# An environmental and economic life cycle assessment of Rooftop Greenhouse (RTG) implementation in Barcelona, Spain.

Assessing new forms of urban agriculture from the greenhouse structure to the final product level.

Esther Sanyé-Mengual[1,*], Jordi Oliver-Solà[1,2], Juan Ignacio Montero[1,3], Joan Rieradevall[1,4]

[1]Sostenipra (ICTA-IRTA-Inèdit)-Institut de Ciència i Tecnologia Ambientals (ICTA). Universitat Autònoma de Barcelona (UAB). Campus de la UAB. 08193. Bellaterra (Spain)
[2]Inèdit. Inèdit Innovació, S.L. UAB Research Park. Carretera de Cabrils, km 2 (IRTA) 08348. Barcelona (Spain)
[3]Institut de Recerca i Tecnologia Agroalimentàries (IRTA). Carretera de Cabrils. km 2. 08348. Barcelona (Spain)
[4]Departament d'Enginyeria Química. Universitat Autònoma de Barcelona. Campus de la UAB. 08193 Bellaterra (Spain)
*Corresponding author: Esther.Sanye@uab.cat; Tel: +34.935.868.645

## Abstract

**Purpose:** Rooftop greenhouses (RTGs) are increasing as a new form of urban agriculture. Several environmental, economic, and social benefits have been attributed to the implementation of RTGs. However, the environmental burdens and economic costs of adapting greenhouse structures to the current building legislation have already been pointed out as a limitation of these systems in the literature. In this sense, this paper aims to analyze the environmental and economic performance of RTGs in Barcelona.

**Methods:** A real RTG project is here assessed and compared to an industrial greenhouse system (i.e., multi-tunnel), from a life cycle perspective. Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methods are followed in the assessment. The analysis is divided into three parts that progressively expand the system boundaries: greenhouse structure (cradle-to-grave), at the production point (cradle-to-farm gate), and at the consumption point (cradle-to-consumer). The applied LCIA methods are the ReCiPe (hierarchical, midpoint) and the cumulative energy demand. A Cost-Benefit analysis (CBA) approach is considered in the economic analysis. For the horticultural activity, a crop yield of 25 $kg \cdot m^{-2}$ is assumed for the RTG reference scenario. However, sensitivity analyses regarding the crop yield are performed during the whole assessment.

**Results and discussion:** The greenhouse structure of an RTG has an environmental impact between 17 and 75% higher and an economic cost 2.8 times higher than a multi-tunnel greenhouse. For the reference scenario (yield: 25 $kg \cdot m^{-2}$), 1 kg of tomato produced in an RTG at the production point has a lower environmental impact (10-19%) but a higher economic cost (24%) than in a multi-tunnel system. At the consumption point, environmental savings are up to 42% for local RTGs tomatoes, which are also 21% cheaper than tomatoes from multi-tunnel greenhouses in Almeria. However, the sensitivity assessment shows that the crop efficiency is determinant. Low yields can produce impacting and expensive vegetables, although integrated RTGs with energy from the building can lead to low impacting and cheap local food products.

**Conclusions:** RTGs face law limitations that make the greenhouse structure less environmentally-friendly and less economically competitive than current industrial greenhouses. However, as horticultural systems and local production systems, RTGs can become an environmentally-friendly option for further develop urban agriculture. Besides, attention is paid to the crop yield and, thus, further developments on integrated RTGs and their potential increase in crop yields (i.e., exchange of heat and $CO_2$ with the building) are of great interest.

**Keywords:** rooftop farming, building-integrated agriculture, urban agriculture, local production, industrial ecology

**Acknowledgments:** The authors thank the architects and technical staff of *H arquitectes* for the information supplied, the Spanish Ministerio de Economía y Competitividad (MINECO) for the financial support to the research project *“Agrourban sustainability through rooftop greenhouses. Ecoinnovation on residual flows of energy, water and* $CO_2$ *for food production”* (CTM2013-47067-C2-1-R), and the Spanish Ministerio de Educación for awarding a research scholarship (AP2010-4044) to Esther Sanyé Mengual.

## 1. Introduction

The construction of Rooftop Greenhouses (RTGs) on urban buildings has intensified in recent years. The trend has resulted from a growing interest in the development of new agricultural spaces and in the promotion of food self-sufficiency in urban areas. An RTG consists of a greenhouse built on the roof of a building that typically generates produce via soil-less culture systems (Cerón-Palma et al. 2012). These structures are considered a component of the "building-based Urban Agriculture (UA)" movement, which is also referred to as Vertical Farming (VF) (Despommier 2008; Despommier 2009; Despommier 2010; Despommier 2011), Skyfarming (Germer et al. 2011), and Zero-Acreage Farming (ZFarming) (Specht et al. 2014). Recent years VF has grown in popularity leading to the creation of a sector that seeks improving indoor cropping technologies and designing VF buildings. All devoted to boost local production, indoor farms in Singapore use high-yield hydroponic technology (Sky Greens), spherical buildings are designing by Plantagon (Sweden) or former warehouses are filled with LED-lighted hydroponic systems in the United States (such as Green Spirit Farms).

Table 1 provides a list of RTG projects and companies currently in operation, which are largely located in North America. Gotham Greens, The Vinegar Factory, and Lufa Farms are local producers based in New York and Montreal that have built RTGs ranging in size from 830 to 2900 m$^2$. Produce from these farms is sold in supermarkets, their own specialized shops, or distributed through a Community Supported Agriculture (CSA) model (Resh 2012). Vegetables grown from RTGs have been widely accepted by customers in such a way that Lufa Farms is currently planning to build two additional RTGs, thereby increasing the company's overall production area to 18,000 m$^2$. Other companies are planning to build RTGs in several Canadian cities, and the Blue Sea Development Corporation aims to construct an RTG on top of an apartment building in New York City. In Europe, RTGs are currently being operated for research purposes and therefore remain as experimental projects. Beyond food production, Vida Verde, a Dutch floriculture company based in Honselersdijk, built an RTG on top of its logistics centre for temporary product storage due to high land prices (400 €/m$^2$) (*Pers.Comm.* Vida Verde).

<Table 1>

Though RTG projects currently exist as isolated plots, RTGs can also be integrated with a building and thereby provide further benefits. Integrated RTGs (i-RTGs) can exchange metabolic flows with the building upon which they are built based on the industrial ecology concept (Cerón-Palma et al. 2012). In particular, i-RTGs can exchange and optimise the following flows: energy, water, and air emissions (e.g., $CO_2$). For instance, the ICTA-ICP research-oriented i-RTG was designed to exchange energy and $CO_2$ flows with the building and will also utilise rooftop rainwater (see Section 2).

### 1.1. RTG benefits

RTGs (both isolated and integrated) can provide environmental, economic, and social benefits, and can therefore improve the sustainability of urban areas (Cerón-Palma et al. 2012; Specht et al. 2014). Such benefits can be found at different scales: by reducing transportation (product scale) (Sanyé-Mengual et al. 2013), lessening pressure on fertile agricultural areas (global scale) (Droege 2012), and increasing the availability of urban fresh produce (local scale) (Cerón-Palma et al. 2012). RTGs also benefit buildings differently depending on the type of RTG concerned. Isolated RTGs can provide thermal insulation for buildings and therefore reduce energy consumption for acclimatisation purposes (Cerón-Palma 2012). However, benefits associated with integrated RTGs are more significant. Integrated RTGs can optimise water metabolism processes and can utilise building-residual heat for agriculture production. Table 2 elaborates further on the numerous potential benefits of RTGs.

<Table 2>

Environmental research has primarily focused on quantifying the abovementioned environmental benefits. At the food product level, Sanyé-Mengual et al. (2013) quantified environmental savings from local RTG production in Barcelona and found that resulting reductions in environmental impact from RTG production are related to reduced transportation. A comparison between the conventional supply-chain and RTG local supply-chain showed that RTG tomatoes grown in Barcelona could replace tomato production in Almeria (900 km) (the main tomato producer in Spain), thereby avoiding 441 g of $CO_2$ eq. and 12 MJ of energy consumed per kg. At the building-greenhouse system level, Cerón-Palma (2012) performed a preliminary assessment of i-RTGs. Energy modelling results illustrated the environmental benefits of energy flow exchange between RTGs and office buildings. The results showed that the introduction of residual heat from the greenhouse into the building on an ideal winter day could substitute 87 kWh of the heating demand.

The literature has thus not yet extensively focused on the potential environmental impacts of RTGs or their economic feasibility. The RTG structure has been found to be a possible barrier to the implementation of such systems due to environmental burdens associated with materials and investments required (Cerón-Palma et al. 2012). In particular, meeting legal requirements for buildings in urban areas involves reinforcing the RTG structure, which results in increased resource consumption. Furthermore, the construction stage is more energy intensive due to more intensive machinery use (e.g., rising materials to the rooftop). Finally, although real experiences already exist, there is a lack of research about real projects that could considerably contribute to a comprehensive evaluation of the potential benefits of RTGs.

### 1.2. Objectives

Given this context, the goal of this paper is to complete an environmental and economic assessment of RTGs with a focus on the RTG as a greenhouse structure and horticultural production system. This new urban horticultural structure is also compared against the multi-tunnel greenhouse model as a representative conventional greenhouse commonly used in Spain. To accomplish these objectives, this paper explores the following research questions:

a) As greenhouse structures, what are the main differences between RTGs and multi-tunnel greenhouses in environmental and economic terms?
b) At the production point (i.e., from a cradle-to-farm gate perspective), what are the main differences between RTGs and multi-tunnel greenhouses in environmental and economic terms?
c) At the consumption point (i.e., from a cradle-to-consumer perspective), what are the main differences between the local RTG supply-chain and conventional multi-tunnel production in environmental and economic terms?
d) How sensitive are the results to crop yield variability given that i-RTGs may increase crop yields by exchanging energy and $CO_2$ with buildings?

