

# Environmental assessment of urban horticulture structures: Implementing Rooftop Greenhouses in Mediterranean cities

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## ABSTRACT

The Rooftop Greenhouse (RTG) of the Rooftop Greenhouse Lab (ICTA-UAB) is analyzed from an environmental perspective as a new form of urban agriculture. The global warming potential of an RTG structure was 2.5 kg of CO<sub>2</sub> eq., while the cumulative energy demand was of 46.4 MJ, considering a functional unit of 1m<sup>2</sup> and 1 year. When comparing the RTG structure with a multi-tunnel greenhouse, these values resulted in 80% and 53% higher, respectively. 1 kg of tomato produced in an RTG had a GWP of between 178 and 297 g of CO<sub>2</sub> eq. and a CED of between 2.9 and 4.8 MJ, depending on the crop yield. When compared with the horticultural production in a multi-tunnel greenhouse, 1 kg of tomato can be 33% less impacting or 25% more impacting for the GWP and 31% less impacting or 26% more impacting for the CED.

Keywords: rooftop farming, greenhouse technology, urban agriculture, smart cities

## 1. Introduction

Urban agriculture (UA) is spreading over the urban areas of developed countries in response to a growing awareness of the environmental impact of food systems (Howe and Wheeler 1999; Cohen et al. 2012; Mok et al. 2013). UA types are numerous and vary in placement, property and aim, such as community gardens for social inclusion, private backyard gardens for self-supply and public-property spaces for individual small gardens. Nowadays, UA is also colonizing buildings through building-based UA forms. These forms of UA have been defined by multiple authors as Vertical Farming (Despommier 2010), Skyfarming (Germer et al. 2011), Building-Integrated agriculture (Caplow 2009) or Zero-Acreage Farming (Specht et al. 2014).

Within the multiple forms of building-based UA, rooftop farming is the most common since rooftops are currently unused spaces that can be occupied and revalorized. Rooftop Greenhouses (RTGs) are greenhouses built on the rooftop of buildings devoted to, mostly, horticulture production (Cerón-Palma et al. 2012). Up to now, several companies in North America have built RTGs for their local production businesses. Gotham Greens (Brooklyn, New York) or Lufa Farms (Montreal) sell different kind of vegetables that have been produced in RTGs of 1400 m<sup>2</sup> and 2900 m<sup>2</sup>, respectively, by offering, thus, km.0-products that avoid food-miles.

### 1.1. Current research on rooftop greenhouses

Only few studies have focused on rooftop greenhouses as urban horticulture systems. Cerón-Palma et al. (2012) identified the barriers to and opportunities of implementing RTGs in the Mediterranean region, by performing discussion groups with experts on architecture, agronomy and urban sustainability. Specht et al. (2014) did a literature review of urban horticulture in and on buildings, including RTGs, to determine the potentialities and limitations of these systems. Both studies found opportunities in the three pillars of sustainability: environment (e.g., reducing food-miles and transport emissions), society (e.g., improving community food security) and economy (e.g., revaluation of unproductive spaces). Notwithstanding the large potential benefits, barriers were also noted. Particularly, the studies highlighted social (e.g., lack of acceptance) and economic limitations (e.g., investment costs).

Sanyé-Mengual et al. (2013) quantified the potential environmental benefits of the local food production in terms of the avoided distribution of products from RTGs in Barcelona. A kilogram of tomato produced in a RTG in the city of Barcelona could substitute 1 kg of tomato from Almeria (1000 km), where 60% of the tomatoes consumed in Barcelona are produced. The local production could avoid 441 g of CO<sub>2</sub> eq. and 12 MJ of energy per kg due to the optimization of the packaging use, and the reduction in the transport requirements and in the

product losses. Moreover, RTGs can integrate their flows (i.e., energy, water, materials, gases) in the metabolism of the building. Cerón-Palma (2012) has worked on the quantification of the environmental benefits of the interconnection of the energy flow.

However, the implementation of greenhouses in cities must accomplish legal specifications of the urban context that imply an intensification of the materials consumption for the structure. Greenhouse structures in urban areas may face strict reinforcement, stability and security requirements. As a result, the greenhouse structure of RTGs may have larger environmental burdens than current horticulture production technologies, in contrast to the already quantified potential environmental savings of these systems in the literature (e.g., transport savings).

### 1.2. The Rooftop Greenhouse Lab (RTG-Lab)

The Rooftop Greenhouse Lab (RTG-Lab) is a RTG implemented for horticulture production in Bellaterra (Barcelona, Spain). The RTG-Lab is placed on the new building that houses the Institute of Environmental Science and Technology (ICTA) in the Universitat Autònoma de Barcelona (UAB). The RTG-Lab consists of two greenhouses of around 125m<sup>2</sup> each that are integrated in the rooftop of the building and aim to produce vegetables by means of soil-less techniques (i.e., substrate) (Figure 1).

