Building-integrated agriculture: are we shifting environmental impacts? An environmental and structural improvement assessment of greenhouses structures.

Joan Muñoz-Liesa*[1], Susana Toboso-Chavero[2], Angelica Mendoza Beltran[2], Eva Cuerva[3], Esteban Gallo[4], Santiago Gassó-Domingo[3], Alejandro Josa[1].

[1] Department of Civil and Environmental Engineering (DECA), School of Civil Engineering (Escola de Camins), Universitat Politècnica de Catalunya (UPC), Jordi Girona 1-3, Barcelona, Spain

[2] Sostenipra Research Group (2017 SGR 1683), Institut de Ciència i Tecnologia Ambientals (MDM-2015-0552), Z Building, Universitat Autònoma de Barcelona (UAB), Campus UAB, 08193 Bellaterra, Barcelona, Spain

[3] Department of Project and Construction Engineering (EPC), Group of Construction Research and Innovation (GRIC), Universitat Politècnica de Catalunya (UPC), Edifici H, Av. Diagonal, 647, Barcelona, Spain

[4] Department of Architectural Technology, Polytechnic University of Catalonia (UPC), Barcelona School of Architecture, Av. Diagonal, 649, Barcelona, Spain

*Corresponding author email: joan.munoz.liesa@upc.edu, jmunozliesa@gmail.com.

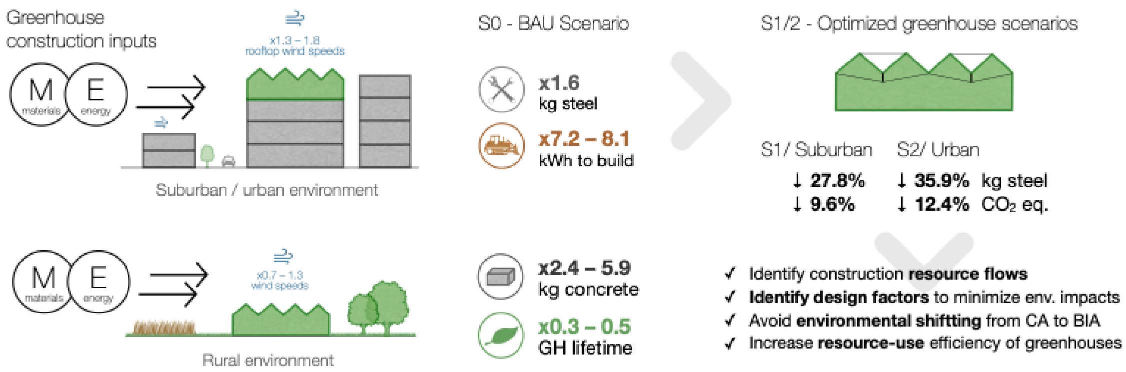
Abstract:

Urban and building systems are awash with materials. The incorporation of green infrastructure such as rooftop greenhouses (RTG) has the potential to contribute to buildings and cities circularity but, in turn, its higher sophistication compared to conventional agriculture (CA) could lead to a shift of environmental impacts. One of the key elements for greenhouse building-integrated agriculture (BIA) and CA to achieve high levels of environmental performance is their structural design, which largely impacts the economic and environmental life-cycle costs. In this context, this study assessed RTGs material and energy flows and its environmental burdens at the structural level ($m^2 \cdot y$) within life cycle assessment (LCA) based on a case study in Barcelona. An improvement structural assessment following the European standards allowed to identify key design elements to minimize RTGs environmental impacts within improvement scenarios. The assesment revealed that the steel structure in the BAU scenario caused between 31.5 to 67.3% of the impact categories analyzed, followed by the polycarbonate covering material (21.8 - 45.9%). The key design factors responsible for such greenhouse structural design were the ground height, ventilation design, integration with the building and its urban location. The improvement scenarios allowed to compensate for additional steel inputs up to 35.9% and decrease environmental impacts that might occur in the BIA context by 24.1%. The assessment also revealed that the urban environment does not imply shifting environmental impacts per se, as greenhouse BIA structures can take profit of its advantageous characteristics or be compensated by optimized greenhouse structures.

Keywords

Material flow analysis, resource use-efficiency, industrial ecology, structural modelling, urban agriculture, urban metabolism.

Graphical abstract



Building-integrated agriculture: are we shifting environmental impacts? An environmental and structural improvement assessment of greenhouses structures.

Abstract:

Urban and building systems are awash with materials. The incorporation of green infrastructure such as rooftop greenhouses (RTG) has the potential to contribute to buildings and cities circularity but, in turn, its higher sophistication compared to conventional agriculture (CA) could lead to a shift of environmental impacts. One of the key elements for greenhouse building-integrated agriculture (BIA) and CA to achieve high levels of environmental performance is their structural design, which largely impacts the economic and environmental life-cycle costs. In this context, this study assessed RTGs material and energy flows and its environmental burdens at the structural level ($m^2 \cdot y$) within life cycle assessment (LCA) based on a case study in Barcelona. An improvement structural assessment following the European standards allowed to identify key design elements to minimize RTGs environmental impacts within improvement scenarios. The assesment revealed that the steel structure in the BAU scenario caused between 31.5 to 67.3% of the impact categories analyzed, followed by the polycarbonate covering material (21.8 - 45.9%). The key design factors responsible for such greenhouse structural design were the ground height, ventilation design, integration with the building and its urban location. The improvement scenarios allowed to compensate for additional steel inputs up to 35.9% and decrease environmental impacts that might occur in the BIA context by 24.1%. The assessment also revealed that the urban environment does not imply shifting environmental impacts per se, as greenhouse BIA structures can take profit of its advantageous characteristics or be compensated by optimized greenhouse structures.

Keywords

Life cycle assessment, Material flow analysis, resource use-efficiency, structural modelling, urban agriculture, urban metabolism.

1. Introduction

Environmental impacts derived from urban systems are one of the main concerns in contemporany societies (IPCC, 2014); these impacts are expected to grow due to the 68% increase on the world population predicted for 2050 (Population Division, 2018). Despite consuming a vast amount of resources, cities offer unique opportunities for circular-resource urban systems, contributing to sustainable development promotion. An example is urban agriculture, which offers an opportunity to add value to urban waste resources reusing them as inputs on crop production thanks to the circular management of urban resource flows (Grard et al., 2015). That allows to decrease urban resource needs while contributing to key societal challenges such us food security in a growing population context.

Different forms of Building-Integrated Agriculture (BIA) have been addressed, including urban gardens, allotments and rooftop farming which provide diferent direct and indirect resource savings. Among them, building-integrated rooftop greenhouses (iRTGs, also referred as RTGs) are one of the most sophisticated BIA structures that in turn, offer major benefits. For instance, they improve energy efficiency in buildings (Specht et al., 2013) by taking advantage of greenhouse insulation (Muñoz-Liesa et al., 2020a; Nadal et al., 2017b) and by utilizing building waste energy flows with high humidity content and occupant-generated CO_2 to promote plant growth (Sanyé-Mengual et al., 2014). By these means, iRTGs enhance crop productivity that could provide local communities with fresh food while promoting more efficient food-supply chains (Nadal et al., 2017a). In turn, iRTGs as well as other building-integrated agriculture (BIA) forms are nature-based solutions that bring agricultural ecosystem services to the urban form (Artmann and Sartison, 2018), contributing to the overall goal of decarbonizing the economy by improving land and resource efficiency within urban systems (European Union, 2018).