## 2. The ICTA-ICP building rooftop greenhouse

In 2014, the research-oriented i-RTG will be constructed on the top of the building that hosts the Institute of Environmental Science and Technology (ICTA) and Catalan Institute of Palaeontology (ICP). The building has an area of 7500 $m^2$ (6 floors) and is situated in the Universitat Autònoma of Barcelona (UAB) campus (Bellaterra, Barcelona). The building design is based on compact volume, reversibility and multifunctionality, energy efficiency, passive house, greenhouse, and building-integrated agriculture principles.

The Rooftop Greenhouse Lab (RTG-Lab), which will consist of two 125 $m^2$ RTGs (Figure 1), is situated on the building roof (Figure 1). The purpose of the RTG-Lab is to demonstrate the feasibility of RTGs in Mediterranean areas and the potentialities of i-RTGs. The i-RTG will utilise residual heat from the building (e.g., lab air), $CO_2$ concentrations in this residual air (i.e., which will be used as natural fertiliser), and rainwater collected from the rooftop. More specifically, residual heat and $CO_2$ integration are expected to increase crop yields. Notwithstanding the potential benefits of i-RTGs, the present paper analyses the greenhouse structure and predicts potential crop outputs but does not include an assessment on flow exchange due to lacking data on this issue.

A number of legal requirements needed to be addressed throughout the construction of the RTG and ICTA-ICP building to comply with the Spanish Technical Code of Edification (CTE) (RD 314/2006 (BOE 2006)) and fire safety laws (RD 2267/2004 (BOE 2004), Law 3/2010 (BOE 2010)). These modifications resulted in an RTG structure that utilises larger amounts of materials, some of which may also have a higher environmental impact compared to conventional greenhouse components. First, the RTG structure was reinforced to conform to CTE requirements, and thus additional resources were used. Second, LDPE was not permitted for use as the greenhouse roof due to its incompatibility with safety requirements (e.g., fire) and thus the RTG cover was constructed from polycarbonate, resulting in a higher use of resources per area (i.e., thicker material) and the use of higher-impact materials.

<Figure 1>

## 3. Life Cycle Assessment (LCA and LCC)

A life cycle approach is employed for both the environmental and the economic analyses. The Life Cycle Assessment (LCA) method (ISO 2006) quantifies the environmental burdens of the analysed systems. The Life Cycle Costing (LCC) (ISO 2008) method assesses their economic performance.

### 3.1. Goal and scope

The RTG assessment is divided into three parts to evaluate this new urban horticulture system from its greenhouse structure to its final product level. Consequently, the analysis progressively expands system boundaries as illustrated in Figure 2.

<Figure 2>

*A. Greenhouse structure assessment:*

The RTG-Lab greenhouse structure is analysed using a cradle-to-grave approach to quantify related environmental burdens and economic costs. The multi-tunnel greenhouse structure is referred to as a conventional horticulture system for comparative purposes. The multi-tunnel greenhouse is a steel-framed, arched-roofed greenhouse with vertical sidewalls (Antón et al. 2005; Montero et al. 2011) that is commonly used in Mediterranean countries. The assessment includes the following stages: materials (extraction, processing, and transportation), construction, maintenance, and end of life (Figure 2). The functional unit of the assessment is 1 $m^2$ of a greenhouse structure for a timeframe of one year. Although the functional unit corresponds to one year, the assessment considers the divergent lifespan of both greenhouse structures. The lifespan of the RTG is 50 years according to project data and building elements, whereas the lifespan of a multi-tunnel greenhouse is 15 years according to regulations (CEN 2001).

*B. Assessment at the production point:*

The production in a RTG is analysed and compared to that in a multi-tunnel system using a cradle-to-farm gate perspective. The system boundaries of horticultural production include the greenhouse structure, the production inputs, and the waste management (Figure 2). Tomato production in a multi-tunnel greenhouse in Almeria is used as the conventional system. Tomato production from Almeria is selected due to its importance to the vegetable market of the study area. Tomatoes are the second most frequently sold product (14% of share) in MercaBarna (the food distribution centre of Barcelona), and 60% of this produce is produced in Almeria (MercaBarna 2014). While the RTG is situated in Barcelona, the multi-tunnel system is located in Almeria. As a result, the crop periods of the two systems differ due to climatic conditions. While tomatoes are produced in Almeria as a nine-month crop (because the summer season is too hot for horticultural production), the crop period can extend to 11 months in Barcelona by combining two crop cycles: the winter-summer and autumn-winter cycles. This extension is made possible through the introduction of residual heat from the building into the greenhouse, thereby extending the crop period during colder months. The functional unit of the assessment is 1 kg of tomatoes produced over one year at the farm gate.

*C. Assessment at the consumption point:*

A cradle-to-consumer approach is used to compare the two systems at the consumption point. Accordingly, system boundaries are expanded to include additional life cycle stages: agricultural production, packaging production, distribution, and retail. The consumption phase is excluded from the assessment due to its dependence on tomato preparation methods (e.g., from raw consumption to oven grilled) (Figure 2). With respect to distribution, the RTG represents a case of local production in which production is driven directly to the retail location with limited transport (25 km from Bellaterra to Barcelona). In contrast, the conventional case includes three different transportation stages (900 km from Almeria to Barcelona), and tomatoes are distributed through a food distribution centre. The functional unit of the assessment is 1 kg of tomatoes retailed for consumption in Barcelona.

### 3.2. Life cycle inventory

#### 3.2.1. Greenhouse structure assessment

RTG and conventional multi-tunnel greenhouse inventory data and costs are detailed in Supporting Information 4. The following sections describe assumptions made with respect to the data compilations for both systems.

**(i) RTG**

RTG inventory and economic cost data were drawn from ICTA-ICP building architectural project records, data provided by producers, and our own calculations. Stages related to materials (extraction and processing) are defined according to the structural design of the project. Transportation requirements for the materials are calculated based on the distance of the destination from the production site, as shown in Supporting Information 2. The construction stage accounts for both the labour and energy consumption requirements of machinery used to raise the materials to the rooftop. Construction machinery consumes electricity from the grid, and total consumption levels are calculated according to technical specifications and construction requirements (detailed data is provided in Supporting Information 2). The construction stage does not consider the occupation of land, since RTGs take advantage from available surfaces in cities while land use and occupation corresponds to the existing building. Structure maintenance is calculated based on the lifespans of different materials according to data from producers (Supporting Information 1). For each material, the environmental burdens and economic costs of the maintenance are calculated as the quantity of material needed to achieve the expected RTG lifespan (50 years). Finally, because the structure is designed to be 100% recyclable, only transportation is considered (recycling plants are located 30 km away from the site). This approach is appropriate because waste material recycling practices are excluded from the system boundaries due to the fact they are included in future life cycles as input processes (Ekvall and Tillman 1997).

Specific data on concrete manufacturing are obtained from the regional iTec database (ITeC 2012). Electricity mixes in 2013 for Spain (REE 2013), the United Kingdom (DECC 2014), and the Netherlands (CBS 2013a; CBS 2013b) are used in the materials processing assessment. The ecoinvent database v2.2 (Swiss Center for Life Cycle Inventories 2010) is used to collect background data on material LCI, processing, and transportation characteristics. Costs are obtained from ICTA-ICP building architectural project records.

#### (ii) Conventional system: multi-tunnel greenhouse

Inventory and economic cost data for the conventional multi-tunnel greenhouse design are obtained from EUPHOROS project data (Montero et al. 2011). The data are adapted accordingly: recycled materials obtained from the market are modelled according to the cut-off perspective, where the input resource is assumed to be zero although processing steps are included (Ekvall and Tillman 1997); and the electricity mix in 2013 for Spain (REE 2013) is assumed for electricity consumption.

### 3.2.2. Assessment at the production point: a cradle-to-farm gate perspective

Inventory data and costs of tomato production in an RTG and in a conventional multi-tunnel greenhouse are detailed in Supporting Information 5. The following section lists assumptions made for both systems throughout the data compilation stage.

#### (i) RTG tomato production in Bellaterra (Spain)

LCI and economic data are obtained from architectural project data, EUPHOROS project data (Montero et al. 2011), and from our own calculations. Apart from the greenhouse structure, production inputs include: auxiliary equipment, which includes equipment used in the crop system (i.e., substrate), for irrigation (i.e., pipes, pumps, injectors, water distribution systems, water tanks), for input application (i.e., fertiliser tank); and the consumption of water, energy, fertilisers and pesticides. Data on auxiliary equipment are drawn from EUPHOROS project data (Montero et al. 2011). Crop input costs and data (i.e., fertilisers, pesticides, and energy consumption) are adapted from the same project by extending the crop period from nine to 11 months (as mentioned above). Water consumption is calculated using the Fundación Cajamar software program "PrHo v2.0 for irrigation systems of greenhouse horticulture" (González et al. 2008). Fertiliser and pesticide application includes their production as well as their emission into water and the atmosphere. Waste management accounts for transportation requirements for the disposal of crop system outputs, which are intended to be 100% recyclable, and recycling plants are located 30 km away from the site. Because no experimental data are available to determine RTG tomato crop yields, a crop yield of 25 $kg \cdot m^{-2}$ is used as the reference yield in the assessment. This denotes the expected crop yield for a crop period of 11 months in a conventional greenhouse situated in the same geographic context (unpublished work, ICTA). Finally, the price at which producers sell tomatoes includes a 6% margin in accordance with EUPHOROS project data (Montero et al. 2011).

Land costs (i.e., rooftop or agrarian soil use) are excluded from the economic assessment for two reasons. First, RTG business approaches are still unknown due to the lack of experiences in the study area. Consequently, prices are uncertain, as several rooftops may be owned by a single company that utilises the RTG (e.g., food companies) or may be rented to/by another agent. In this second case, the value of the rooftop may be determined as the urban soil price (which varies considerably depending on the location of the building), a lower price (e.g., a percentage of the soil price), or a value based on crop outputs. On the other hand, land costs are often excluded from economic balances of agriculture activities because land is an inversion that is presumed to be recovered when economic activity concludes.