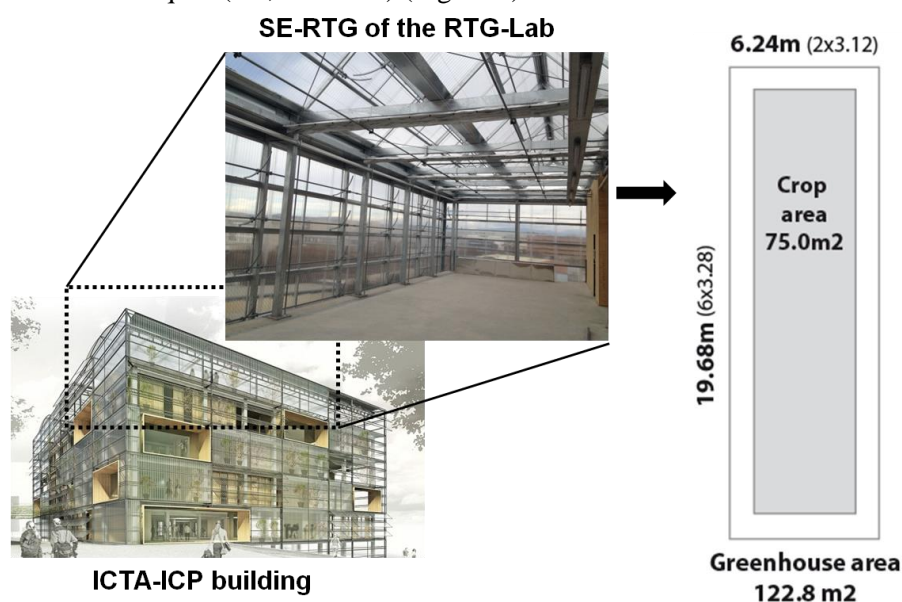


Figure 1. Situation of the RTG-Lab in the ICTA-ICP building, image of the South-East Rooftop Greenhouse of the RTG-Lab and RTG dimensions.

Research in the RTG-Lab will focus on three main issues: to prove the feasibility of crop production through RTGs in Mediterranean urban areas, to demonstrate and quantify the potential exchange of flows between the RTG and the building (i.e., energy, water, CO<sub>2</sub>), and to quantify the environmental balance (both positive and negative impacts) of RTGs and their products. The RTG-Lab will start operating the late summer 2014 as well as the related projects. However, since the construction phase has already finished early environmental research regarding the RTG structure can be performed.

### 1.3. Objectives

The aim of the research is to perform an environmental assessment of the structure of a real RTG project in order to quantify the impacts of this new urban horticulture structure. To do that, the RTG of the RTG-Lab is analyzed through an attributional LCA that follows a cradle-to-grave approach. The assessment focuses on the structure itself (i.e., impact of the greenhouse life cycle) and on the agricultural production of the system (i.e., impact of the tomato production). Furthermore, the results are compared to a common industrial greenhouse structure of the study area, as a reference.

## 2. Methods

### 2.1. Goal and scope

This section presents the methodology of the study which follows the goal and scope definition of the ISO 14044 (ISO 2006).

#### 2.1.1. Goal of the study

The aims of this LCA are to determine the environmental burdens of a Rooftop Greenhouse (RTG) as a new form of urban agriculture production structure and to compare it to the multi-tunnel greenhouse, which is one of the most used greenhouse structures in the industrial horticulture of the South Mediterranean region. The assessment also distinguishes between the greenhouse structure itself and the tomato production, where the greenhouse is an input.

#### 2.1.2. Description of the system

The study focuses on the Rooftop Greenhouse of the RTG-Lab, as an urban agriculture system, although an industrial production system is used as a reference for comparative purposes. Moreover, this study considers the RTG of the RTG-Lab as an isolated RTG that do not exchange any flow with the building. For both systems, the system boundaries defined in the assessment are shown in Figure 2. The analysis of the greenhouse structures done from a cradle-to-grave perspective, where stages embraced are from materials extraction to the end of life of the structure. Secondly, attention is paid to tomato production and, thus, greenhouse structures become part of the life cycle of the agriculture production process. In this case, system boundaries are cradle-to-farm gate, which encompasses from the needed structure and equipment to the waste management. Tomato was chosen as horticulture product due to its importance in the vegetable market of the study area, where represents the second most sold product in MercaBarna (the food distribution center of Barcelona).

