ flows (Figure 1) in the metabolism of the building. The RTG-Lab aims to demonstrate the potential of i-RTGs and quantify their environmental, economic and social benefits.

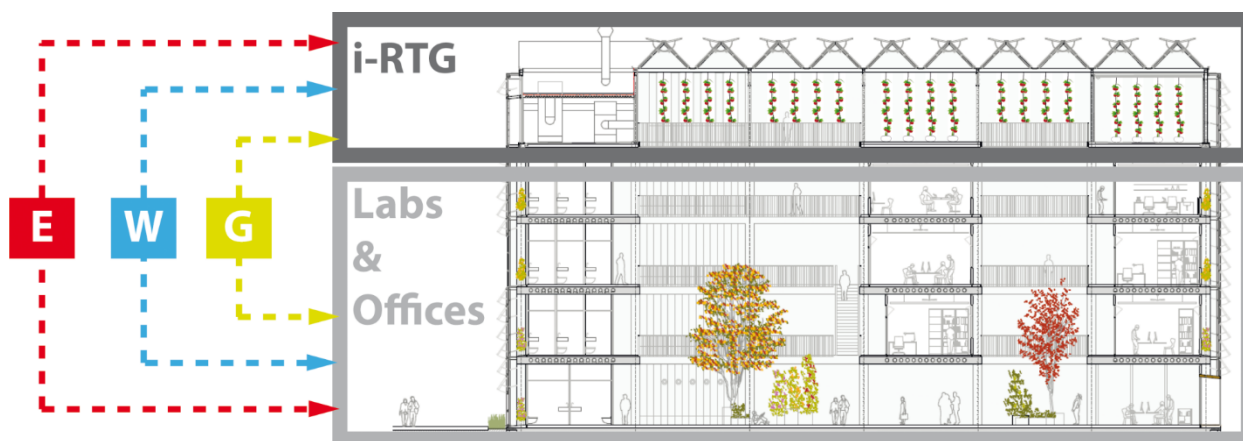


Fig. 1. Exchange of flows between ICTA-ICP building and i-RTG. Legend: E is energy interconnection including residual heat and cold recovery; W is water interconnection considering rainwater and greywater and G is gas interconnection taking into account CO₂.

The ICTA-ICP building has a four levels reinforced concrete hyperstatic bidirectional structure composed of casted on situ columns and solid slabs, which have the pipes of the heating and cooling system embedded. Its RTGs has an isostatic steel structure composed of square 150.150.5 hollow section columns, trusses composed of hollow and rolled sections - for example 120x200x4, 50x80x4 and UPN 140 – and stabilized with wire crosses bracing [20]. Façades and roof are covered with horizontal casement mobile polycarbonate panels in order to take advantage of ventilation depending on interior and exterior conditions (Figure 2).

This paper presents the methods and present results of the following parts of the Fertilecity project: 2.1) review and MIVES assessment of current UA systems; 2.2) LCA analysis of implementing RTGs in Barcelona area, Spain, and 2.3) analysis of the flows between RTGs and building by monitoring the RTG-Lab.