#### (ii) Conventional system: multi-tunnel greenhouse tomato production in Almeria (Spain)

Inventory data and economic costs for tomato production in a multi-tunnel greenhouse in Almeria are obtained from EUPHOROS project data (Montero et al. 2011). The inventory is based on a crop yield of 16.5 $kg \cdot m^{-2}$.

### 3.2.3. Assessment at the consumption point: a cradle-to-consumer perspective

Inventory data and tomato supply-chain costs for a local RTG and conventional multi-tunnel greenhouse are detailed in Supporting Information 6. The following section lists assumptions made for both systems throughout the data compilation process.

#### (i) Local supply-chain: RTG tomato production in Bellaterra

The local supply-chain accounts for residents of Barcelona that consume tomatoes produced in an RTG in Bellaterra. Tomatoes are transported by van (<3.5t) from the production site to the consumption site (25 km). Tomatoes are packaged in trays made from recycled HDPE that weight 600 gr each and hold 6 kg loads of tomatoes, and which are recycled at the end of the lifespan, according to Sanyé-Mengual et al. (2013) the packaging market (e.g., DAPLAST, 2014). Finally, it is assumed that no product losses occur within the local supply-chain due to the freshness of the product and limited manipulation of the product, which is sold immediately after harvesting.

#### (ii) Conventional supply-chain

The conventional supply-chain for tomatoes grown in a multi-tunnel greenhouse in Almeria is based on Sanyé-Mengual et al. (2013). Conventional tomato distribution involves three steps. First, tomatoes are transported from the production site to a warehouse in Almeria (20 km). Second, tomatoes are transported to a food distribution centre in Barcelona (MercaBarna), where the tomatoes are sold to retailers (825 km). Third, retailers transport the product to their shops throughout Barcelona (10 km). Unlike the local supply-chain, considerable product losses occur over the course of the conventional supply-chain. Product losses occur during the transportation (due to dehydration) and retail stages (due to product damage). According to Sanyé-Mengual et al. (2013), total losses that occur throughout the Almeria-Barcelona tomato supply-chain account for 16.6%. Supplying 1 kg of tomatoes at the consumption site necessitates a larger amount of agriculture production in a conventional supply-chain than in a local supply-chain, and this leads into higher associated environmental impacts and costs. Furthermore, damaged products in retail spaces are treated as a waste. For the purposes of this study, product losses that occur during the retail stage are assumed to be composted. In MercaBarna, electricity is used to light warehouse buildings. Finally, packaging practices are considered the same for both systems.

#### (iii) Data sources

LCI data and costs for the different life cycle stages were obtained from various sources. Agricultural production data and costs provided correspond to data drawn from previous sections. LCI data on packaging production and transportation requirements were obtained from the ecoinvent database v2.2 (Swiss Center for Life Cycle Inventories 2010). The packaging cost was obtained from a distribution company of MercaBarna (Pers. Comm., GavàGrup). Economic costs of the different stages were assumed as follows. Transportation costs were calculated according to the “Observatory of road freight transport costs in Catalonia” (Generalitat de Catalunya (DGTM) 2012). The average price of Spanish electricity (EUROSTAT 2014) was used as the cost of electricity consumption in the distribution centre. Composting, the treatment used to address food waste produced during the retail phase, was assessed based on LCI data drawn from the literature (Martínez-Blanco et al. 2011). Finally, the average price of tomatoes in Catalonia in 2013 (MAGRAMA 2014) was assumed to be the cost of product loss during the retail stage (Table 4).

## 3.3. Sensitivity analysis

Sensitivity analyses are performed to illustrate how results depend on two variables: crop yield and distance to conventional production site.

### 3.3.1. Sensitivity analysis: crop yield variability (cradle-to-farm gate)

As mentioned above, RTG crop yields in Mediterranean contexts are still unknown due to a lack of experimental data. On one hand, crop yields may decrease due to limitations, such as shadows generated by the structure. On the other hand, an i-RTG greenhouse can utilise residual building heat via air-flow exchange. This air has different temperature and $CO_2$ concentration that may benefit the agricultural production by increasing the crop yield (Cerón-Palma 2012). Thus, a sensitivity analysis that accounts for various RTG crop yield levels is conducted to observe dependence results and trends. The analysis is applied to the production point assessment (cradle-to-farm gate), and crop yields range between 10 and 55 $kg\cdot m^{-2}$, the latter representing the Dutch crop yield value for tomato production in Venlo greenhouses (Montero et al. 2011). For conventional production (i.e., multi-tunnel) crop yield is considered constant as 16.5 $kg\cdot m^{-2}$ since experimental data is available. As variability on crop yield is mostly based on technological aspects (e.g., benefits from i-RTGs), crop inputs do not depend on crop yield while are considered as a determined application per area (e.g., amount of fertilizer per area of crop) rather than marginal consumption per amount of production.

### 3.3.2. Sensitivity analysis: crop yield and distance to conventional production site (cradle-to-consumer)

One advantage of RTGs is their urban location and thus close proximity to consumers and limited transportation requirements. Furthermore, key aspects of supply-chain environmental impact are related to distance: agriculture production, product loss, packaging use, and food waste treatment. In this sense, the RTG system is considered as a local horticultural production. A distance threshold is calculated to determine the distance at which the RTG system either becomes more environmentally friendly or less cost intensive than the multi-tunnel system. The distance threshold is obtained by matching the environmental impact and economic cost of 1 kg of tomatoes produced in an RTG at the consumer point with the environmental impact and economic cost of 1 kg of tomatoes produced in a multi-tunnel greenhouse (i.e., located at a distance of X) at the consumer point. This threshold allows one to determine whether RTGs may become local production systems that offer environmental and economic benefits. However because the crop yield is determinant, the distance threshold is calculated for three crop yield scenarios: low yield (10 $kg\cdot m^{-2}$), reference yield (25 $kg\cdot m^{-2}$), and high yield (55 $kg\cdot m^{-2}$).

To accomplish this task, a model was designed to predict the environmental impact of the conventional supply-chain ($EI_{CSC}$) by establishing a relation between the environmental impact or economic cost of each life cycle stage and the distance from the production site to the consumption site. The model is shown in Equation 1.

$$EI_{CSC} = (1 + PL_t \cdot d) \cdot EI_{AP} + (1 + PL_t \cdot d) \cdot EI_P + \frac{(1+PL_t \cdot d)\cdot d \cdot EI_T}{1000} + \frac{0.1 \cdot d \cdot EI_{FW}}{1000} \qquad (1)$$

*where $EI_{CSC}$ is the environmental impact of the conventional supply-chain per kg of consumed tomatoes, $EI_{AP}$ is the environmental impact of agricultural production (i.e., per kg of tomatoes produced), $EI_P$ is the environmental impact of packaging (i.e., per kg of packaged tomatoes), $EI_T$ is the environmental impact of transportation (i.e., per tkm), and $EI_{FW}$ is the environmental impact of food waste treatment (i.e., per kg of composted food waste). The constant $PL_T$ refers to product losses occurring during transportation, which is $8.25\cdot 10^{-5}$ kg of tomatoes$\cdot km^{-1}$, according to data provided by Sanyé-Mengual et al. (2013).*

The same model is used to calculate the economic cost of the conventional supply-chain ($EC_{CSC}$) based on distance, according to Equation 2.

$$EC_{CSC} = (1 + PL_t \cdot d) \cdot EC_{AP} + (1 + PL_t \cdot d) \cdot EC_P + \frac{(1+PL_t \cdot d)\cdot d \cdot EC_T}{1000} + \frac{0.1 \cdot d \cdot EC_{FW}}{1000} \qquad (2)$$

### 3.4. Environmental impact and economic assessment

The environmental impact assessment of the two systems is performed by applying the Life Cycle Impact Analysis (LCIA) stage. The SimaPro 7.3.3 program (PRé Consultants 2011) is used to conduct the LCIA, which follows classification and characterisation steps determined as mandatory by the ISO 14044 regulation (ISO 2006). The LCIA is carried out at the midpoint level, and methods applied include the ReCiPe (Goedkoop et al. 2009) and cumulative energy demand (CED) (Hischier et al. 2010). With respect to the ReCiPe, the hierarchical time perspective is considered, as recommended in the ILCD Handbook (EC-JRC 2010). In comparing the RTG to the conventional system, results are shown in relation to three indicators: the normalised ReCiPe value (Norm-ReCiPe, Pt), the global warming potential (GWP, kg of $CO_2$ eq.) (IPCC 2007), and the CED value (MJ).

A Cost-Benefit Analysis (CBA) approach is applied for the LCC assessment. Hence, life cycle costs and revenues for each system are considered. Two indicators are used: Total cost (TC, €) and Total profit (TP, €). The assessment progressively expands the system boundaries, and costs may be borne out of different actors (especially in the conventional system). Actors can have different perspectives of costs (Hunkeler et al. 2008; Swarr et al. 2011). The actor changes depending on the assessment perspective: the producer is the actor of focus for the cradle-to-farm gate, and the retailer is the actor in the case of cradle-to-consumer perspectives. Because 2013 is used as the assessment reference year, costs and prices collected for different years were updated to the present value based on the inflation rate (Supporting Information 3).

## 4. Results and discussion

### 4.1. Greenhouse structure assessment

The results of the greenhouse structure assessment for the RTG and multi-tunnel greenhouse structures are shown in Table 3.