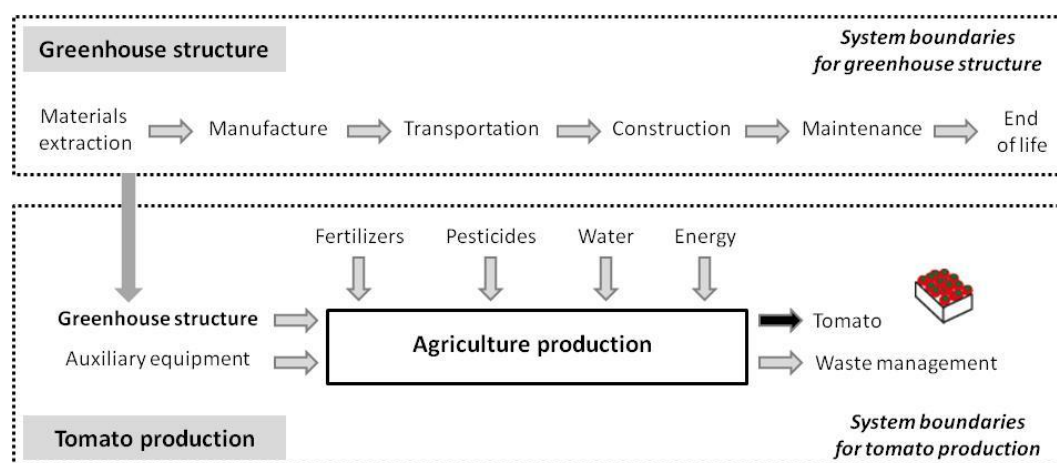


Figure 2. System boundaries of the assessment of the greenhouse structures and the tomato production.

The main differences between the RTG and the industrial system involve the greenhouse structure. The design and construction of the RTG-Lab had to overcome some legal barriers that imply a modification of the greenhouse structure: the Spanish Technical Code of Edification (CTE) (RD 314/2006 (BOE 2006)) and to fire safety laws (RD 2267/2004 (BOE 2004), Law 3/2010 (BOE 2010)). As a result, the RTG structure resulted heavier than an industrial greenhouse due to more intensive use of resources (e.g., steel). Moreover, Mediterranean greenhouses are light structures and commonly use LDPE covers, in contrast to glasshouses from colder areas (e.g., The Netherlands). However, the cover of the RTG-Lab was finally made of polycarbonate to be heavier but more resistant (particularly, offering a higher wind resistance). Finally, the construction requirements of an RTG are more intensive than for a soil-based greenhouse because materials must be raised to the rooftop.

### 2.1.3. Functional unit

The functional unit varies during the research as follows. First, when analyzing the greenhouse structure, the functional unit corresponds to 1m<sup>2</sup> of greenhouse structure for a timeframe of 1 year. Second, the functional unit of the analysis of the tomato production is 1 kg of tomato produced in a timeframe of one crop period, which is of 11 months in an RTG in Barcelona and 9 months in a multi-tunnel greenhouse situated in Almeria (Montero et al. 2011), due to the different climatic conditions. Although functional units correspond to 1 year, both assessments reflect the different lifespan of the greenhouse structures by including the maintenance stage. While the lifespan of the RTG is of 50 years according to project data and building elements, the lifespan of a multi-tunnel is of 15 years, according to law specifications (CEN 2001).

### 2.1.4. LCIA: method and impact categories

Two impact categories are included in the analysis. On one hand, the global warming potential (GWP, kg of CO<sub>2</sub> eq.) is calculated through the IPCC method (IPCC 2007) as an environmental indicator. On the other hand, the cumulative energy demand (CED, MJ) (Hischier et al. 2010) is accounted as an energy flow indicator. The SimaPro 7.3.3 program (PRé Consultants 2011) is used for the Life Cycle Impact Analysis (LCIA), which follows the classification and characterization phases defined as mandatory by the ISO 14044 regulation (ISO 2006).

## 2.2. Life cycle inventory

The life cycle inventory for the assessment of the rooftop greenhouse and the data collection process are detailed in the following section.