However, integrating urban space into new forms of agriculture usually involves higher complexity in agricultural technologies and facilities compared to conventional agriculture. This not only may represent a social barrier and an issue of major concern for stakeholders (Specht and Sanyé-Mengual, 2017), but also a technical, economic and an environmental constrain due to the life cycle stages involved in the greenhouse construction, worsen by building accessibility limitations (Cerón-Palma et al., 2012; Sanyé-Mengual et al., 2015a; Specht and Sanyé-Mengual, 2017).

Environmental impacts derived from greenhouse structures largely contribute to the overall food production impacts in both conventional and rooftop unheated greenhouses (Muñoz et al., 2008; Rufí-Salís et al., 2020a; Sanjuan-Delmás et al., 2018; Sanyé-Mengual et al., 2015c). Rufí-Salís and collaborators (Rufí-Salís et al., 2020a) found that the structure of an iRTG located in the Barcelona area, accounted for 42-61% of the climate change impacts when assessing the life cycle environmental impacts of different crops. Similar impacts of 40% and 78% have been described for European conventional greenhouses (Torrellas et al., 2012) and a Venlo Dutch greenhouse (Anton et al., 2012) respectively. Thus, their impacts can be compared to other operational resource flows, which are commonly the greatest impact in terms of life cycle assessment of food production in both conventional and rooftop greenhouses (Vadiee and Martin, 2013; van Beveren et al., 2015; Wallgren and Höjer, 2009).

In rooftop farming, the structural loads are limited to the existing roof carrying capacity (Castleton et al., 2010; Toboso Chavero et al., 2018), which varies depending on building age and usage as well as the regulatory framework (Caputo et al., 2017). Moreover, BIA structural design and covering material selection is limited by technical, legal and fire-safety requirements, among others, stated in different building codes (Sanyé-Mengual et al., 2015c) and directly affects greenhouse climate behavior and thus building energy needs (Muñoz-Liesa et al., 2020b). Thus, BIA normally addresses multiple building constrains which are translated into greater construction inputs, making them more difficult and expensive to build (Ackerman et al., 2011; Benis et al., 2018). At the same time, BIA as well as other building innovative technologies are needed to boost resource circularity that can support the decarbonization of the economy (European Union, 2018). Accordingly, BIA pilot implementations can be very useful to prove increased efficiency in food production (Sanjuan-Delmás et al., 2018).

The ICTA building is an example of BIA implementation in the south of Europe hosting an iRTG. The ICTA-iRTG system represents a good example of a well characterized pilot study, although an in-depth analysis of structural environmental impacts is lacking.

Beyond the ICTA-iRTG, current methodologies that assess the potential of urban agriculture does not consider structural aspects and its suitability for different urban environments yet (Benis and Ferrão, 2017; Nadal et al., 2017a; 2016; Sanyé-Mengual et al., 2015b; Toboso Chavero et al., 2018). Hence, there is a research gap in assessing urban greenhouse structures and its environmental performance under different urban contexts (Goldstein et al., 2016; Specht et al., 2013).

The construction industry, including buildings and BIA, are increasingly being designed to meet current decarbonization targets and this is steeply gaining attention in literature (Hossain et al., 2020). Structural designers are therefore rising their interest in lightweight structures, which, together with membrane solutions or more flexible structures have the potential to increase material efficiency and reduce environmentally-derived construction impacts compared to conventional rigid and massive structures (Monticelli et al., 2017). In BIA, cost-effective solutions with lightweight materials and techniques should also be further investigated (Specht et al., 2013) In turn, building materials logistics and construction phase could be further improved and simplified, especially when dealing with rooftop greenhouses. Structural loads associated to building rooftop farming may also benefit from this optimization when the existing roof carrying capacity represents a building constrain.

Greenhouses and buildings will necessarily tend to zero or nearly-zero emissions systems in the near future (European Union, 2018; Montero et al., 2010). Hence, the embodied impacts on urban assets will become increasingly important to effectively achieve a low-carbon development. Material usage in the built environment is gaining concern and is listed as a high relevance issue in the 5th IPCC report on climate change (IPCC, 2014). Therefore, Life Cycle Assessment (LCA) will likely become more important in the future when assessing sustainability issues. Among them, several studies in urban agriculture highlight the need to adopt LCA in the analysis (Mok et al., 2013; Specht et al., 2013) to quantify the environmental burdens and explore potential reductions of food production (Sanyé-Mengual et al., 2015c; 2012). Finally, this will avoid environmental shifting of impacts that could derive from efficient UA resource flows to BIA structures such as iRTGs.

1.1 Objectives of the study

This study aims to quantify input construction materials and energy flows of iRTG structures in the European context based on the ICTA-iRTG case study. By understanding how material flows in the urban environments in comparision with rural environments, more resource-efficient greenhouse structures will be designed in different improvement scenarios. In order to do so, key design factors that affect such structures will be identified in order to minimize greenhouse environmental impacts.

The outcome of this assessment has been used to compare them with a standard conventional greenhouse within their related environmental impacts and quantify the potential environmental problem shifting from conventional to BIA in all scenarios assessed. Finally, this data is used to generalize and give guidelines to apply the obtained results across Europe, improving greenhouse structures and BIA resource-use efficiency.

2. Methods

2.1 The ICTA-iRTG case study

The ICTA-iRTG system is located in the research Institute of Environmental Science and Technology (ICTA) in the Universitat Autònoma de Barcelona campus (Barcelona Metropolitan area). The building is designed in all its life cycle stages -from selected construction materials to its later deconstruction- to improve building sustainability. An essential feature of the building design is the bioclimatic envelope made out of a steel structure and a corrugated polycarbonate covering the inner spaces of the building and forming a double skin façade that autoregulates its climate with automatic-window openings. Such mechanism is imported from the greenhouse industry and is also used in the rooftop, which houses four integrated rooftop greenhouses. Four atriums (see Figure 1) enhance these passive bioclimatic strategies and are combined with smart building controls. Both systems enable to monitor and adjust the iRTG and the building internal climate. Additionally, a rainwater harvesting system combined with a separate sewer allow to reduce the building water demand and consumption. Hence, building design and assets try to favor the best use of on-site available resources by dynamically interconnect with them.

The ICTA rooftop is based on a Venlo greenhouse structure replicated over the rooftop space (measuring 1508.4 m^2 of gross area). Venlo greenhouses are very versatile structures and widely used in Northen Europe. The iRTG here assessed is located in the SE façade, where a hydroponic tomato among other crop cycles are grown (see Figure 1). Each iRTG has a serviceable area for growing crops of 84.34 m^2 from the total net area of 122.8 m^2 and 125 m^2 when counting the gross area including all pillars and the whole steel structure. The greenhouse high up to the top of the two ridges of the roof measure 5.55 m high including the truss spacing (4.05 m of net high up to the beam level) and allow 6.23m of span width. The three external sides of the greenhouse are covered with a 0.8 mm corrugate polycarbonate, which envelopes a total area of 243.66 m^2, including the two exterior façades in each iRTG (98.99 m^2) and the Venlo roof (144.67 m^2). The internal sides of the greenhouse facing the building (NW, SW) are a wood building wall and a thermal polyethylene climate screen that can isolate the greenhouse from the rest of the rooftop area when needed.