<Table 3>

Because the RTG structure was noted as a potential limitation to the implementation of RTGs in the literature due to the environmental impact and economic cost (Cerón-Palma et al., 2012), the first component of the assessment focused on the greenhouse structure. The RTG structure has an associated environmental impact per $m^2$ and year of $3.30 \cdot 10^{-2}$ Pt of the normalised ReCiPe indicator, a global warming potential of 2.42 kg of $CO_2$ eq., and an energy demand of 44.0 MJ (Table 3). Among ReCiPe indicators, the majority of the system's environmental impacts are associated with the materials and maintenance stages. Materials represent between 29% and 97.1% of environmental impacts generated by the system and 42.4% of the total cost, and maintenance represents between 3% and 70.6% of environmental impacts and 54.9% of the total cost. The materials stage is the largest contributing one to the toxicity categories (58–95%), due to steel manufacturing processes and related air emissions of mercury and water emissions of manganese and arsenic. Maintenance stage is more impacting in those categories related to fossil resources, such as GWP, mainly due to the production of polycarbonate and consequent emissions of carbon dioxide and methane. Detailed ReCiPe results are shown in Supporting Information 7.

RTG structure materials contribute differently to the indicators and life cycle stages shown in Table 3. Steel is the material that has the largest environmental impact (69.5%-96.4%), followed by polycarbonate (2.2%-26.8%) particularly in those categories where thermoplasts tend to have the most significant impact. Concrete only marginally affects the different indicators (<1%). During the maintenance stage, polycarbonate has the largest environmental impact of all of the materials (58.9%-77.4%).

The RTG structure has a higher environmental impact than the multi-tunnel greenhouse structure: 17% of the normalised-ReCiPe, 45% of the CED, and 75% of the GWP (Table 3). However, differences between the two structures depend on the indicators, which are determined by the amount and type of materials used. With respect to the amount of materials, the RTG structure requires only 13% more material than the multi-tunnel structure (see the LCI value reported in Supporting Information 4), and thus one may assume that the environmental impact and economic cost of the RTG structure would be approximately 13% higher than that of the multi-tunnel structure. However, as the differences are more significant, it is necessary to examine the different types of materials. The most significant difference between the RTG and multi-tunnel structures is the volume of polycarbonate used: the first consumes 14 times more polycarbonate than the multi-tunnel. Consequently, RTG has a larger environmental impact in those categories in which thermoplasts contribute more, such as GWP (75% higher), than in other categories, such as human toxicity (6% higher).

The results of the economic assessment show that the total cost reaches $11.9 € \cdot m^{-2} \cdot year^{-1}$. The most expensive life cycle stage is the maintenance stage, which involves the substitution of plastic elements. Regarding materials, steel is the most expensive material (62.2%), although the climate screen is the most expensive element of the maintenance stage (77.7%). Furthermore, no profits are obtained from the greenhouse structure itself. Consequently, the cradle-to-grave economic cost of the RTG structure is 2.8 times larger than that of the multi-tunnel structure (Table 3). Detailed cost data are shown in Supporting Information 7.

### 4.2. Assessment at the production point: cradle-to-farm gate perspective

The RTG and multi-tunnel greenhouse tomato production results are compared in Table 4.

<Table 4>

At the farm gate, the production of 1 kg of tomatoes in a RTG has an environmental impact of $1.66 \cdot 10^{-3}$ according to the normalised ReCiPe indicator, a GWP of 216 g of $CO_2$ eq., and a CED of 3.25 MJ (Table 4). The greenhouse structure contributes the most to the ReCiPe indicators (41.0 – 79.5%), apart from four: marine ecotoxicity, in which nitrate emissions from fertiliser application are the main effect (95.4%); natural land transformation, in which substrate production contributes most (53.8%); ionising radiation, in which irrigation system electricity consumption is the main contributor (50.9%); and agricultural land occupation, in which waste management contributes the most (34%). Detailed ReCiPe results are shown in Supporting Information 8.

RTG tomato production has a lower environmental impact than conventional multi-tunnel production: GWP (9%), CED (14%) and Norm-ReCiPe (26%). These results differ from those of the greenhouse structure assessment because the RTG crop yield is expected to reach 25 $kg \cdot m^{-2}$ due to the use of a larger crop period (11 months) than in conventional production (nine months). With respect to ReCiPe indicators, RTG tomato production has a between 1% and 40% lower environmental impact than that of the multi-tunnel, with the exception of ozone depletion, on which RTG has a 30% higher impact due to plastic material production processes. RTG tomato production can notably decrease the water depletion potential of conventional production by 98%, as the system harvests rainwater from the top of the building as in the RTG-Lab. In addition, the agricultural land transformation impact is also reduced by 96% because RTGs are situated on rooftops, thereby alleviating pressures on agricultural areas. Nevertheless, impact distributions among production inputs are similar for both systems. Auxiliary equipment, which includes water and energy consumption, contributes the most to the normalised ReCiPe and cumulative energy demand (≈40%), although fertilisers contribute the most to global warming (≈53%) (Table 4).

At the farm gate, the economic cost of 1 kg of tomatoes produced in a RTG is 0.737€, and the total profit per kg is 0.045€. RTG tomato production is thus 21% more expensive than it is using the conventional system, mainly due to greenhouse structure costs. However because profits are based on production costs (i.e., the sale price is calculated based on a 6% profit), RTG tomato production is more profitable than multi-tunnel tomato production (21%) (Table 4). RTG production costs are 18.4 $€ \cdot m^{-2}$ per production system area, to which the greenhouse structure contributes 63%. In contrast, multi-tunnel production costs reach 10.0 $€ \cdot m^{-2}$, and the greenhouse structure accounts for 43%. For both systems, paid labour and fertilisers represent the other most significant inputs. Production costs per area are shown in Supporting Information 5.

### 4.3. Assessment at the consumption point: a cradle-to-consumer perspective

Table 5 shows the results of the tomato production assessment at the consumption point in Barcelona for a local RTG supply-chain from Bellaterra and a conventional supply-chain from Almeria.

<Table 5>

At consumption point, the life cycle of 1 kg of tomatoes produced in a local RTG has an environmental impact of $2.94 \cdot 10^{-3}$ in the normalised ReCiPe indicator, a GWP of 0.78 kg of $CO_2$ eq., and a CED of 8.44 MJ (Table 5). The agricultural production stage contributes most to the normalised ReCiPe indicator (56.4%), while packaging contributes the most to GWP (69.5%) and CED (61.5%). For the other ReCiPe indicators, packaging is the most important life cycle stage (51.6% - 86.0%), apart from metal depletion, for which agriculture production (i.e., greenhouse structure) represents 58.7% of the impact; marine ecotoxicity, for which agriculture production (i.e., fertilisers) exhibits the highest impact (90.5%); and other toxicity indicators, for which agricultural production (i.e., emissions from metal production) represents the most influential stage (55.0% - 66.4%). Transportation from Bellaterra to Barcelona has a minimal (<1%) environmental impact. Trends are slightly different with respect to economic cost, for which agricultural production represents 87.1%, packaging represents 12.2%, and transportation accounts for 0.7%. The cost distribution is mainly dependent on the greenhouse structure cost during the agricultural production stage. A reusable packaging scenario in which packaging is reused 20 times was quantified to further assess the environmental impact of local RTG tomato production. In this case, packaging becomes the second most influential contributor (between 1% and 18% of the impact), and agricultural production instead emerges as the most impactful stage. Overall, the impact of the local tomato supply-chain can be reduced by between 32% and 82% (apart from marine ecotoxicity – 9%). The cost at the consumer point can also be reduced by 12%. Results are detailed in Supporting Information 9.

Locally-supplied RTG tomatoes have an environmental impact that is between 33% and 42% lower than tomatoes produced through the conventional supply-chain, depending on the indicator. The economic cost of the RTG supply-chain is also lower for each kg of tomatoes (21%) (Table 5). Among ReCiPe indicators, environmental savings reach between 20% and 74%, with the exception of water depletion, for which the use of rainwater boosts environmental impact reductions to 93%, although rainwater harvesting can also be used as a sustainable source of irrigation water for conventional greenhouses. Finally, the economic profits of RTGs are higher when the same tomato price for both systems (1.47€) is assumed. A local RTG supply-chain obtains profits 1.58 times higher than the conventional supply-chain (Table 5). These results are related to the following factors. First, RTGs follow a local supply-chain in which transportation is largely reduced. Second, food waste is not produced in the RTG supply-chain as the product is sold immediately after harvesting. As a result, additional tomato production is not needed to satisfy the 1 kg demand in the RTG scenario.

These results assume the use of single-use packaging for both systems. However, packaging practices were assessed for both systems by comparing single-use and re-usable (20 uses) packaging options. When both systems use re-usable packaging, RTGs are still 21% cheaper than the conventional supply-chain and have a lower environmental impact (between 36% and 98%). Sanyé-Mengual et al. (2013) noted that local systems have a higher capacity to reuse packaging than conventional systems. The environmental impact of a RTG local supply-chain that uses re-usable packaging was thus compared to the results for a conventional supply-chain that uses single-use packaging. In this case, local RTG tomatoes have a 41% to 98% lower environmental impact than the conventional scenario and are 30% cheaper (Results are shown in Supporting Information 9).

### 4.4. Sensitivity analysis: crop yield variability

An agricultural production system has an associated environmental impact per area that is allocated for each kg of product based on the crop yield. For the RTG system, a crop variability sensitivity analysis was conducted due to high levels of uncertainty surrounding crop yields. Results in Figure 3 show the same pattern for the three environmental indicators and for the economic cost. At the farm gate, 1 kg of tomatoes produced in an RTG has the same environmental impact as 1 kg of tomatoes produced in a multi-tunnel greenhouse when crop productivity reaches between 20.3 and 23.7 $kg\cdot m^{-2}$, depending on the indicator. Regarding economic costs, the crop yield can be increased further to 30.4 $kg\cdot m^{-2}$.