### 2.2.1. The Rooftop Greenhouse (RTG) system

#### (a) The greenhouse structure

The life cycle of the greenhouse structure consists of 6 stages, as illustrated by Figure 2: materials extraction, processing, transportation, construction, maintenance, and end of life. Data from the architectural project was used to quantify the amount of materials and their processing requirements. The transportation of materials was calculated according to the production site of each one, as reported in Table 1. The construction stage comprises the energy consumption of the machinery used to raise the materials to the rooftop and to build the greenhouse. Machinery consumed electricity from the grid and total consumption was calculated according to technical specifications. The maintenance of the structure was calculated based on the lifespan of the different materials, which according to producers' data were: 50 years for the steel and the concrete, 10 years for polycarbonate, 5 years for the climate screen, and 3 years for LDPE. In the maintenance stage, the amount of each material to complete the expected lifespan of the RTG (50 years) was considered. The end of life of the greenhouse structure includes both the transportation and the waste management. The structure is expected to be 100% recycled and recycling plants are 30 km far from the site.

Table 2 shows the life cycle inventory data of the Rooftop Greenhouse of the RTG-Lab for the entire greenhouse (122.8 m<sup>2</sup>) and a lifespan of 50 years, and by functional unit (1m<sup>2</sup> and 1 year). The ecoinvent database v2.2 (Swiss Center for Life Cycle Inventories 2010) was used to complete background data of the LCI. The electricity mix for 2013 of Spain (REE 2013), of The United Kingdom (DECC 2014) and of The Netherlands (CBS 2013a; CBS 2013b) were used in the assessment of the materials processing.

Table 1. Origin, distance, and mode of transportation, by material of the RTG structure.

| Material       | Origin                          | Distance (km) | Mode of transportation    |
|----------------|---------------------------------|---------------|---------------------------|
| Steel          | Martorell, Spain                | 77            | Lorry 16-32t, EURO5       |
| Polycarbonate  | Doncaster, UK                   | 1008.44       | Transoceanic freight ship |
|                |                                 | 991.7         | Lorry 16-32t, EURO5       |
| Polyethylene   | Tarragona, Spain                | 101           | Lorry 16-32t, EURO5       |
| Concrete       | Barcelona, Spain                | 40            | Lorry 16-32t, EURO5       |
| Climate screen | Hellevoetsluis, The Netherlands | 1487          | Lorry 16-32t, EURO5       |

Table 2. Life cycle inventory of the 122.8-m<sup>2</sup> Rooftop Greenhouse of the RTG-Lab for a lifespan of 50 years, and for the functional unit of 1 m<sup>2</sup> and 1 year, by life cycle stage.

| Flow                                 | Unit | Total (50 years) | Per m <sup>2</sup> and year | Source       |
|--------------------------------------|------|------------------|-----------------------------|--------------|
| <b>Materials (incl. maintenance)</b> |      |                  |                             |              |
| Steel (85% recycled)                 | kg   | 6430,54          | 1,05                        | Project data |
| Concrete                             | kg   | 1299,6           | 0,21                        | Project data |
| LDPE                                 | kg   | 640,5            | 0,10                        | Project data |
| Polycarbonate                        | kg   | 985,74           | 0,16                        | Project data |
| Polyester                            | kg   | 47,3             | 0,01                        | Project data |
| Aluminum                             | kg   | 47,3             | 0,01                        | Project data |
| Lorry 35-40t EURO5                   | tkm  | 1723,3           | 0,28                        | Calculation  |
| Transoceanic freight ship            | tkm  | 994,07           | 0,16                        | Calculation  |
| <b>Construction</b>                  |      |                  | 0,00                        |              |
| Machinery use                        | kWh  | 2,32             | 0,00                        | Calculation  |
| <b>End of life</b>                   |      |                  | 0,00                        |              |
| Lorry 35-40t EURO5                   | tkm  | 284              | 0,05                        | Calculation  |
| Recycling process                    | kg   | 9452,27          | 1,54                        | Project data |

#### (b) The tomato production

The potential tomato production in the RTG of the RTG-Lab is assessed from a cradle-to-farm gate approach. Therefore, further life cycle stages, such as distribution and retail are excluded. Moreover, the RTG of the RTG-Lab is considered as an isolated RTG that do not exchange any flow with the building. The life cycle of the tomato production includes the equipment, the agriculture inputs and the management of the outputs (i.e., waste) as shown in Figure 2. The equipment consists of both the greenhouse structure and the auxiliary equipment, which includes the elements used in the crop system (i.e., perlite as substrate), in the irrigation (i.e., pipes, pumps, injectors, water distribution system, water tank) and in the inputs application (i.e., fertilizer tank). The application of fertilizers and pesticides includes their production as well as their emissions to air and water. Finally, the waste management accounts for the transportation requirements for the disposal of the outputs of the crop system, which are expected to be 100% recycled and recycling plants are 30 km far from the site.