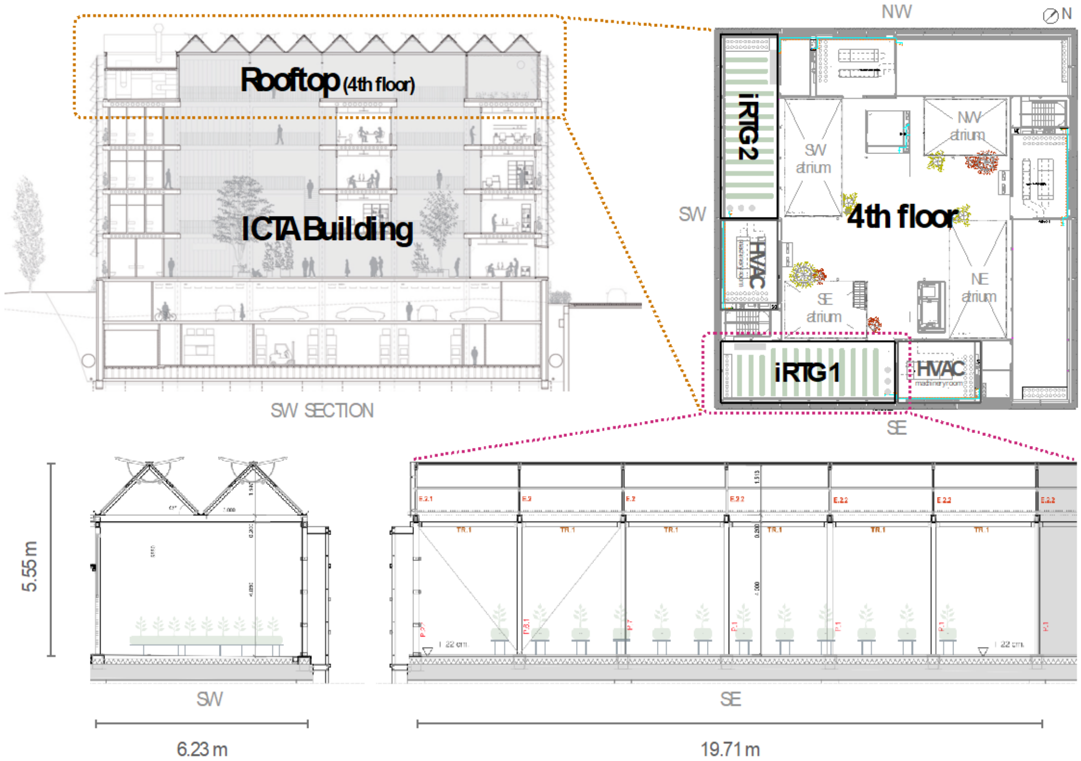


Figure 1. Cross section of ICTA building and iRTG 1 location and geometry in the 4th floor.

2.2 Structural assessment

The Venlo main structure of the iRTG is made out of tubular vertical pillars of galvanized steel designed to support steel trusses that constitute the two chapels of the greenhouse (Figure 1). These modular structure is the basis of a Venlo greenhouse, normally replicated throughout the available space with common gutters, forming a range as it is in the ICTA rooftop (Figure 1). Pillars are welded to steel plates anchored in the building concrete slab while the polycarbonate covering is supported with auxiliary steel elements and rubber supports that hold the covering material with the steel frame. Besides, the steel frame also supports 4 one-side window frames and its automatic-opening mechanisms located in the rooftop and in each façade (Figure 2). The iRTG SE and SW façades are also structurally connected with the double skin façade steel frame, though this frame is excluded in both structural and environmental assessments. Isolating the greenhouse from the rest of the building penalizes the iRTG structure as it does not consider any other building elements that could aid supporting the iRTG environmental loads. However, it allows to optimize a standard module of a Venlo greenhouse that can be applied to almost any rooftop conditions.

The ICTA building and the rooftop steel structure are subjected to the legal requirements established to comply with the Spanish Technical Code of Edification (CTE, 2009) which is in line with Eurocode 1 and EN 13031-1 . Moreover, fire safety laws (RD 2267/2004 and Law 3/2010, BOE 2004 & 2010) are also taked into account, while the structural loads considered are also in accordance with the CS2 service class established by the CTE (see supplementary material for details). Wind loads have been considered on top of the iRTG ridge at 28m high (according to Eurocode guidelines for a Venlo roof type) and have been subdivided into pressure and suction forces to structuraly assess the greenhouse. Suction forces have been considered due to the large ventilation areas by more than 30% in two façades needed for the greenhouse and building bioclimatic operation. As noted in this assessment, these are higher than pressure forces as it is in conventional greenhouse construction (Max et al., 2012). In addition to wind loads, live loads also included maintenance work (0.4 kN/m^2) and snow loads (0.4—1.6 kN/m^2), as stated in EC-1 for the different regions of Europe assessed (see results section for details). Finally, dead loads from the building materials considered sum 0.5 kN/m^2. The serviceability limit has been set at L/300 for all beams and columns. Softwares CYPE 3D (CYPE Ingenieros, 2018) and Wineva (Universitat Politècnica de Catalunya, Sastre et al., 2014) have been used to test all load combinations and various optimized design cases to meet the ultimate and serviceability limit states of the structure.

2.3 Improvement studied scenarios

Greenhouse design is not a trivial issue and many factors influence its operational performance. Thus, the structural components of the greenhouse have been assessed without changing its geometry (roof slope, iRTG height or dimensions), which would directly impact the light transmissivity, ventilation rates, inner temperatures and thus, crop productivity. The scenarios proposed derive from the factors identified by structural modelling as the most relevant for greenhouse design. Accordingly, internal and external greenhouse variables have been modified as follows:

1. *Internal variables:* (i) optimizing profiles section and orientation; (ii) increasing the steel strength from 275 to 355 MPa in accordance with EN 1993-1-1 (CEN, 2019); and by (iii) substituting beams with lightweight tensioned cables (Figure 3) according to tensegrity design principles .
2. *External variables:* terrain category conditions according to EC-1 (cat. II for rural-suburban area as it is located the ICTA building; and cat. IV for dense urban environment). Rural environment (cat. I) has been also assessed, as it applies to conventional greenhouses here also compared with.

These variables have been evaluated in different improvement scenarios (S1, S2, see Figure 2) respect to the baseline scenario (S0). Then, they have been compared with existing literature and with further detail with conventional Venlo greenhouse scenarios placed on soil and covered with a 4mm single glass (SCG.1) and with an EVA single-plastic film (SCG.2), both adapted from (Boulard et al., 2011).

S0. BAU – Baseline scenario

S1. Suburban structural improvement

S1.1 Steel S275, suburban environment
S1.2 Steel S355, suburban environment

S2. Urban structural improvement

S2.1 Steel S275, urban environment

S2.2 Steel S355, urban environment

SCG. Conventional greenhouse scenarios (Boulard et al., 2011)

SCG.1 Steel structure + horticultural glass, rural environment

SCG.2 Steel structure + EVA plastic film, rural environment

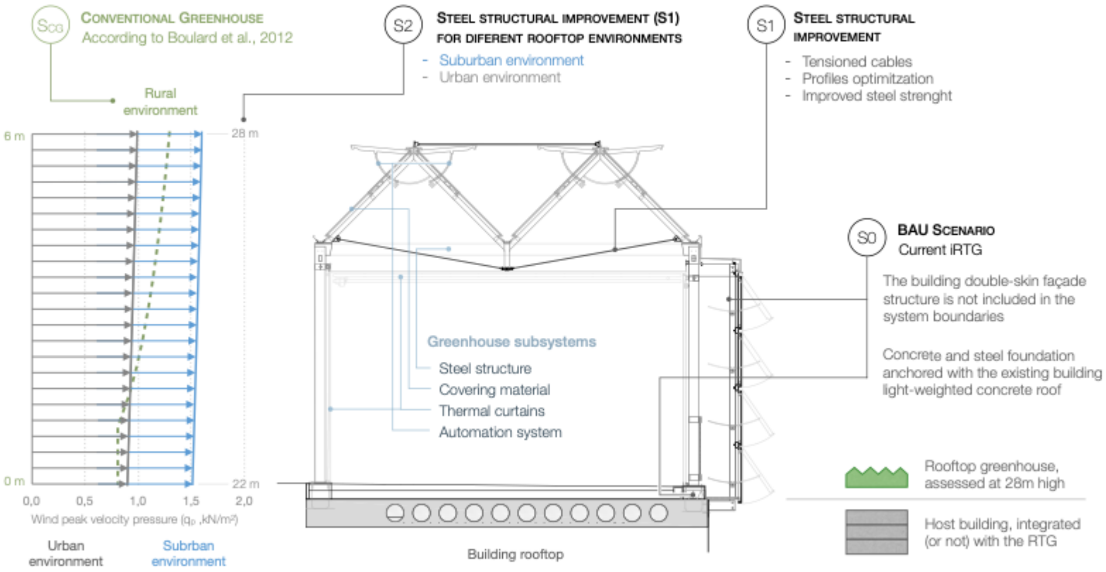


Figure 2. Cross section of the ICTA iRTG with all identified scenarios assessed and its main characteristics.