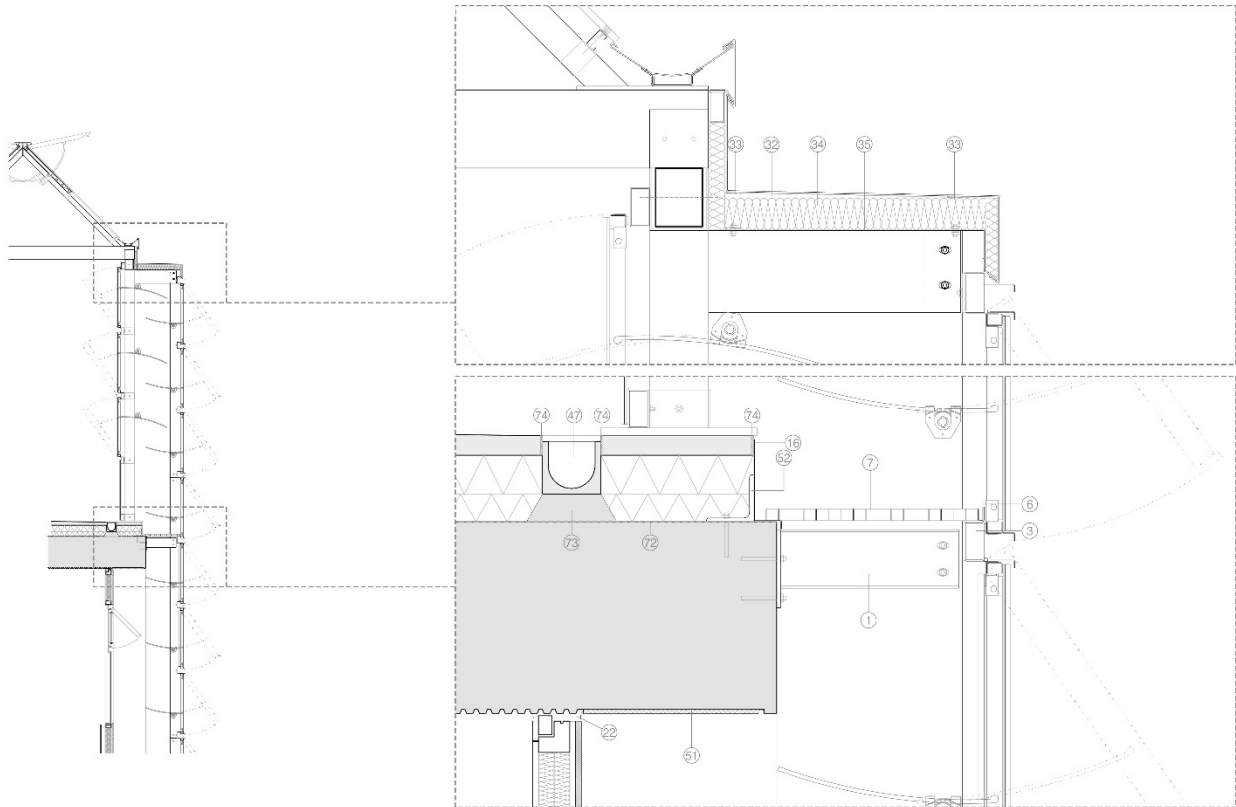


Fig. 2. Façade and roof details of ICTA RTG from [15]. Legend: 1) galvanized steel bracket supporting the hollow steel section façade stud; 3) 50.100.3 galvanized steel hollow section façade track each 3117/3275 mm; 6) 50.43.3 galvanized steel L section supporting 7; 7) steel grating pavement; 16) roof finishing: 2 mm steel sheet with drip; 22) joint grouting with polyethylene cylinder and polyurethane sealing; 32) exterior 2 mm steel sheet; 33) supporting structure: U steel section; 34) 80 mm XPS insulation; 35) interior 2 mm steel sheet; 47) drainage system; 51) 0,6 mm steel sheet with insulation; 52) rolled steel section: L 120; 71) fiberglass fabric curtain; 73) mortar bed fixing the drainage system; 74) 5 mm EPS thermal expansion joint.

2.1. Review and MIVES assessment

This part is an analysis of the main present UA systems: a) Urban vegetable gardens and orchards (UVGO), which can be public like “Added Value” in New York or private like “Tomba L’Olla” in Valencia, Spain; b) Urban parks with vegetable gardens (UPVG) like “Lincoln Park Chicago”; c) Rooftop gardens (RTG) like “Gotham Greens” also in New York; d) Vertical agriculture (VA) like “Pasona Inc” in Tokyo, Japan, and c) Indoor agriculture (IA) like “The Plant ” in Chicago.