Data for the auxiliary equipment was obtained from the EUPHOROS project (Montero et al. 2011), while fertilizers, pesticides and energy consumption was adapted from the same project by enlarging the crop period from 9 to 11 months. Water consumption was calculated through the “PrHo v2.0 for irrigation systems of greenhouse horticulture” of the Fundación Cajamar (González et al. 2008). No experimental data was available to determine the crop yield for producing tomato in a RTG, although the expected crop yield for a crop period of 11 months in the geographic context it is expected to be of 25 kg·m<sup>-2</sup>, which combines a spring-summer and a summer-autumn crop cycles. However, since this value is still uncertain, two scenarios were assessed: an expected yield scenario (RTG), 25 kg·m<sup>-2</sup>, and a low yield scenario (RTG<sub>L</sub>), 15 kg·m<sup>-2</sup>, to show potential constraints of crop production in RTGs, such as shadows from the structure or adjacent buildings.

#### 2.2.2. Industrial horticulture: the multi-tunnel greenhouse

An industrial horticulture system is used as reference to compare with the RTG results. Horticulture production in Almeria is one of the most competitive horticulture production regions in Europe and, particularly, 60% of the tomatoes commercialized in MercaBarna (the food distribution center of Barcelona) are produced in Almeria. In this study, the multi-tunnel greenhouse structure and the tomato production in Almeria are used as reference for comparative purposes. LCI data for these systems were obtained from the EUPHOROS project, which assessed protected horticulture in Europe (Montero et al. 2011). According to the project, the crop yield considered for the industrial system is 16.5 kg·m<sup>-2</sup>.

Table 3. Life cycle inventory of the tomato production in a RTG for 1 crop cycle (1 year) per area and per kg of product, by life cycle stage and crop yield scenario (RTG – 25 kg·m<sup>-2</sup>; and RTG<sub>L</sub> – 15 kg·m<sup>-2</sup>).

| Flow  | Unit           | Per m <sup>2</sup> and year | Per kg (RTG) | Per kg (RTG <sub>L</sub> ) | Source                      |
|---|----------------|-----------------------------|--------------|----------------------------|-----------------------------|
| <b>Greenhouse structure</b>                 |                |                             |              |                            |                             |
| Steel (85% recycled)                        | kg             | 1,05E+00                    | 4,19E-02     | 6,98E-02                   | Project data                |
| Concrete                                    | kg             | 2,12E-01                    | 8,47E-03     | 1,41E-02                   | Project data                |
| LDPE  | kg             | 1,04E-01                    | 4,17E-03     | 6,95E-03                   | Project data                |
| Polycarbonate                               | kg             | 1,61E-01                    | 6,42E-03     | 1,07E-02                   | Project data                |
| Polyester                                   | kg             | 7,70E-03                    | 3,08E-04     | 5,14E-04                   | Project data                |
| Aluminum                                    | kg             | 7,70E-03                    | 3,08E-04     | 5,14E-04                   | Project data                |
| Lorry 35-40t EURO5                          | tkm            | 2,81E-01                    | 1,12E-02     | 1,87E-02                   | Calculation                 |
| Transoceanic freight ship                   | tkm            | 1,62E-01                    | 6,48E-03     | 1,08E-02                   | Calculation                 |
| Machinery use                               | kWh            | 3,78E-04                    | 1,51E-05     | 2,52E-05                   | Calculation                 |
| Lorry 35-40t EURO5                          | tkm            | 4,63E-02                    | 1,85E-03     | 3,08E-03                   | Calculation                 |
| Recycling process                           | kg             | 1,54E+00                    | 6,16E-02     | 1,03E-01                   | Project data                |
| <b>Auxiliary equipment</b>                  |                |                             |              |                            |                             |
| LDPE  | kg             | 2,30E-02                    | 9,20E-04     | 1,53E-03                   | Montero et al. (2011)       |
| Polystyrene                                 | kg             | 2,60E-02                    | 1,04E-03     | 1,73E-03                   | Montero et al. (2011)       |
| HDPE  | kg             | 9,40E-03                    | 3,76E-04     | 6,27E-04                   | Montero et al. (2011)       |
| PVC   | kg             | 4,40E-03                    | 1,76E-04     | 2,93E-04                   | Montero et al. (2011)       |
| Steel (100% recycled)                       | kg             | 5,00E-04                    | 2,00E-05     | 3,33E-05                   | Montero et al. (2011)       |
| Expanded perlite                            | kg             | 6,20E-01                    | 2,48E-02     | 4,13E-02                   | Montero et al. (2011)       |
| Van, <3.5t                                  | tkm            | 2,00E-04                    | 8,00E-06     | 1,33E-05                   | Montero et al. (2011)       |
| <b>Inputs consumption</b>                   |                |                             |              |                            |                             |
| Water                                       | m <sup>3</sup> | 7,97E-01                    | 3,19E-02     | 5,31E-02                   | Calculated                  |
| Electricity                                 | kWh            | 1,08E+00                    | 4,30E-02     | 7,17E-02                   | Adap. Montero et al. (2011) |
| Fertilizer (N)                              | g              | 9,76E+02                    | 3,90E+01     | 6,51E+01                   | Adap. Montero et al. (2011) |
| Fertilizer (P <sub>2</sub> O <sub>5</sub> ) | g              | 6,18E+01                    | 2,47E+00     | 4,12E+00                   | Adap. Montero et al. (2011) |
| Fertilizer (K <sub>2</sub> O)               | g              | 1,91E+01                    | 7,64E-01     | 1,27E+00                   | Adap. Montero et al. (2011) |
| Pesticides                                  | g              | 4,00E+00                    | 1,60E-01     | 2,67E-01                   | Adap. Montero et al. (2011) |
| <b>Waste management</b>                     |                |                             |              |                            |                             |
| Transport, van <3.5t                        | tkm            | 1,32E-01                    | 5,28E-03     | 8,80E-03                   | Calculated                  |