2.5 Life Cycle Assessment

Life Cycle Assessment has been widely used as a standard methodology defined by ISO 14040 (International Organization for Standardization, 2006) to identify resources and assess its environmental performance throughout the life cycle of all alternative system scenarios set in this study.

2.5.1 Goal and scope definition

The functional unit employed in this assessment was "1 m^2 of a greenhouse structure for a timeframe of 1 year". This functional unit is in line with previous studies in greenhouses (Sanyé-Mengual et al., 2015c) and buildings (Cabeza et al., 2014; Chau et al., 2015), while excludes the crop production processes commonly assessed in agriculture (usually measured in kg of produced crops) to place the environmental focus in the greenhouse structure solely.

The greenhouse system here considered all input construction materials as well as all permanent technical infrastructure (Figure 3), distinguishing all material flows in all its life cycle stages for 50 years of greenhouse structural maintenance. The fertigation system and the energy to passively operate the greenhouse indoor climate are considered operational flows which vary depending on the crop and thus, are excluded from the assessment. The system model used was cut-off, assuming that all impacts and benefits of the recycling process are allocated to secondary products.

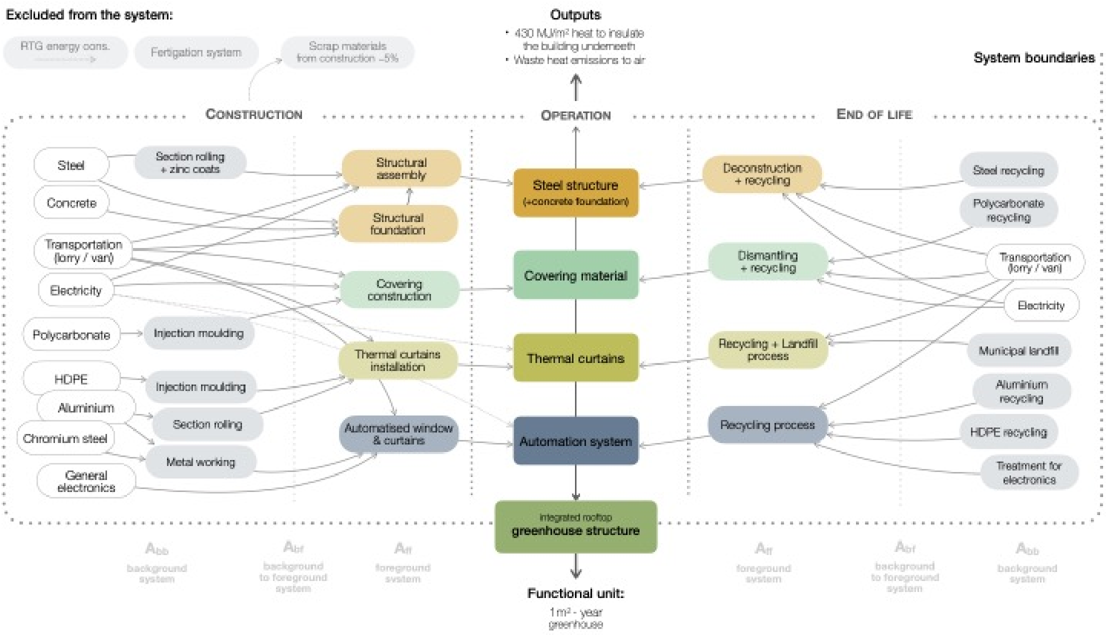


Figure 3. System boundaries of the greenhouse system.

<u>2.5.2 Life cycle inventory</u>

Data compilation of the system under study included the production, transportation, construction, maintenance and waste management of all 4 subsystems in which the iRTG has been analyzed: steel structure (including concrete foundation); covering material; thermal curtains and automation system.

Data from previous work in this iRTG has been used (Rufí-Salís et al., 2020a; 2020b; Sanjuan-Delmás et al., 2018; Sanyé-Mengual et al., 2015c) and updated with the available construction details after consulting the architects and stakeholders involved in the building construction process. All subsystems have been updated for this study, taking into account additional input materials not accounted before. Moreover, the automation subsystem has been added, which covers all mechanisms necessary to operate the greenhouse passive climate controls (windows and thermal curtains). This additionally allowed to distinguish the steel amounts needed for automation mechanisms to those that strictly belong to the structure that could be improved from the structural assessment perspective of this paper. In order to do so, direct measurements and project data has been used to account such mechanisms as well as the electronic equipment needed as reported by (Muñoz-Liesa et al., 2020b). Space allocation has been applied to part of the automation subsystem components that also operate the rest of the passive climate building controls.

To account the machinery and energy needs for the construction process of the iRTG, on-site building monitoring information has been used. The dismantling phase of the iRTG has been estimated to be half of the inputs needed for its construction. Specific details of the construction process of the iRTG can be found in Supplementary material. All selected materials and processes were contrasted with existing literature in greenhouses (Boulard et al., 2011) and buildings construction (Monticelli, 2010).

The reference scenario for conventional greenhouses used in agriculture has been based on the study by (Boulard et al., 2011), which has been adapted from the Agribalyse 1.2 database as stated in Ecoinvent database version 3.5 (Swiss Center for Life Cycle Inventories, 2018). The foreground data from a glass and a plastic Venlo-type greenhouse has been adapted to match with the functional unit of this study. Other background life cycle inventory from all scenarios has been also retrieved from the Ecoinvent database. The end of life of materials have been considered to be recyclable at the nearest point from the iRTG at 35km, despite a small fraction of materials which would be landfilled. Details on all compilated data, as well as inputs and outputs from the system, transportation distances and the waste scenarios, are available in the Supplementary Material.

2.5.3 Environmental impacts calculation

To perform the life cycle impact assessment (LCIA), the software Simapro version 9.0 has been used with the latest ReCiPe method at the midpoint level (hierarchical perspective). The most pertinent impact categories were selected based on authors judgment and previous literature in buildings (Cabeza et al., 2014; Chau et al., 2015) and crop production (Sanyé-Mengual et al., 2015c): Global Warming (GW, kg CO_2 eq.), Terrestrial Acidification (TA, kg SO_2 eq.), Freshwater Eutrophication (FE, kg P eq.), Marine Eutrophication (ME, kg N eq.), Fossil Resource Scarcity (FRS, kg oil eq.), Ecotoxicity (ET, kg 1,4-DB eq., including Marine, Terrestrial and Freshwater Ecotoxicity), Stratospheric Ozone Depletion (SOD, kg CFC-11 eq.) and Cumulative Energy Demand (CED, MJ, including renewable and non-renewable energy sources).