<Figure 3>

Although RTG tomato production in the reference scenario (25 $kg\cdot m^{-2}$) is associated with lower environmental impacts but slightly higher economic costs than those of conventional greenhouses, two trends can be found in the sensitivity assessment (Figure 3). First, very low RTG yields (<15) (e.g., due to shadows from other buildings or the greenhouse structure on crops) can result in expensive food products of high environmental impact. On the other hand, i-RTGs can utilise residual building air (heat and $CO_2$), thereby increasing RTG crop yields without enlarging environmental burdens. Consequently, food products grown in i-RTGs that reach high yields (>40) may be of considerable interest due to their low environmental impact and economic competitiveness. This finding contribute to the existing debate on the pros and cons of local production in relation to conventional options (Edwards-Jones et al. 2008).

Regarding potential economic benefits, a local producer (e.g., RTGs) can capitalise on retail options that avoid supply-chain agents (i.e., direct selling to consumers). RTG businesses are in an especially optimal position to sell their products through different venues, as shown in the following examples: Gotham Greens sells products in supermarkets, Lufa Farms distribute horticultural products through a Community Supported Agriculture (CSA) model, and The Vinegar Factory operates its own specialty store. When calculating the minimum tomato price necessary to cover RTG production costs by crop yield, it becomes evident that RTG-grown tomatoes can be sold at prices even lower than the producer tomato price (0.61€) (updated from Montero et al. 2011) (Figure 4). With respect to the reference scenario, an RTG with a crop yield of 25 $kg\cdot m^{-2}$ could cover production costs by adopting a tomato price lower than the current retail price (1.47€), and could thus become more competitive by selling tomatoes at prices lower than the current wholesale price (1.18€). However, as shown in the sensitivity analysis listed in Figure 4, these results strongly depend on crop yields (Detailed information is provided in Supporting Information 10).

<Figure 4>

### 4.5. Sensitivity analysis: crop yield and distance to conventional production site

The environmental impact and economic cost of conventional supply-chain (i.e., multi-tunnel) tomato production is calculated for a transportation distance of 0 to 1000 km. Through a comparison between local RTG tomato values, one can determine the distance at which local tomatoes are better to conventional tomatoes in environmental and economic terms. Figure 5 shows comparisons for the four indicators.

<Figure 5>

With respect to the reference yield (25 kg·m$^{-2}$), local RTG tomatoes exhibit a superior environmental profile than tomatoes grown from conventional production. Otherwise, local tomatoes are more expensive than conventional tomatoes due to costs associated with the RTG structure. Consequently, RTG tomatoes will only become cheaper than conventional tomatoes when grown in an area at least 400 km away from Barcelona. In the case of i-RTGs with high yields (55 kg·m$^{-2}$), tomatoes from local RTGs would be preferable to conventional options with respect to both environmental and economic indicators (Figure 5).

In contrast, local tomatoes grown from low-yield RTGs (10 kg·m$^{-2}$) would need to substitute conventional tomatoes from areas situated between 120 km and 870 km to become more environmentally friendly. Distances depend on the indicator considered: 120 km (ReCiPe-norm), 650 km (GWP), and 870 km (CED). These results demonstrate how the definition of environmental products affects results. Current eco-labels typically focus on the global warming or energy consumption impacts of products, such as carbon footprint labelling used in Tesco supermarkets. In this case, local RTG tomatoes may be superior to other local products (<100 km) from a global environmental perspective (i.e., ReCiPe-norm indicator), but worse than other products when focusing on certain aspects (i.e., GWP or CED). Consequently, the prioritisation of indicators can significantly affect how environmentally friendly local products are relative to other market options. Finally, local tomatoes grown in low-yield RTGs will not become cheaper than tomatoes grown via conventional production in Spain (Figure 5).

## 5. Conclusions

The paper contributes to the current theoretical knowledge of building-based urban agriculture (Cerón-Palma et al. 2012; Despommier 2010; Specht et al. 2014: Thomaier et al. 2014). This assessment of greenhouse structures to final products provided a comprehensive understanding of the environmental and economic performance of RTGs in the Barcelona area. Comparisons with conventional greenhouse systems contextualised the results within the current agriculture sector. The assessment found that the RTG infraestructure has a larger environmental impact and is more expensive than a multi-tunnel system. However, tomatoes produced in RTGs have a lower environmental impact than those produced in multi-tunnel greenhouses, both at the farm gate and at the point of consumption. In contrast, RTG-grown tomatoes are more expensive at the farm gate, but cheaper at the point of consumption, when all the supply-chain costs are included.

At the greenhouse structure level, RTGs have greater environmental impacts than multi-tunnel greenhouses (between 17% and 75%), though economic costs associated with the former were 2.8 times higher. Therefore, at the greenhouse structure level, RTGs are less attractive than multi-tunnel greenhouses from an environmental and economic perspective. These results reiterate risks and limitations associated with RTGs that have been previously mentioned in the literature (Cerón-Palma et al. 2012; Specht et al. 2014). The present study assessed a pilot project that was adapted to current building legislation and which exhibited higher resources consumption than conventional greenhouse systems. However, future efforts may balance legislative requirements with innovation by, for instance, limiting greenhouse structure overweighting.

As horticultural production systems, RTG and multi-tunnel greenhouse tomato production systems were compared. At the production point (cradle-to-farm gate), 1 kg of RTG-grown tomatoes had an environmental impact between 9% and 26% lower than that of the multi-tunnel system. The economic cost of RTG tomatoes was 21% higher than associated multi-tunnel cost, although the RTG system obtained a 21% higher profit. Differences between RTG and conventional system production were based on crop yields. Crop yields were higher in the RTG than in the multi-tunnel greenhouse system because RTGs are designed to combine two crop cycles in a single year, resulting in a crop yield of 25 kg·m$^{-2}$. At the consumption point (cradle-to-consumer), tomatoes locally produced through RTGs in Bellaterra had a lower environmental impact and were cheaper than those produced through conventional supply-chains originating from Almeria. More specifically, the environmental impact was between 33% and 42% lower and the cost was 21% cheaper. These results vary depending on the extent to which local produce distribution and food waste production are avoided. Furthermore, the type of packaging (single-use or re-usable) can affect the results significantly.

Crop yield variability was found to significantly affect assessments of these new systems. First, no experimental data exist to determine the real RTG crop yield for the Mediterranean context. Second, i-RTGs are expected to increase crop yields without increasing environmental burdens or economic costs. Consequently, the sensitivity assessment showed potential variations in the environmental impacts and economic costs of RTGs. When considering the entire supply-chain, the balance between local, RTG-grown products and conventional products strongly depends on the crop yield. Local RTGs with high crop yields (>25 kg·m$^{-2}$) may produce tomatoes with lower environmental impact than conventional supply-chains. Thus, the agronomic efficiency of each RTG project will determine whether RTGs are superior to conventional systems in environmental and economic terms.

### 5.1. RTGs contribution to urban agriculture and sustainability: economic and social aspects

Overall, RTGs promote sustainable urban agriculture by addressing key aspects of environmental policy: energy consumption and global warming. As local production systems, RTGs offer sustainable distribution practices by limiting food miles and associated environmental impacts. Furthermore, environmental benefits are not only found in distribution stages due to reduced distances but along the entire life cycle of the product: in initial stages, lower product loss in distribution results in a reduction in agricultural production; while in final stages, this also derives in a smaller amount of food waste. In addition, i-RTGs that exchange energy flows with buildings can minimise energy consumed through both agricultural production and building operation (e.g., reduced heating demand) (Cerón-Palma 2012).

RTGs and urban vertical farming strategies can effectively supplement the urban self-supply of food through local consumption (Cerón-Palma et al. 2012; Specht et al. 2014). Local production should only complement the conventional agricultural sector, which currently serves the vegetable market. However, local production schemes such as RTGs can address the growing demand for local products. Moreover, some RTG projects have focused their production on added-value options, such as producing marmalade or offering off-season products at a competitive price. Even more, RTGs can take advantage of their situation by producing vegetables that are prone to spoilage during transportation. Furthermore, urban agriculture will contribute to the green economy, which represents one of the key features of sustainability policies applied in developed countries (UNEP 2011). For instance, the European Commission published the communication "Towards a circular economy: a zero waste programme for Europe" for establishing a common and coherent EU framework to promote the circular economy (European Comission 2014), given its potential to enhance and diversify the economy while also creating quality jobs (UNEP 2011). However, a hypothetical boost of local products could disrupt the current conventional sector, leading into a decrease in national demand. This effect could cause a decrease in the sector (e.g., job loss) or an increase in national exportation to maintain production, thereby originating an environmental re-bound effect due to increased transport distances.

### 5.2. Limitations of the study and further research

This study exhibits a number of limitations related to the incipient implementation of RTGs and lacking data available on this issue. First, this study considers the lifespan of the RTG structure to be 50 years, according to project data and information provided by architects and engineers. However, environmental characteristics associated with greenhouses (e.g., humidity) may reduce the lifespan or other features of an RTG, thereby increasing maintenance requirements and associated environmental impacts and economic costs. Second, a lack of experimental data on existing RTGs in the Mediterranean area resulted in crop yield uncertainty. This was a weakness of the study, which was solved by adding a sensitivity analysis to the assessment. Nevertheless, RTG crop yield values will determine the environmental impact and economic costs of local RTG vegetables. Moreover, further sensitivity assessments may include crop yield variability of conventional technologies. Third, the assessment of RTG tomato production uses 1 $m^2$ of productive area to analyse both the RTG and the multi-tunnel systems as commercial activities. However, RTGs use space in a less efficient manner than conventional greenhouses due to an imbalance in the scale of activities: while the RTG examined in this study occupies 122.8 $m^2$, the multi-tunnel greenhouse occupies nearly two hectares. Finally, although the RTG-Lab will focus on the exchange of flows between greenhouses and buildings (i-RTGs), the study does not consider the metabolic interconnection and infrastructure requirements needed for this purpose.