### 3. Results and discussion

#### 3.1. Environmental assessment of the RTG structure

The global warming potential of an RTG structure is of 2.50 kg of CO<sub>2</sub> eq., considering the functional unit of 1m<sup>2</sup> for a timeframe of 1 year. The impact is mostly associated to the materials stage (including materials extraction, materials processing, transportation, and maintenance requirements) which contributes up to 99% on the GWP (Figure 3). The energy consumption during the construction phase and the transportation to the waste management site had, thus, a little impact on the entire life cycle of the structure. Consequently, the implementation of greenhouses on buildings has no large differences with industrial greenhouses on rural areas regarding their construction requirements.

Among materials, polycarbonate is the most contributor to GWP (54.7%), due to three factors: (a) the extraction and processing requirements (i.e., oil-based material); (b) the transportation requirements; and (c) the maintenance requirements that increase the polycarbonate consumption during the life cycle, even though other materials (i.e., steel) have a large presence in the structure in weight terms. For instance, steel contributes only to 29% of the GWP although representing the 68.0% of the total amount of materials. Polyethylene and the climate screen contribute to 10.4% and 5.2% of the GWP, respectively. Particularly, the transportation of the climate screen is the most contributing stage of this material. Finally, the anchor is the least contributing material to the GWP.

The cumulative energy demand of the system is of 46.4 MJ per m<sup>2</sup> and year. The distribution of the impact follows the same pattern as for the GWP regarding the life cycle stages (Figure 3). Among the materials, poly-

carbonate and steel are the most contributors, although the impact of polyethylene represents the 20% of the CED, because of the energy demand during the extraction and processing phases of this material.

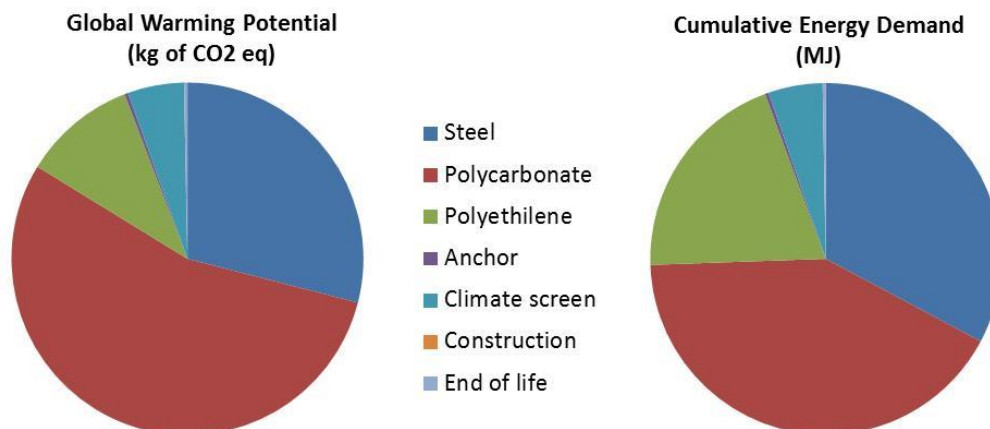


Figure 3. Distribution of the global warming potential impact and the cumulative energy demand of the RTG structure among the materials, construction and end of life stages.