3 Results and Discussion

3.1 Current iRTG (BAU – S0 scenario)

3.1.1 Impact assessment

Figure 4 illustrates the environmental performance of 1m2 per year of the current iRTG (S0) and the share of impacts among all greenhouse subsystems for all 8 impact categories analyzed. Besides, impacts for conventional greenhouses scenarios (SCG.1 and 2) have been added to compare and contextualize S0 impacts. The majority of environmental impacts are associated with the steel structure in half of impact categories analyzed (ranging from 31.5 to 67.3%), especially due to the steel production and processing (section bar rolling and zinc coating). Polycarbonate covering impacts range from 21.8 to 45.9%, especially to its consequent emissions of carbon dioxide and methane (Sanyé-Mengual et al., 2015c) except for the Ecotoxicity category, which contributes less than 5% of the overall impacts. Only in FE and ME, polycarbonate covering impacts (particularly due to its construction energy burdens) are comparable with the automation subsystem impacts due to the metal inputs for automation and steel structure subsystems.

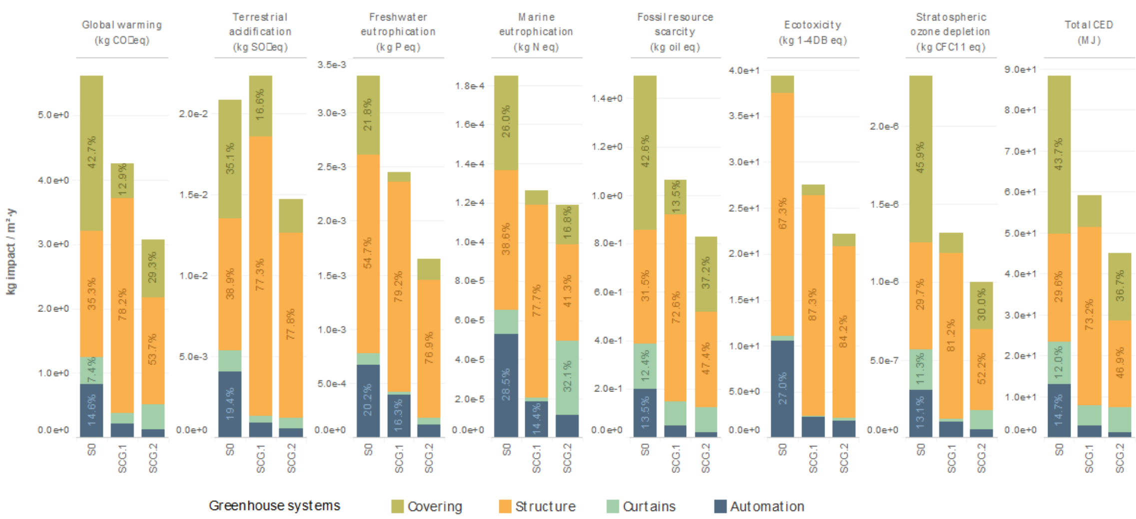


Figure 4. Environmental performance of 1m^2 per year of the iRTG in the current situation (scenario 0) and conventional greenhouse scenarios (SCG.1, 2) for all addressed impact categories. Percentatges indicate the share of impacts among greenhouse subsystems analyzed.

For both structure and covering subsystem their impact differs during the iRTG lifetime. Since polycarbonate and steel structure have 10 and 50 years of lifetime respectively, steel contributes to more than 70.0% of all impact categories during the construction phase while polycarbonate only impacts less than 20.7%. In contrast, during the operational phase, between 42.0 and 65.3% of all impact categories (except for ET, with 14.6%) are due to covering material replacement, followed by the automation subsystem. Finally, the energy needed to dismantle the iRTG accounted for more than 82.5% at the end of life phase for all impact categories as the majority of metals and polycarbonate are considered recyclable. Such consideration has been done due to the simplicity of the greenhouse structure which facilitates its dismantling process. Details for each subsystem impacts during its lifetime are available at Supplementary material.

3.1.2 Differences with conventional greenhouse scenarios (SCG)

The overall assessment revealed a fold increase between the iRTG (S0) and the conventional greenhouse scenarios (SCG.1 glass, SCG.2 plastic-film) of 1.3–1.8 and 1.6-2.3 respectively in 7 out of 8 impact categories analyzed. TA showed minor differences, of 0.9 and 1.4 respectively. The rationale behind these findings are the following.

First, the structure impacts are greater as a result of the higher complexity of the iRTG (S0, see section 3.1.3) respect to conventional greenhouses (as SCG.1 and SCG.2). However, this is compensated to some extent with the presence of aluminum in the conventional greenhouse structures, especially used to reinforce the glass covered greenhouse (SCG.1). That causes between 27.8% to 39.8% of the overall SCG.1 impacts for all impact categories, while only contributes around 1% of all impact categories in SCG.2.

Second, the construction process entails greater energy needs than conventional greenhouse construction especially due to the rooftop accessibility constraints (Kortright, 2001). Here, 4.78 $MJ/m^2\cdot y$ was needed to build the greenhouse, which represents between 7.2- to 8.1-fold increase compared to the conventional greenhouse scenarios (SCG.1 and 2, respectively, (Boulard et al., 2011)). Moreover, unlike CA, more energy was needed to build the covering material rather than the steel frame due to the articulated boom lift considered (which depend on the building accessibility, see Supplementary material for details) to rise and install the polycarbonate panels at the rooftop level up to 28m high. Besides, both greenhouse construction would require building machinery and specialized installation at the construction point, while in addition, conventional greenhouses normally require agricultural machinery to prepare the soil (Boulard et al., 2011) which increases by 4-6% the steel construction impacts for all impact categories.

Third, concrete amounts for BIA are much lower than CA as the former takes profit of the existing building fabric and is only required to reinforce the steel anchoring system. In particular, the multi-tunnel greenhouse assessed by (Sanyé-Mengual et al., 2015c) requires 2.4 times the amount of concrete of this RTG (0.212 kg/m^2·y), while in Venlo-type greenhouses concrete fold increase ranges between 4.6 and 5.9 (Anton et al., 2012; Bosona and Gebresenbet, 2018; Röös and Karlsson, 2013; Torrellas et al., 2012). Similar trends show SCG.1 and 2, with a 4.7- and 5.2-fold increase compared to S0, despite concrete contributes only between 1.0% and 4.8% of the conventional greenhouse scenarios environmental impacts. However, increased thermal inertia derived from higher concrete loads in RTGs, representing an indirect quantifiable benefit (Muñoz-Liesa et al., 2020b). In turn, this could compensate for the increasing height of currently built and projected greenhouses designed to improve its thermal inertia.

Finally, the lifetime of greenhouse structures. While for the iRTG the service lifetime is considered to be equal as the hosted building (50 years), conventional greenhouses are expected to last maximum 15 years according to EN 13031-1 (CEN, 2019). Despite many studies consider this reference value in their assessments (Anton et al., 2012; Sanyé-Mengual et al., 2015c; Torrellas et al., 2012), others consider that longer lifetimes could be assumed as the conventional greenhouses scenarios here assessed (SCG.1 and 2) for 25 years as published by (Boulard et al., 2011). In contrast, 15 years of lifetime would result in a 1.66-fold increase of their impacts. From the authors perspective, that probably relies on the greenhouse structure and whether its design is less sophisticated and more understood as a provisional solution (as some soil-based multi-tunnel greenhouses covered with simple plastic-films) or not (such as Venlo-greenhouse structures highly insulated).