Further research on new forms of urban agriculture and on rooftop greenhouses in particular may focus on the following issues. First, agronomic data on existing RTGs will reduce result variability related to crop yields. Second, i-RTGs that exchange energy, water, and gases may shed light on the metabolism of such as structure and associated agronomic, environmental, and economic advantages. Third, an environmental and economic assessment of local production systems and other urban agriculture systems may provide a more nuanced contextualisation of RTGs within this sector. Furthermore, studies may pay additional attention to potential uses of RTG models. Other applications may include the development of private, commercial RTGs or public RTGs for community use. Finally, social indicators should be included in future studies on RTGs.

## References

Antón A, Montero J, Muñoz P, Castells F (2005) LCA and tomato production in Mediterranean greenhouses. Int J Agric Resour Gov Ecol 4:102 – 112.

Arosemena G (2012) Urban agriculture: Spaces of cultivation for a sustainable city. 128.

Barthel S, Isendahl C (2013) Urban gardens, agriculture, and water management: Sources of resilience for long-term food security in cities. Ecol Econ 86:224–234.

BOE (2006) REAL DECRETO 314/2006, de 17 de marzo, por el que se aprueba el Código Técnico de la Edificación. Boletín Of del Estado 74:11816–11831.

BOE (2004) REAL DECRETO 2267/2004, de 3 de diciembre, por el que se aprueba el Reglamento de seguridad contra incendios en los establecimientos industriales. Boletín Of del Estado 303:41194 – 41255.

BOE (2010) Ley 3/2010, de 18 de febrero, de prevención y seguridad en materia de incendios en establecimientos, actividades, infraestructuras y edificios. Boletín Of del Estado 89:32918 – 32943.

CBS (2013a) Electricity; production by energy source. Den Haag

CBS (2013b) Renewable electricity; gross and net production, imports and exports. Den Haag

CEN (2001) EN 13031. Greenhouses: design and construction—part 1: commercial production greenhouses.

Cerón-Palma I (2012) Strategies for sustainable urban systems: introducing eco-innovation in buildings in Mexico and Spain. Universitat Autònoma de Barcelona

Cerón-Palma I, Sanyé-Mengual E, Oliver-Solà J, et al. (2012) Barriers and Opportunities Regarding the Implementation of Rooftop Eco.Greenhouses (RTEG) in Mediterranean Cities of Europe. J Urban Technol 19:87–103.

Cerón-Palma I, Sanyé-Mengual E, Oliver-Solà J, et al. (2011) Energy savings from a roof top greenhouse in a public building of Barcelona, Spain. 6th Int. Conf. Ind. Ecol. Sci. Syst. Sustain. (Berkeley, 7-10 June 2011)

DAPLAST (2014) Plastic trays for transportation. http://www.daplast.com/productos/cajas-de-plastico/197. Accessed 22 Jul 2014

DECC (2014) UK energy statistics: 2013 provisional data. London

Despommier D (2008) Cities dream of a second agricultural revolution. Sp Mag 488:103–105.

Despommier D (2009) The rise of vertical farms. Sci Am 301:80–87.

Despommier D (2010) The vertical farm: Feeding the world in the 21stCentury. Thomas Dunne Books., New York

Despommier D (2011) The vertical farm: controlled environment agriculture carried out in tall buildings would create greater food safety and security for large urban populations. J für Verbraucherschutz und Leb 6:233–236.

Droege P (2012) 100 Per Cent Renewable: Energy Autonomy in Action. Earthscan, London

EC-JRC (2010) International Reference Life Cycle Data System (ILCD) handbook: General guide for Life Cycle Assessment - Detailed guidance.

Edwards-Jones G, Milà i Canals L, Hounsome N, et al. (2008) Testing the assertion that “local food is best”: the challenges of an evidence-based approach. Trends Food Sci Technol 19:265–274.

Ekvall T, Tillman A-M (1997) Open-loop recycling: Criteria for allocation procedures. Int J Life Cycle Assess 2:155–162.

EUROSTAT (2014) Energy statistics. http://epp.eurostat.ec.europa.eu/. Accessed 2 May 2014

Generalitat de Catalunya (2014) Impuls a l’economia verda [Boost to the green economy] (Draft). Barcelona

Generalitat de Catalunya (DGTM) (2012) Observatori de costos del transport de mercaderies per carretera a Catalunya [Observatory of road freight transport costs in Catalonia]. Butlletí Transp. 64:

Germer J, Sauerborn J, Asch F, et al. (2011) Skyfarming an ecological innovation to enhance global food security. J für Verbraucherschutz und Leb 6:237–251.

Goedkoop M, Heijungs R, Huijbregts M, et al. (2009) ReCiPe 2008, A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level; First edition Report I: Characterisation. Ministerie van VROM, Den Haag

González M, Céspedes López A, González Céspedes A (2008) PrHo V. 2,0: Programa de Riego para cultivos Hortícolas en invernadero. Serie Las Palmerillas - Cuadernos técnicos 01. Almería

Hischier R, Weidema B, Althaus H, et al. (2010) Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent v2.2 No. 3. Swiss Centre for Life Cycle Inventories, Dübendorf

Hunkeler D, Lichtenvort K, Rebitzer G (2008) Environmental Life Cycle Costing, Boca Ratón. CRC Press

IPCC (2007) Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. 12–17.

ISO (2006) ISO 14040: Environmental management - Life cycle assessment - Principles and framework. International Organization for Standardization, Geneva

ISO (2008) ISO 15686-5: Buildings and constructed assets - Sevice-life planning - Part 5: Life-cycle costing.

ITeC (2012) Institut de Tecnologia de la Construcció de Catalunya. MetaBase ITeC, Online ITeC database: prices, technical details, companies, certificates, product pictures and environmental data. http://www.itec.es/nouBedec.e/bedec.aspx. Accessed 28 Sep 2012

Jones A (2002) An environmental assessment of food supply chains: a case study on dessert apples. Environ Manage 30:560–76.

Kirwan J, Maye D (2012) Food security framings within the UK and the integration of local food systems. J Rural Stud 29:91–100.

MAGRAMA (2014) Food consumption panel 2013: Catalonia. Madrid

Martínez-Blanco J, Muñoz P, Antón A, Rieradevall J (2011) Assessment of tomato Mediterranean production in open-field and standard multi-tunnel greenhouse, with compost or mineral fertilizers, from an agricultural and environmental standpoint. J Clean Prod 19:985–997.

MercaBarna (2014) Mercabarna Stats: Vegetables - Commercialized tonnes - 2013. http://www.mercabarna.es/estadistiques/. Accessed 30 Apr 2014

Montero J, Antón A, Torrellas M, et al. (2011) EUPHOROS Deliverable 5. Report on environmental and economic profile of present greenhouse production systems in Europe. European Commission FP7 RDT Project Euphoros (Reducing the need for external inputs in high value protected horticultural and ornament. http://www.euphoros.wur.nl/UK. Accessed 10 Jul 2013

Montero J, Stanghellini C, Castilla N (2009) Greenhouse technology for sustainable production in mild winter climate areas: trends and needs. Proc. Int. Symp. Strateg. Towar. Sustain. Prot. Cultiv. Mild Winter Clim.

PRé Consultants (2011) SimaPro software version 7.3.3.

REE (2013) Daily real-time electricity demand in Spain. http://www.ree.es/es/actividades/balance-diario. Accessed 25 Sep 2013

Resh H (2012) Hydroponic food production: A definitive guidebook for the advanced home gardener and the commercial hydroponic grower, 7th ed. 560.

Sanyé-Mengual E, Cerón-Palma I, Oliver-Solà J, et al. (2013) Environmental analysis of the logistics of agricultural products from roof top greenhouses in Mediterranean urban areas. J Sci Food Agric 93:100–109.

Specht K, Siebert R, Hartmann I, et al. (2014) Urban agriculture of the future: an overview of sustainability aspects of food production in and on buildings. Agric Human Values 31:33–51.

Swarr TE, Hunkeler D, Klöpffer W, et al. (2011) Environmental life-cycle costing: a code of practice. Int J Life Cycle Assess 16:389–391.

Swiss Center for Life Cycle Inventories (2010) Ecoinvent Data v2.2.

Torreggiani D, Dall’Ara E, Tassinari P (2012) The urban nature of agriculture: Bidirectional trends between city and countryside. Cities 29:412–416.

UNEP (2011) Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication. UNEP, Beijing

Wallgren C, Höjer M (2009) Eating energy—Identifying possibilities for reduced energy use in the future food supply system. Energy Policy 37:5803–5813.

## Tables and Figures

**Table 1.** Characteristics of current RTG experiences and projects.

| Name | City | Area | Year | Produce | Building type | Type |
|---|---|---|---|---|---|---|
| Gotham Greens[a] | Brooklyn, NY, United States | 1,400 $m^2$ | 2011 | 6 varieties of lettuce and basil | Former warehouse | Isolated |
| The Vinegar Factory[b] | Manhattan, NY, United States | 830 $m^2$ | Unknown | Tomatoes, salad greens and herbs | Commercial | Isolated |
| Lufa Farms[c] | Montreal, Canada | 2,900 $m^2$ | 2011 | Greens, tomato, cucumber, pepper and eggplants | Commercial | Isolated |
| Forest houses | South Bronx, NY, United States | 930 $m^2$ | Project | - | Apartment building | Isolated |
| Local Garden[d] | Vancouver, Canada | 550 $m^2$ | Project | - | - | Isolated |
| Urban produce[e] | Toronto, Canada | 4,200 $m^2$ | Project | - | - | Isolated |
| VidaVerde | Honselersdijk, The Netherlands | Unknown | 2012 | Plant nursery - Storage | Garden centre | Isolated |
| Fresh from the Roof | Berlin, Germany | 7,000 $m^2$ | Project | - | Former factory | Isolated |
| ICTA-ICP | Bellaterra, Spain | 250 $m^2$ | 2014 | Lettuce, tomato | Research centre | Integrated (i-RTG) |