In comparison to the industrial system, the global warming potential of an RTG structure resulted 81% more impacting than for a multi-tunnel greenhouse, while the cumulative energy demand was 53% higher (Figure 4). Main differences among the structures are of resources consumption for the materials. The RTG must accomplish more restrictive laws due to their situation in urban areas (e.g., security and resistance of building structures) and in height (e.g., wind resistance). For instance, the steel requirements per  $m^2$  are 5 times higher in an RTG than in a multitunnel. Beyond law requirements, the analyzed RTG is an experimental system with an area of  $122.8 m^2$ , while the industrial system operates in a  $19440 m^2$  commercial greenhouse. Therefore, certain “(in)efficiency of scale” produces a bias on the results for the RTG scenario and further case studies should be assessed in future research.

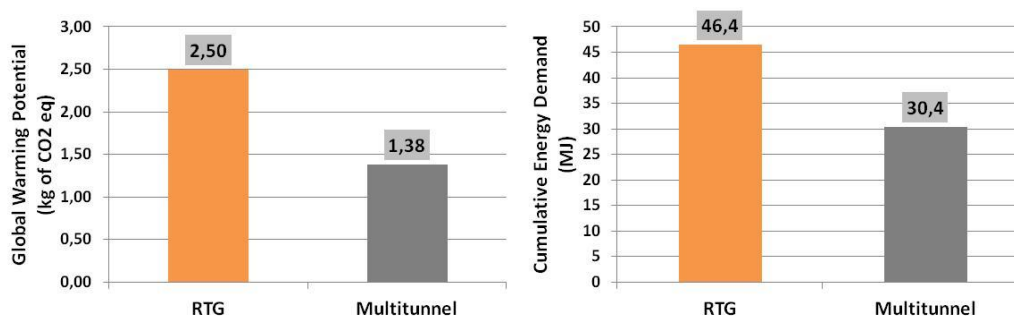


Figure 4. Comparative environmental assessment between the RTG and the multi-tunnel system, for a functional unit of  $1m^2$  for a timeframe of 1 year.

### 3.2. Environmental assessment of the tomato production in RTGs

The production of 1 kg of tomato in an RTG has a global warming potential of between 178 and 297 g of  $CO_2$  eq., depending on the crop yield. The RTG structure is the most contributor to the GWP (56.2%), a fact that is commonplace in horticultural systems (Torrellas et al. 2012), because of the large amount of materials consumed (e.g., steel and polycarbonate). Fertilizers and auxiliary equipment contribute to 22.8% and 17.1% of the GWP, respectively, since there is little energy and inputs consumption rather than fertilizers and water in an unheated greenhouse (Torrellas et al. 2012). Pesticides and waste management are the least contributors to the GWP value (<4%). The cumulative energy demand of 1 kg of tomato produced in an RTG is of between 2.9 and 4.8 MJ, depending on the crop yield, and the distribution of the impact among the life cycle stages follows a similar pattern as for the GWP indicator (Figure 5).



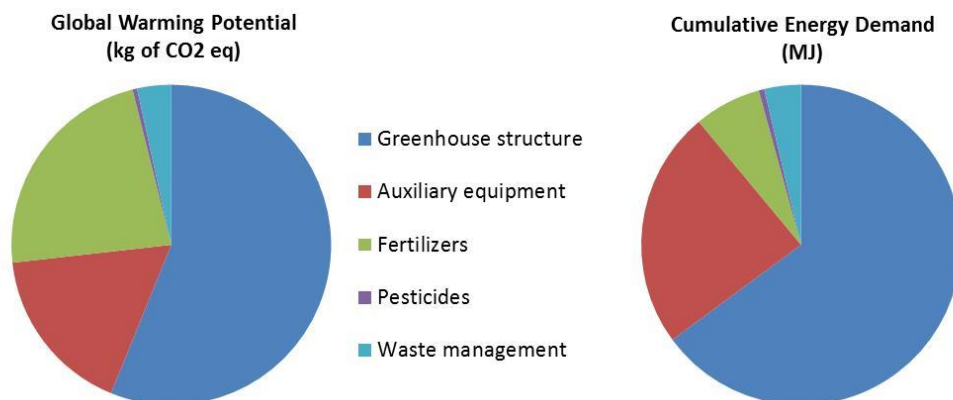


Figure 5. Distribution of the global warming potential impact and the cumulative energy demand of the tomato production in an RTG among the different life stages.

When comparing the tomato production in an RTG to industrial systems, the crop yield value becomes the most important variable. 1 kg of tomato produced in an RTG that has an expected yield of 25 kg·m<sup>-2</sup> has a 33% lower GWP than produced in a multi-tunnel. However, assuming a crop yield of 15 kg·m<sup>-2</sup> for an RTG can change drastically the results obtaining a GWP 25% higher per kg of tomato. The same results are obtained in the CED assessment, where the RTG scenario has a 31% lower value than the multi-tunnel, while the RTG<sub>L</sub> scenario was 26% higher (Figure 6). Therefore, the assessment of the horticultural activity is sensitive to the crop yield considered, and there is a need to obtain experimental data from horticultural crops in RTGs in the Mediterranean area to reduce uncertainty in further studies.