3.1.3 Greenhouse design factors

The higher sophistication of the ICTA-iRTG compared to CA lies on key design factors that have been identified within the structural assessment. Particularly, design factors 1-4 heavly penalizes structure boundary conditions of the ICTA-iRTG leading to greater steel reinforcement. Each key factor and its structural implications have been analyzed in relation with BAU scenario (S0) and in comparision with the improved associated scenarios assessed (Table 1).

Design factor	Structural implications	Associated scenario
1. Building integration	The host building boundary conditions determine the steel sections, in order to match with building structural profiles and asthetics to better integrate the RTG.	Scenarios 1.1 and 2.1 represent a standard module of a iRTG, with optimized steel sections efficiently orientated to minimize its costs. A standard S275 steel is used.
2. Urban / suburban / rural environment	Wind speeds for greenhouse located in different rural or urban environments vary between 0.6—1.7x due to the upper terrain roughness, which affects wind design loads.	Scenario 1 represents a RTG located in a suburban environment, while scenario 2 in a dense urban environment. Scenarios SCG.1 and 2 represent a greenhouse in a rural environment.
3. Greenhouse ground height	Wind design loads in higher altitudes such in building rooftops at 28m height, are between 1.3—1.8x times the design load in the ground (for a greenhouse 6m height). Similarly, as higher is the greenhouse ridge, higher are the wind design loads.	Scenarios 0, 1 and 2 are located at 28m height, while scenario SCG.1 and 2 are 6m height at the ground level. Greenhouse geometry, including ridge height, has been unchanged as that would change internatal climate conditions.
4. Lateral ventilation design: suction forces	If there are more than >30% of holes in two or more façades, suction forces must be accounted, which largely penalizes environmental loads to be accounted.	For iRTGs placed in Southern Europe, natural ventilation in façades has been accounted, needed to reduce iRTG overheating during summer (Muñoz-Liesa et al., 2020b). As conventional venlo greenhouses, no lateral ventilation has been accounted for Northen European RTGs, leading to higher resistance to snow loads up to 1.6 kN/m^2.
5. Dead and snow loads	Because suction forces (4) and its derived environmental loads are greater than dead loads, covering material loads do not affect the iRTG design. Similarly, no suction forces are accounted for Northen Europe, which compensates to certain extent snow loads.	All scenarios are tested for heavier materials than polycarbonate (S0) such as double glass (0.3 kN/m^2). Snow loads with suction forces could be up to 0.4kN/m^2 (Southern Europe) and up to 1.6 kN/m^2 without it (Northen Europe regions located H<1000m AMSL).
6. Building accessibility: construction costs	According to S0 assessment, construction costs represent between 3.1—24.1% (and more than 10.5% in 7 out of 8 categories) share of all impact categories. Building machinery needs greatly relies on building accessibility.	No alternative scenarios have been proposed in order to account the worst structural hypothesis. However, alternative machineries are presented in Supplementary Material.

Table 1.Greenhouse design factors identified in the structural assessment and a description of its structural implications and the proposed associated scenarios covering each factor.

Thus, in order to minimize the steel structure impacts revealed in S0, the alternative optimized scenarios for different rooftop conditions have been proposed according to the key design factors of greenhouses structures which apply in both BIA and CA contexts). As a result, improvement scenarios aim to generalize the iRTG structure to other environments and boundary conditions while improving its structural design. Similarly, these key design factors can be used in further assessments as a guideline to design resource-efficient greenhouse structures.

3.2 Structural improvement

3.2.1 Suburban environment: S1 scenarios

Scenario 1.1 a profile optimization has been done mailnly by replacing the squared steel columns of the RTG, originally chosen to match with all rooftop structure and the double skin façade, simplifying this way the building structure and improving RTG integration in terms of buildings architecture. This allowed to reduce by 9.6% the structural steel weight compared to the current iRTG structure (Figure 5 and Figure 6). Therefore, by using rectangular profiles properly orientated, they better efficiently use their inertia and take profit of their maximum strength side. By doing so, this scenario represents a standard rooftop Venlo greenhouse structure attached to a building in a suburban environment with a standard S275 steel structure.

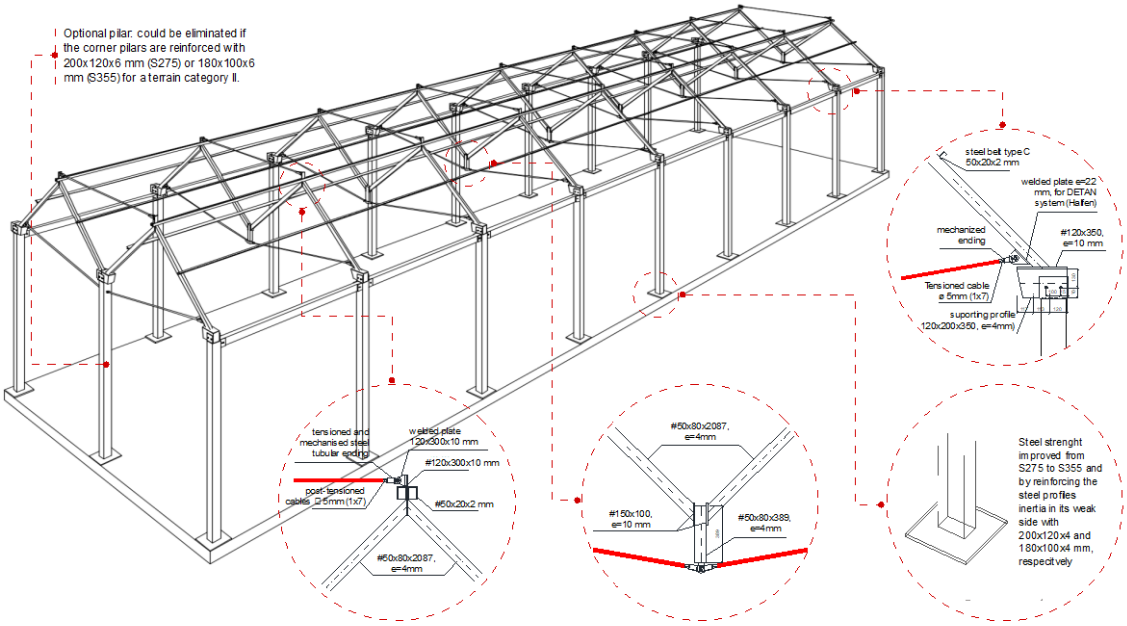
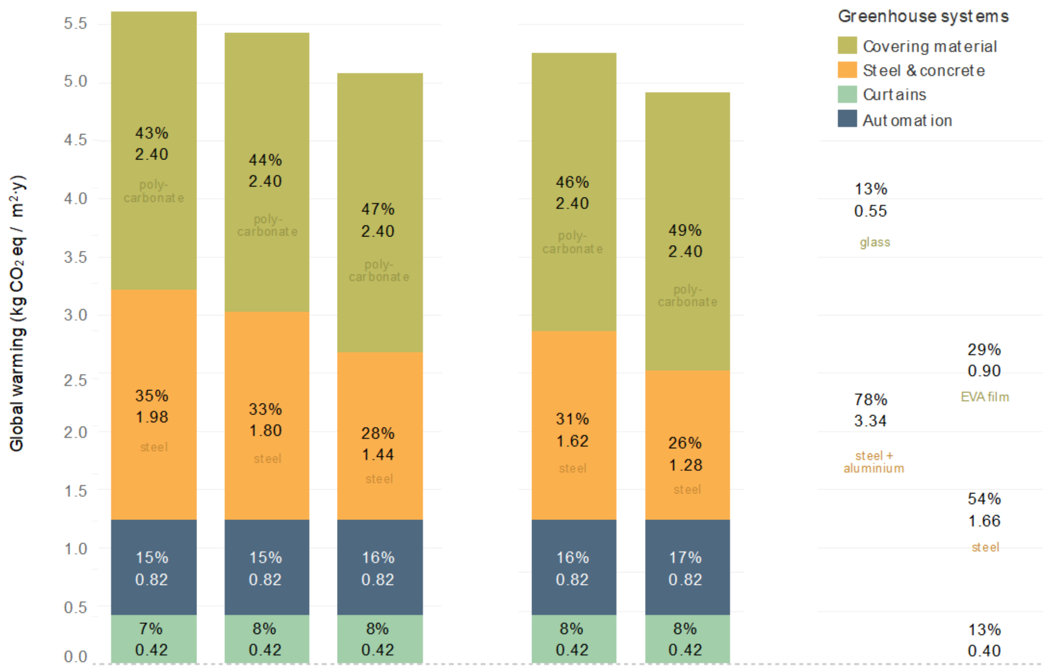


Figure 5. Greenhouse perspective of the optimized iRTG main steel structure for the ICTA case study with a redesigned tensegrity Venlo-type chapels and steel sections. Auxiliary steel components, as well as greenhouse bearing systems, have been not represented to show major optimized elements.