*([a]http://www.gothamgreens.com, [b]http://www.elizabar.com, [c]https://lufa.com/,[d] http://www.localgarden.com/, [e]http://www.urbanproduce.ca/)*

**Table 2.** Main potential environmental (E), economic (Ec) and social (S) benefits of Rooftop Greenhouses (RTGs), by scale (global, local, building-greenhouse system and product). Benefits are divided into two categories: general benefits of local food production (●) and specific benefits of RTGs (♦).

| Scale | Potential benefit | E | Ec | S |
|---|---|---|---|---|
| **Global** | Enhancing closed cycles in urban food flows[a] | ● | ● | ● |
| | Contributing to food self-supply[b,c] and urban resilience to climate change[d] | ● | | ● |
| | Lessening pressure to fertile agricultural land[e] | ● | | |
| **Local** | Optimizing urban space[a,f], revaluating unproductive spaces[a] and increasing urban multifunctionality[g] | ♦ | ♦ | ♦ |
| | Naturalising urban areas[a] and increasing urban biodiversity | ♦ | ♦ | ♦ |
| | Increasing availability of fresh produce[a] and reducting product losses[h] | ● | | ● |
| | New technology and market development | | ♦ | ♦ |
| **System (isolated RTGs)** | Reducing building energy consumption due to thermal insulation[i] | ♦ | ♦ | |
| **System (i-RTGs)** | Recycling of building wastewater[a] and water use optimization through recirculation[j] | ♦ | ♦ | |
| | Reducing building energy consumption due to insulation and heat exchange[i] | ♦ | ♦ | |
| | Using building-residual energy and $CO_2$ in greenhouse production[a] | ♦ | ♦ | |
| **Product** | Avoiding distribution stage[a,g,k] | ● | ● | |
| | Production with low resources and energy inputs[a] | ♦ | ♦ | |
| | Increasing food quality[e] | ♦ | ♦ | ♦ |
| | Producer-consumer direct and short-term relation[l] | | ● | ● |

*([a]Cerón-Palma et al. (2012); [b]Barthel and Isendahl (2013); [c]Kirwan and Maye (2012); [d]Despommier (2010); [e]Droege (2012); [f]Torreggiani et al. (2012); [g]Arosemena (2012); [h]Sanyé-Mengual et al. (2013); [i]Cerón-Palma et al. (2011); [ji]Montero et al. (2009); [k]Jones (2002); [l]Wallgren and Höjer (2009)).*

**Table 3.** Environmental impact assessment and economic cost of the RTG structure, by life cycle stage, and comparison with the multi-tunnel structure, for a functional unit of 1 $m^2$ of a greenhouse structure for a timeframe of 1 year.

| | Norm-ReCiPe [Pt] | GWP [kg $CO_2$ eq] | CED [MJ] | TC [€] | TP [€] |
|---|---|---|---|---|---|
| **Rooftop Greenhouse (RTG)** | **3,30E-02** | **2,42E+00** | **4,40E+01** | **11,9** | **0** |
| Materials | 2,97E-02 | 1,02E+00 | 1,98E+01 | 5,02 | - |
| *- Steel [%]* | *96,4* | *69,5* | *75,6* | *62,2* | - |
| *- Polycarbonate (PC) [%]* | *2,2* | *26,8* | *19,7* | *5,3* | - |
| *- Polyethylene (PE) [%]* | *0,1* | *1,5* | *2,8* | *21,3* | - |
| *- Climate screen [%]* | *0,1* | *1,3* | *1,2* | *11,2* | - |
| *- Concrete [%]* | *1,0* | *0,8* | *0,8* | *0,1* | - |
| Construction | 1,71E-06 | 1,40E-04 | 3,94E-03 | 0,32 | - |

| | | | | | |
|---|---|---|---|---|---|
| Maintenance | 3,28E-03 | 1,39E+00 | 2,41E+01 | 6,51 | - |
| *- Polycarbonate (PC) [%]* | *77.4* | *75.2* | *58.9* | *16.2* | - |
| *- Polyethylene (PE) [%]* | *17.4* | *16.8* | *33.1* | *6.0* | - |
| *- Climate screen [%]* | *5.1* | *8.0* | *8.0* | *77.7* | - |
| End of life | 3,18E-05 | 7,74E-03 | 1,29E-01 | n.d. | - |
| **Multi-tunnel (M)** | **2,81E-02** | **1,38E+00** | **3,04E+01** | **4,26** | **0** |
| *- Steel [%]* | *91,7* | *39,6* | *29,7* | - | - |
| *- Polycarbonate (PC) [%]* | *1,1* | *10,1* | *6,6* | - | - |
| *- Polyethylene (PE) [%]* | *3,3* | *27,9* | *45,9* | - | - |
| *- Polyvinylchloride (PVC)[%]* | *0,5* | *2,7* | *3,5* | - | - |
| *- Polypropylene (PP) [%]* | *0,5* | *3,6* | *5,9* | - | - |
| *- Concrete [%]* | *0,8* | *8,0* | *2,0* | - | - |
| *- Transportation [%]* | *2,0* | *8,1* | *6,4* | - | - |
| **Ratio RTG/M** | **1,17** | **1,75** | **1,45** | **2,79** | **0** |

**Environmental indicators: Normalised-ReCiPe (norm-ReCiPe), Global Warming Potential (GWP), and Cumulative Energy Demand (CED; Economic indicators: Total cost (TC) and Total profit (TP).*

**Table 4.** Environmental and economic indicators of the tomato production and comparison with the production in a multi-tunnel system, for a functional unit of 1 kg of tomato at the farm gate, by life cycle stage.

| | **Norm-ReCiPe [Pt]** | **GWP [kg $CO_2$ eq]** | **CED [MJ]** | **TC [€]** | **TP [€]** |
|---|---|---|---|---|---|
| **Rooftop Greenhouse (RTG)** | **1,66E-03** | **2,16E-01** | **3,25E+00** | **0.737** | **0.044** |
| Greenhouse structure | 1,15E-03 | 8,81E-02 | 1,60E+00 | 0.476 | - |
| Production inputs | 5,12E-04 | 1,28E-01 | 1,65E+00 | 0.128 | - |
| *-Auxiliary equipment [%]* | *43,0* | *18,5* | *41,0* | *40,1* | - |
| *-Substrate [%]* | *21,1* | *20,3* | *27,5* | *19,5* | - |
| *-Fertilisers [%]* | *16,0* | *52,3* | *19,3* | *25,5* | - |
| *-Pesticides [%]* | *4,6* | *1,0* | *1,6* | *14,9* | - |
| *-Waste management [%]* | *15,4* | *7,9* | *10,6* | *0,0* | - |
| Labour | - | - | - | 0.133 | - |
| Revenues | - | - | - | - | 0.781 |
| **Multi-tunnel (M)** | **2,25E-03** | ***2,37E-01*** | ***3,78E+00*** | ***0.607*** | ***0.036*** |
| Greenhouse structure | 1,72E-03 | 8,38E-02 | 1,84E+00 | 0.260 | - |
| Production inputs | 5,38E-04 | 1,53E-01 | 1,93E+00 | 0.183 | - |
| *-Auxiliary equipment [%]* | *40,2* | *17,1* | *39,2* | *34,6* | - |
| *-Substrate [%]* | *30,4* | *25,7* | *35,6* | *24,2* | - |
| *-Fertilisers [%]* | *18,8* | *54,0* | *20,4* | *26,0* | - |
| *-Pesticides [%]* | *6,6* | *1,3* | *2,1* | *15,2* | - |
| *-Waste management [%]* | *3,9* | *1,9* | *2,6* | *0,0* | - |
| Labour | - | - | - | 0.164 | - |
| Revenues | - | - | - | - | 0.643 |
| **Ratio RTG/M** | **0,74** | **0,91** | **0,86** | **1,21** | **1,21** |

**Environmental indicators: Normalised-ReCiPe (norm-ReCiPe), Global Warming Potential (GWP), and Cumulative Energy Demand (CED; Economic indicators: Total cost (TC) and Total profit (TP).*

**Table 5.** Environmental and economic indicators of the tomato supply chain and comparison with the conventional supply-chain (multi-tunnel), for a functional unit of 1 kg of tomato at the consumer, by life cycle stage.

| | **Norm-ReCiPe [Pt]** | **GWP [kg $CO_2$ eq]** | **CED [MJ]** | **TC [€]** | **TP [€]** |
|---|---|---|---|---|---|
| **Rooftop Greenhouse (RTG)** | **2,94E-03** | **7,08E-01** | **8,44E+00** | **0,863** | **0,607** |
| Agriculture production | 1,66E-03 | 2,16E-01 | 3,25E+00 | 0,752 | - |
| Packaging production | 1,28E-03 | 4,92E-01 | 5,19E+00 | 0,105 | - |
| Distribution | 3,72E-07 | 4,74E-05 | 8,26E-04 | 0,006 | - |
| Retail | - | - | - | - | - |
| Revenues | - | - | - | - | 1,47 |
| **Multi-tunnel (M)** | **5,11E-03** | **1,54E+01** | **1,39E+01** | **1,086** | **0,384** |
| Agriculture production | 2,63E-03 | 2,76E-01 | 4,41E+00 | 0,750 | - |
| Packaging production | 1,50E-03 | 5,74E-01 | 6,05E+00 | 0,123 | - |
| Distribution | 8,94E-04 | 1,94E-01 | 3,27E+00 | 0,067 | - |
| Retail | 9,41E-05 | 1,46E-02 | 2,14E-01 | 0,147 | - |
| Revenues | - | - | - | - | 1,47 |
| **Ratio RTG/M** | **0,58** | **0,67** | **0,61** | **0,79** | **1,58** |

**Environmental indicators: Normalised-ReCiPe (norm-ReCiPe), Global Warming Potential (GWP), and Cumulative Energy Demand (CED; Economic indicators: Total cost (TC) and Total profit (TP).*

## Figures

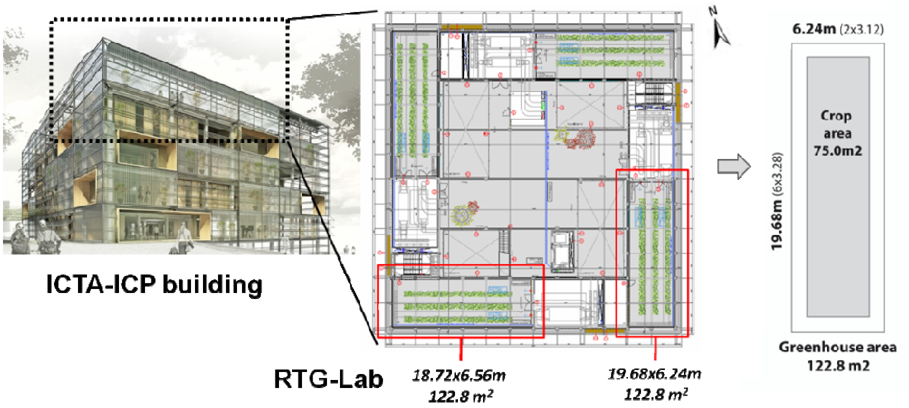

**Figure 1.** Layout of the RTG-Lab, situation in the ICTA-ICP building, and rooftop greenhouse dimensions (The RTG elements are detailed in Supporting Information 1).