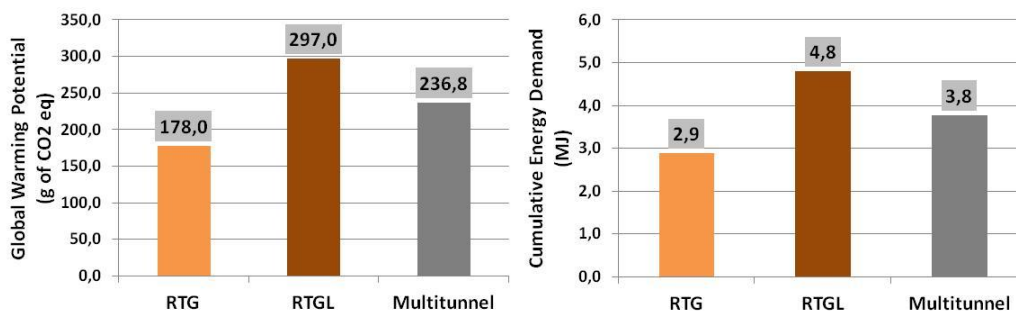


Figure 6. Comparative environmental assessment between the tomato production in a RTG with the expected crop yield – light orange; a RTG with a low crop yield – dark orange; and in a multi-tunnel system, for a functional unit of 1kg of produced tomato.

#### 4. Conclusion

The RTG of the RTG-Lab (Bellaterra, Spain) was assessed to quantify the environmental burdens of a real case study of rooftop greenhouses to analyze new urban horticulture structures that are spreading over the developed world. The global warming potential of an RTG structure resulted of 2.5 kg of CO<sub>2</sub> eq. per m<sup>2</sup>, where most of the impact came from the materials. Polycarbonate and steel were the most contributing materials to the total GWP. The construction and end of life stages of the life cycle of the structure were negligible to the final GWP value. The cumulative energy demand of the system was of 46.4 MJ per m<sup>2</sup>, and the distribution of the impact followed the same pattern as for the GWP regarding the life cycle stages. When comparing the RTG structure to an industrial greenhouse structure, the impact was 80% higher for the GWP and 53% higher for the CED. This is caused, mainly, by the larger amount of materials used in an RTG structure due to legal requirements, which are more strict in buildings of urban areas than in rural areas (e.g., security).

The RTG system was also assessed as horticultural production system. The production of 1 kg of tomato in an RTG had a global warming potential of between 178 and 297 g of CO<sub>2</sub> eq., depending on the crop yield



which is expected to be between 15 and 25 kg·m<sup>-2</sup> (although no experimental data is still available). The cumulative energy demand of 1 kg of tomato produced in an RTG was of between 2.9 and 4.8 MJ. For both indicators, the greenhouse structure, the fertilizers and the auxiliary equipment were the most contributing elements. Compared to an industrial system, results were sensitive to the crop yield considered in the RTG. As a result, the GWP was 33% lower for 1kg of tomato produced in an RTG (25 kg·m<sup>-2</sup>) than in a multi-tunnel system, although when produced in an RTG with a low yield the GWP of 1 kg of tomato resulted 25% higher. For the CED indicator, the RTG scenario obtained positive results (31% lower) when compared with the horticultural production in a multi-tunnel greenhouse, in contrast to the RTG<sub>L</sub> scenario (26% higher).

Rooftop greenhouses (RTGs) had a larger environmental impact than industrial greenhouses. The main cause of the results was the law requirements in the urban context, which lead into an increase in the materials use in order to ensure the stability and resistance of RTGs. However, further case studies should be assessed in future research since the RTG-Lab has a largely smaller area than industrial systems. The environmental impact of horticultural production in RTGs is sensitive to the crop yield and, thus, showed benefits or negative impacts when compared with the production in a multi-tunnel greenhouse. Experimental data from horticultural crops in RTGs in the Mediterranean area are needed to reduce the uncertainty in future studies. Moreover, the integration of the RTG flows with the metabolism of the building can benefit the horticultural production by reducing the impact of water consumption (e.g., rainwater harvesting in building's roof) or increasing the crop yield (e.g., energy and CO<sub>2</sub> exchange). Nevertheless, further research and experimental data may demonstrate the potentialities related to integrated RTGs and their environmental balance.

## 5. References

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