An additional 14.4% weight reduction has been obtained by increasing the steel strength from 275 to 355 MPa. Despite 275 MPa is the most available commercial steel, strengthen steels such as 355 MPa are also available for a +17% increased cost (ITeC, 2020), which does not economically compensate the steel reduction and thus, probably explains the chosen strength in the ICTA case study. Finally, the steel beams that support the greenhouse chapel have been substituted by two post-tensioned steel cables (Figure 5). Applying a 3.5 kN pre-stress force to both cables, compression loads are avoided improving this way the steel efficiency. Such structural design results from tensegrity principles (Cowcher, 2015) and, similarly to the bearing systems, it constitutes a simple and effective way to improve the structural stiffness and performance. By doing so, the greenhouse chapel works as a part of the structure forming a steel truss instead of being supported by the traditional steel frames and beams. This resulted in an optimized structure 13.4% lighter that sums up a total steel weight reduction of 27.8% (scenario 1.2, see KPI table from Figure 6).

Scenario 1.2 is, therefore, a more complex greenhouse but without compromising too much neither its construction process nor its costs, as the use of post-tensioned cables is a well-known technique in building industry (such in ICTA building) but here applied in the greenhouse system. Such design also largely reduces RTG steel weight, which is especially relevant when rooftop loads are a limitation in BIA as in rehabilitated buildings (Toboso Chavero et al., 2018). Besides, the use of steel cables in conventional greenhouses mainly to reduce its costs can also be found at the most simple Parral-type greenhouses in Almeria (Montero, 2012) or in multi-tunnel greenhouses to increase the greenhouse span (FAO, 2002) and even in more sophisticated and visually attractive greenhouses as the Edinburg Royal Botanical Gardens, UK (Maunder, 2008).



Characteristics	S0	S1.1	S1.2	S2.1	S2.2	S_{CG}.1	S_{CG}.2
tensioned cables	No	No	Yes	No	Yes	No	No
steel strenght	S275	S275	S355	S275	S355	S275	S275
terrain category	II	II	II	III	III	I	I
wind pressure	1.60 kN/m^2	1.60 kN/m^2	1.60 kN/m^2	0.99 kN/m^2	0.99 kN/m^2	1.30 kN/m^2	1.30 kN/m^2
KPIs (per FU, in m^2 y)							
steel amount (kg)	0,868	0,785	0,627	0,706	0,557	0,521	0,571
steel savings (%)	0,0%	9,6%	27,8%	18,6%	35,9%	40,0%	34,2%
GW savings (%)	0,0%	3,3%	9,6%	6,5%	12,4%	24,0%	45,1%
ME savings (%)	0,0%	3,6%	10,6%	7,1%	13,6%	31,6%	35,6%
ET savings (%)	0,0%	6,4%	18,6%	12,5%	24,1%	30,1%	43,9%
		BIA Suburban		BIA Urban		CA Rural	

Figure 6. Steel structure characteristics and key performance indicators (KPIs) for each studied scenario. Lighter colours diferenciate adapted data of CA from original data (BIA).

3.2.2 Suburban environment (S2 scenarios)

Scenarios 2.1 and 2.2 applied the same profiles optimization and increased strength combined with tensile principles applied in sceanarios 1.1 and 1.2 respectively but considering the iRTG was located in an dense urban area instead (category IV in EC-1). That results in a wind pressure forces reduction up to 38.1% (see table from Figure 6), which have led to a structural steel reduction of 18.2% and 35.9% for scenarios 2.1 and 2.2 respectively (see Figure 6). Note that as the wind pressure for a rural environment is even higher than a rooftop at 28m high in urban conditions (see wind graph from Figure 2), the non-optimized steel structure of conventional greenhouses have a major steel amount (0.571 kg/m²·y) and environmental impact than urban scenarios (S1.3 and S1.4, Figure

6). Details on wind pressure design loads in BIA and CA environments are available in Supplementary Material.

3.2.3 Environmental assessment of greenhouse improvement scenarios

The environmental burdens of the steel structure susbsystem in all improvement scenarios are reduced at a similar rate than the steel weight savings (Figure 6). Particularly, 6 out of 8 impact categories decrease from 9 to 35% for scenarios 1.1 and 2.2 respectively, while little more improvement exists in ET and FE impact categories (10 – 36%). Compared to SCG scenarios, the structural improvement compensed the greater amounts of steel of the suburban environment. In SCG.2 this is also translated, for instance, into 13.3% less GW impacts, while SCG.1 the aluminium contribution greatly penalizes its environmental performance. Since polycarbonate impacts are of great importance in all BIA scenarios, the overall environmental savings of the structural improvement range from 3 to 12% for GW, FRS, SOD and CED; 4 to 14% for ME and TA; and 5 to 24% for ET and FE (see table from Figure 6). Besides, all impact categories are reduced with similar behavior as the GW here presented (see Figure A.1 for further details).

The increased relative impacts of covering materials after the optimitzation underlines the importance to optimize its performance with less impacting materials such as glass (SCG.1) or plastic films (SCG.2) suitable for buildings (e.g., ETFE films) in further research. As noted earlier, all scenarios here assessed accounted wind suction loads, and since these are more important than dead loads, the structural design heavily relies on suction environmental loads rather than dead loads. As a side effect, no structural changes are required for heavier materials than the ICTA-iRTG polycarbonate such as double glass panel (0.3 kN/m^2). This also occurs in rural environments, where the structural design for conventional greenhouse structures covered with glass or plastics differ only slightly (Max et al., 2012).

3.3 Environmental impacts shifting between CA and BIA

RTGs are one of the most complex BIA structures in urban agriculture. The comparison of greenhouse structures between BIA and CA contexts revealed that material and energy construction flows are generally greater in BIA. Because BIA and RTG are still a novel field not studied in depth, authors previously suggested that those additional impacts where derived from the greenhouse building integration and building codes requirements (Cerón-Palma et al., 2012; Sanyé-Mengual et al., 2015c) as well as due to the greater wind loads on rooftops compared to soil-based greenhouses (Montero et al., 2017). That would turn BIA RTG structures less suitable in environmental terms compared to CA.

However, the identified factors that affect greenhouse structural design reveals that the construction impacts in the urban environment do not imply environmental shifting of impacts per se. Particularly, the current assessment revelaed that ICTA-iRTG structure integration with the building implies sub-optimal steel profiles that caused 10.5% of additional steel inputs (scenarios 1.1, 2.1). Moreover, the structure is also harmed by suburban environment location (S1), less suitable than a urban location (S2) as wind desing loads are higher (1.60 and 1.30 kN/m^2, respectively, see table from Figure 6). In order to compensate these additional constrains, the optimized structure allowed to reduce the steel amounts of BIA up to 22.9% compared to SCG.2.