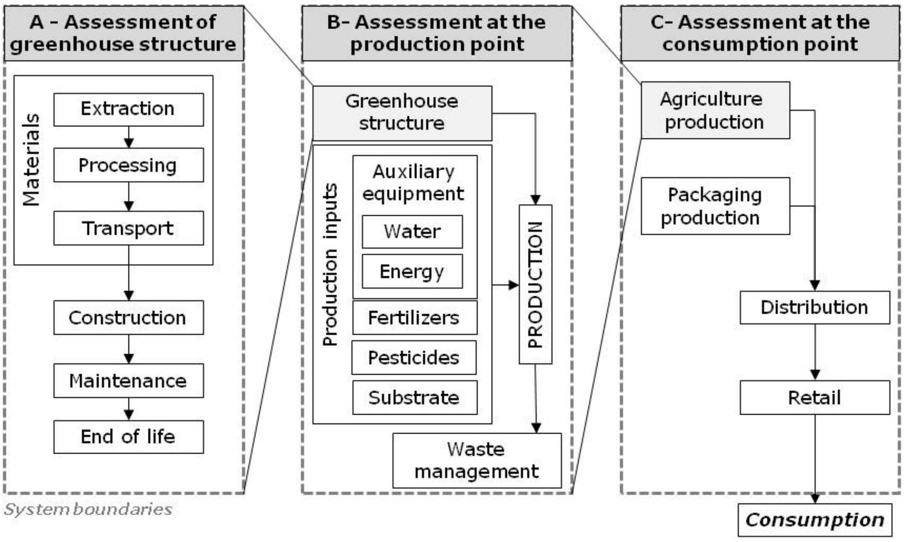

**Figure 2.** System boundaries and life cycle stages of the three assessments: greenhouse structure (cradle-to-grave), production point (cradle-to- farm gate), and consumption point (cradle-to-consumer).

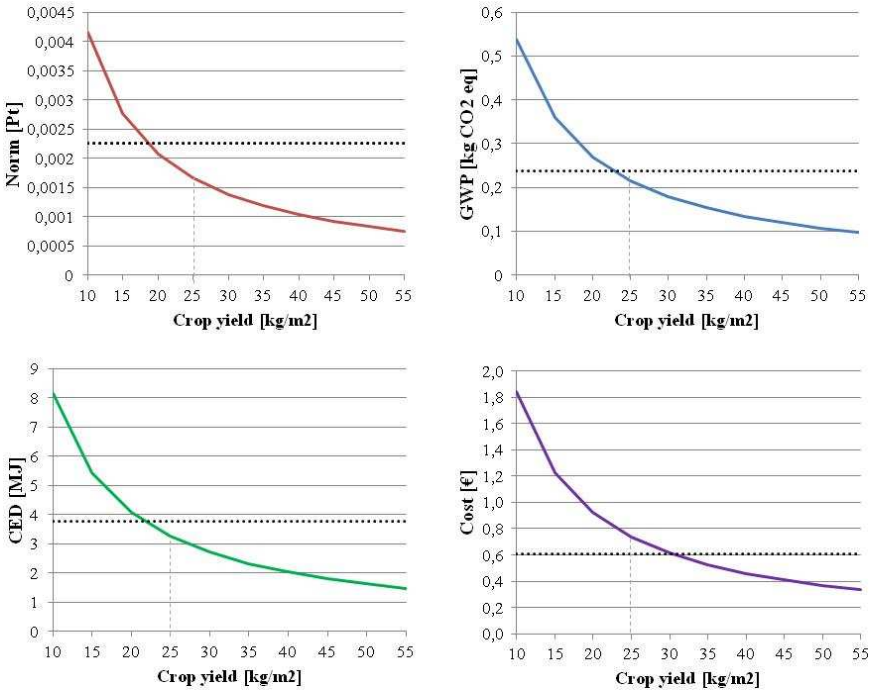

**Figure 3.** Sensitivity analysis of the environmental indicators related to the crop yield variability. Solid line indicates the indicator value, and the dotted line indicates the indicator value for a tomato produced in a multi-tunnel greenhouse.

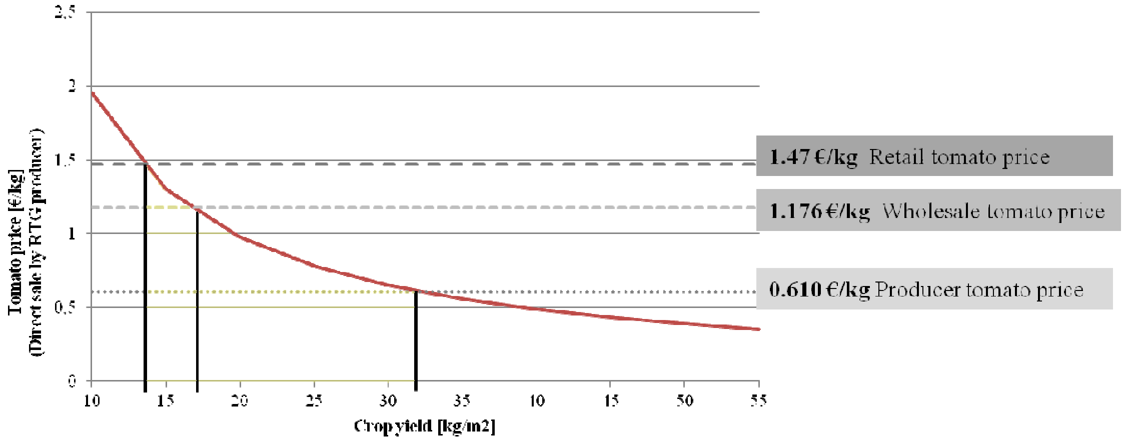

**Figure 4.** Sensitivity analysis of the minimum tomato price to cover RTG production costs and comparison to current tomato prices in the market, by crop yield.

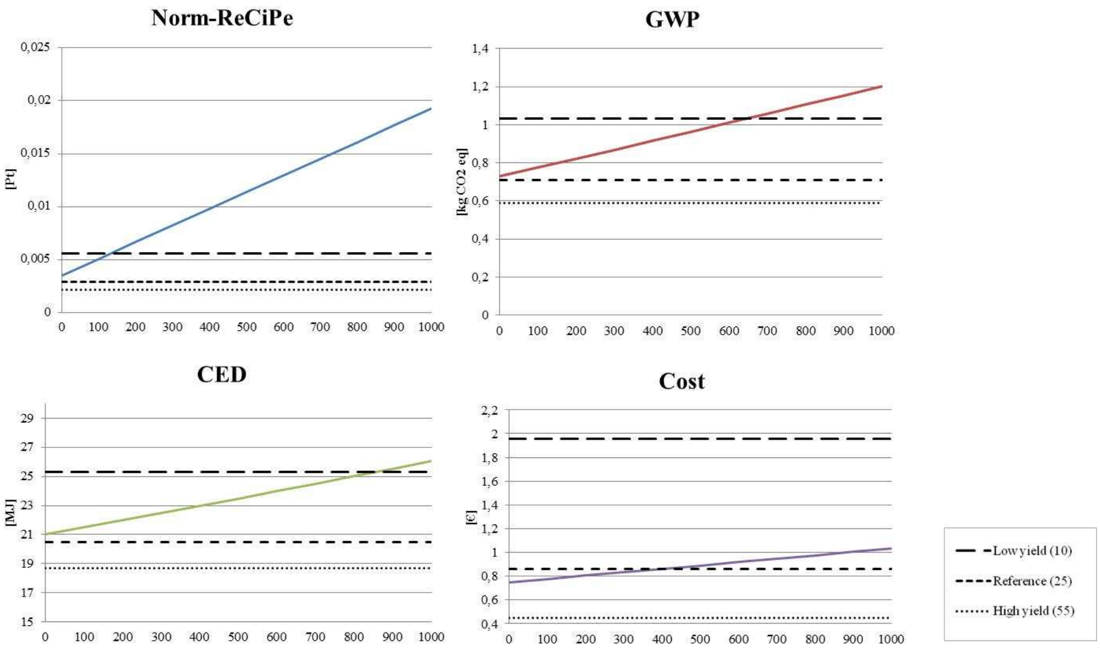

**Figure 5.** Environmental and economic indicators for 1 kg tomato from a conventional supply-chain at the consumption point by transported distance, and comparison with the value of 1 kg of tomato from local RTGs with a low yield (10 kg·m$^{-2}$), reference yield (25 kg·m$^{-2}$), and high yield (55 kg·m$^{-2}$).