First, this UA systems have been studied and classified according to: i) its metropolis, district or building scale; ii) its business, community-social, domestic, educational, research or integral purpose; iii) their types of crops either fruits or vegetables and iv) the technologies to exchange flows of energy and water such as thermal curtains, advanced glass skins, Light Emitting Diode (LED), recirculating watering, watering with nutrients like Hydroponics and Aeroponics technologies among others.

Then, an Integrated Value Model for Sustainable Assessment of UA is being defined using MIVES. MIVES is a Multi-Criteria Decision-Making (MCDM) method developed in the 2000s that includes the value function concept. This method has already been used to define several sustainability assessment models to assess the construction of schools [21], wind turbine support systems [22], etc. Following MIVES, Fertilecity is building a decision making tree for UA, which includes only the main and the most discriminatory indicators, in order to obtain a correct assessment decision because indicator amount is not excessive. This tree has 3 requirements: 1) economic, 2) environmental and 3) social and each requirement has several criteria and indicators. These requirements, criteria and indicators have different weights. Multidisciplinary experts in UA are deciding these indicators and their weights during several seminars, in which they rely upon extensive bibliography and using Analytic Hierarchy Process (AHP). These experts also decide the value function of each indicator. Assigning weights and value functions during these workshops brings rigor and objectivity to the assessment.

These seminars are considering the following economic indicators: food cost, food affordability, support to local economy, jobs creation. Some of the environmental indicators under study are: cities sustainability improvement, resources efficient usage, biodiversity increase, urban landscape improvement. Finally, some of the social indicators under analysis are: support to food safety, support to environmental and nutritional sensibility education, life quality and health improvements, recuperation of abandoned urban sites.

Their value functions vary from 0 to 1, 0 being the minimum satisfaction and 1 the maximum satisfaction for each indicator. These adimensional values $V_{i(xi)}$ can be aggregated in order to obtain the global sustainability index V , although they are the result of different indicators with different units. Each value functions depend on 5 parameters, as can be seen in equation 1. These parameters define its shape and consequently how each indicator value variation is translated to the adimensional scale. For example, if the function shape is an S, then the initial and final indicator value variation will have an adimensional value variation smaller than the middle value variation. In equation 1, A is the response value X_{max} (indicator’s abscissa), and X_{alt} is the assessed indicator abscissa which generates a value V_{ind} . P_i is a shape factor that defines if the curve is concave, convex or shaped as a “S”. C_i establishes, in curves with $P_i > 1$, abscissa’s value for the inflexion point. K_i defines the response value to C_i . B is the value that keeps the function in the range from 0 to 1 [23].

$$V_{I1} = A + B \cdot \left[1 - e^{-k_i \cdot \left(\frac{|X_{alt} - X_{max}|}{C_i} \right)^{P_i}} \right] \tag{1}$$

2.2. LCA analysis of implementing Rooftop Greenhouses (RTGs) in Barcelona area, Spain.

Within the Fertilecity project, the environmental and economic performance of the RTG-Lab will be assessed from a life cycle perspective, thereby applying the Life Cycle Assessment (LCA) [24] and Life Cycle Costing (LCC) [25] methodological frameworks. The quantification of the energy, water and CO₂ flows’ exchange and the agronomic assessment of food production agronomic assessment will be complemented with the corresponding environmental and economic analysis.

To date, preliminary analysis of the greenhouse structure and the theoretical production and local supply-chain have been accounted for [26]. This analysis quantified the environmental burdens and the economic cost of 1m² of the greenhouse structure of the RTG-Lab and compared it to the values for the conventional greenhouse technology of the study area (i.e., multitunnel greenhouses). The RTG structure showed a greater environmental impacts than multi-

tunnel greenhouses (between 17% and 75%), and an economic costs was 2.8 times higher. Thus, RTGs are a less attractive greenhouse structure than conventional technologies from an environmental and economic perspective. These results agree with the RTGs risks and limitations already mentioned in the literature [10, 17].

Beyond the greenhouse structure, the potential production of 1 kg of tomatoes in the RTG-Lab was compared to the production in multitunnel greenhouses in Almeria, which is the main source of tomatoes to the Barcelona area [27]. LCA data for this conventional production was available from the EUPHOROS project [28]. Since no experimental data is still available for the production stage, a theoretical scenario was analyzed. The assessment considered that in the RTG-Lab two crop periods during 11 months can be performed: a spring-summer crop and an autumn-winter crop, while in Almeria crop period is limited to 9 months due to climatic constraints in summer. The theoretical crop yield of this RTG-Lab scenario is of $25 \text{ kg}\cdot\text{m}^{-2}$, while reference crop yield for Almeria is of $16.5 \text{ kg}\cdot\text{m}^{-2}$ [28]. From a cradle-to-farm gate approach, the environmental impacts of 1 kg of RTG-grown tomatoes were between 9% and 26% lower than that of the multi-tunnel production. However, the economic cost was 21% higher.

Finally, the entire supply-chain of tomatoes was compared. For both systems (i.e., the local RTG and the multitunnel in Almeria) the tomato supply of tomatoes to Barcelona city center was considered. The consumption life cycle stage was excluded of the system boundaries. From a cradle-to-consumer perspective, locally produced tomatoes through RTGs in Bellaterra (25 km away from Barcelona) would have between 33% and 42% lower environmental impacts and would be 21% cheaper.

Further research on the environmental and economic balance of the RTG system and the RTG products will focus on introducing experimental data in the life cycle inventories (e.g., crop yield, production of multiple vegetables), exploring improvement scenarios (e.g., water recirculation, residual heat use) and assessing potential local supply-chains for RTG products (e.g., community-supported schemes).

2.3. Analysis of the flows between RTGs and building by monitoring the RTG-Lab

The building in which the RTG-Lab is located was designed by H Architects [29], who considered compact volume, multi-functionality, energy efficiency and building-integrated agriculture concepts among others. This building has a total area of 7500 m^2 and the current RTG-Lab consists of two RTGs 125 m^2 each (Figure 3). The implementation of this RTG obviously satisfies the Spanish Technical Code of Edification [30] and the fire safety laws [31]. So, its structure is reinforced concrete and its covering is polycarbonate instead of cold formed steel sections and LDPE respectively. In consequence, RTG-Lab has a higher environmental impact compared to conventional greenhouses.

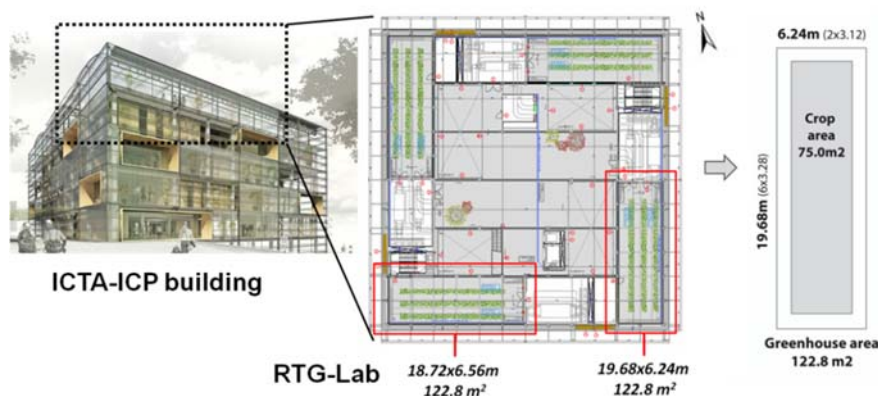


Fig. 3. RTG-Lab location in the ICTA-ICP building, in the rooftop level and greenhouse in use dimensions.

In 2014, RTG-Lab started running in order to demonstrate the feasibility of RTGs in Mediterranean areas as well as the potentialities of i-RTGs. It takes advantage of the residual heat from the building (e.g., air from the labs), the CO_2 concentration in this residual air (i.e., which will be used as natural fertilizer), and the rainwater collected on the

rooftop. To this end, the first software tool to control and a rooftop greenhouse integrated to a building has been developed and applied to RTG-Lab. This tool is flexible and permits researchers a management of the RTG-Lab that improves the greenhouse thermal conditions based on the crops requirements. This management of the RTG-Lab is also compatible with the building usage because the mentioned software tool takes into account building requirements like users' optimum temperature and air quality. This management tool permits researchers to define multiple control configurations that permit to carry out tests in order to determine the most efficient and effective management for i-RTG. This management system will improve by incorporating an intelligent system, capable to take automatic decisions in order to achieve a predefined temperature, humidity and CO₂ conditions.

In the RTG-Lab, to control the temperature and humidity researchers use the following Campbell instruments with radiation protection: a data logger *CR3000*, 12 temperature probes model *107* using thermistor and 3 *T/%HR* probes model *CS215*. These instruments are uniformly distributed inside the RTG and in other spaces of the rooftop level of the building. They are located at the levels 0.40 m, 1.20 m, 1.70 m and 2.20m of four vertical supports. Each vertical support has 3 temperature probes and some also have a *T/%HR probe*. Measurements are taken every 5 seconds and an average is done every 10 minutes. External data is obtained from the meteorological station of Sabadell Agricultural Park. For example Figure 4 shows the temperature measurements from the 19th to the 23rd of February 2015.

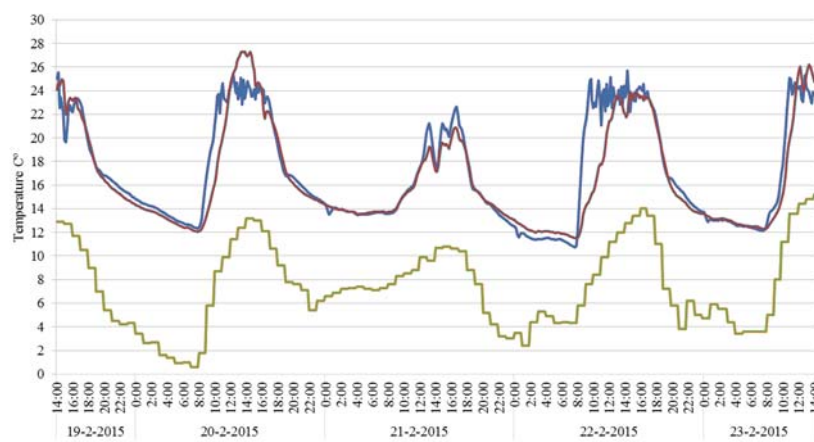


Fig. 4. Temperatures from the 19th to the 23rd of February 2015. The blue curve is RTG-Lab temperature, the red curve is rooftop level temperature and green is the temperature outside the building.

RTG-Lab temperatures differ an average of 10 C° compared to temperatures recorded outside the building. During the night, this 10 C° difference is really important because it means keeping an adequate overnight temperature for cultivation. This difference is due to the thermal inertia that has the building and specifically the greenhouse reinforced concrete slab floor inertia. This difference does not occur in conventional greenhouses, where at night the indoor and outdoor temperatures are similar.

3. Summary

In the first phase of Fertilecity Project some first results highlight after reviewing UA systems, carrying out a LCA about the implementation of rooftop greenhouses near Barcelona and controlling energy and emissions flows of RTG-Lab. At present, UA is a growing trend with a broad variety of typologies, from high-tech to traditional, from private terraces to public gardens, which is foreseen to continue increasing in the future. UA brings numerous advantages: it promotes sustainable development, food safety and affordability, environmental and food education, local economy, biodiversity... and therefore it should be included in cities urban and management plans. In the particular case of i-RTG, the presented LCA demonstrates that from a cradle-to-consumer point of view, locally cultivated tomatoes in RTG-Lab are cheaper and have lower environmental impacts. And control of RTG-Lab temperatures show that i-RTG

has higher temperatures at nighttime due to underneath buildings thermal inertia that keep an adequate cultivation temperature, a phenomena that not occurs in conventional greenhouses.

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