Overall, even environmental shifting exists from CA to BIA in the assessed scenarios due to the covering material impacts, BIA structures in urban areas could benefit from less wind speeds that could avoid this effect, independently from the chosen covering materials or the structural design and materials (aluminium and/or steel). Thus, rooftop conditions do not always imply higher environmental impacts, as only if BIA structures are located in suburban areas construction environmental impacts might result higher. In any case, the optimized structural design here proposed could aid to compensate BIA boundary conditions (including its greater construction costs) in order to reduce structural impacts of RTG in further BIA projects.

These findings are applicable at the greenhouse structural level (i.e., per functional unit, m^2·y), including the environmental burdens of the whole life cycle stages of the structure. Thus, despite they not cover the whole life cycle of greenhouse crop production, they place the environmental focus on one of the major impacts in unheated greenhouse crop production for both BIA and CA contexts (Anton et al., 2012; Muñoz et al., 2008; Rufí-Salís et al., 2020a; Sanjuan-Delmás et al., 2018; Torrellas et al., 2012). Covering materials structural implications have been also included in order to assess alternative less impacting materials in furher research (such as glass, assessed in SCG.1). Therefore, by avoiding environmental shifting of its construction impacts, the overall BIA impacts could be avoided as well. Further assessment at the production point would probably demonstrate that potential initial construction burdens could be further compensated with the advantageous operational flows derived from BIA (e.g., by recovering waste building heat), demonstrating the feasibility of BIA structures and urban agriculture compared to conventional greenhouses.

3.4 Generalization to other BIA / CA contexts

The structural improvement of the RTG here assessed has been done following the European standards to generalize the proposed greenhouse structures in urban environments beyond the ICTA-iRTG case study. Moreover, because the Venlo greenhouse is a highly versatile structure with a "quasi-standard" design (Montero and Van Henten, 2011), it that can meet different requirements. Alternative covering materials are also possible with the designed scenarios as well as lateral and roof ventilation if needed. However, certain conditions apply when generalizing these results to other European regions: i) RTGs located below 1000m from the sea level; ii) snow loads up to 0.4kN/m^2 in Southern Europe where lateral ventilation is needed and up to 1.6kN/m^2 in Nothern Europe regions without lateral ventilation (which covers the majority of cities in Europe except for some Scandinavian countries and Iceland according to CEN, 1991); and iii) RTGs must be located below the maximum rooftop height depending on the scenario and urban environment. Detailed guidelines on extrapolations of the assessed scenarios to other European contexts can be found in Supplementary Material.

The generalization to other environments here mentioned could derive to non-optimized structures and, therefore, would need to recalculate the structure for each specific conditions. Moreover, it is important to note that specific environments located near the sea or next to a plane area with less terrain rugosity are less suitable for BIA as wind loads are higher compared to a centric location of a urban area. However, it can be useful as a first assessment as the current ICTA-iRTG's inventory (Sanyé-Mengual et al., 2015c) has been used in other studies such as (Benis et al., 2018). Finally, the tensegrity structure design can also be replicable to conventional Venlo greenhouse structures, though adaptations would be needed to match with specific boundary conditions beyond the urban environments here assessed.

Conclusions

Achieving better levels of environmental performance of resource consumption in buildings and agricultural systems is crucial to improve cities metabolism. This study assessed the material and energy flows and its environmental impacts at the European level of rooftop greenhouse structures based on the ICTA-iRTG case study in order to identify the main key design factors and propose alternative optimized scenarios.

Business as usual scenario revealed that the steel structure and covering material are responsible for the majority of material environmental burdens, up to 67.3% and 45.9% respectively, from all impact categories analyzed. The iRTG structure required higher steel amounts and needed an initial energy investment around 8 times higher than in the case of conventional greenhouses. In turn, it resulted in a 6-fold reduction in terms of concrete amount, due to the existing urban fabric and its increased thermal inertia. Finally, the iRTG assessed in this study, as well as other BIA structures benefited from greater lifetime expectancies (between 2 and 3.3-fold) than conventional greenhouses.

The proposed optimized greenhouse structural design and the identification of key design factors resulted in 4 improvement scenarios that allowed to mitigate BIA environmental burdens and extrapolate RTG impacts in the European context. These key design factors that affect material use-efficiency in RTGs were: (i) building rooftop height and accessibility; (ii) greenhouse location (i.e., rural, suburban or uban); and iii) greenhouse ventilation design. The improvement scenarios resulted in overall savings from 3.3 to 24.1% among the impact categories addressed. Moreover, such design was tested for alternative covering materials that could aid to decrease iRTG life-cycle impacts in further assessments.

Understanding the design factors applied in a Venlo greenhouse design allowed us to demonstrate that urban environment characteristics (such as lower wind loads or existing building fabric) could favor BIA structures compared to CA structures in rural environments. Thus, BIA does not imply greater material inputs and environmental burdens per se, as other authors previously suggested due to the greater wind loads in rooftops or more strict building codes. In conclusion, shifting main environmental burdens from CA to BIA is avoidable in favorable urban contexts or when compensated by optimized greenhouse structures.

Acknowledgement

The authors are grateful to the Secretaria d'Universitats i Recerca del Departament d'Economia i Coneixement de la Generalitat de Catalunya (Catalunya) for the award of a research scholarship (FI-DGR 2018) to Joan Muñoz-Liesa; to the Spanish Ministry of Economy and Competitiveness (MINECO) for the financial support to the research project Fertilectiy II "Integrated rooftop greenhouses: energy, waste and CO_2 symbiosis with the building. Towards foods security in a circular economy" (CTM2016-75772-C3-1-R; CTM2016-75772-C3-2-R). Authors also acknowledge financial support from the Spanish Ministry of Science, Innovation and Universities, through the "María de Maeztu" program for Units of Excellence (MDM-2015-0552). Authors would also gratitude Dr. Xavier Gabarrell, Dr. Joan Rieradevall, Dr. Violeta Vargas, Martí Rufí-Salís, and the ICTA-UAB staff for the very valuable support advise and help.

Appendix

Figure A.1 Environmental impacts of the improvement studied scenarios compared with the conventional greenhouse ones.

References

Ackerman, K., Plunz, R., Conard, M., Katz, R., Dahlgren, E., Culligan, P., 2011. The Potential for Urban Agriculture in New York City.

Anton, Á., Torrellas, M., Montero, J.I., Ruijs, M., Vermeulen, P., Stanghellini, C., 2012. Environmental impact assessment of dutch tomato crop production in a venlo glasshouse, in:. Presented at the Acta Horticulturae, pp. 781–792.

Artmann, M., Sartison, K., 2018. The Role of Urban Agriculture as a Nature-Based Solution: A Review for Developing a Systemic Assessment Framework. Sustainability 10, 1937–32. doi:10.3390/su10061937

Benis, K., Ferrão, P., 2017. Potential mitigation of the environmental impacts of food systems through urban and peri-urban agriculture (UPA) – a life cycle assessment approach. Journal of Cleaner Production 140, 784–795. doi:10.1016/j.jclepro.2016.05.176

Benis, K., Turan, I., Reinhart, C., Ferrão, P., 2018. Putting rooftops to use – A Cost-Benefit Analysis of food production vs. energy generation under Mediterranean climates. Cities 78, 166–179. doi:10.1016/j.cities.2018.02.011

Bosona, T., Gebresenbet, G., 2018. Life cycle analysis of organic tomato production and supply in Sweden. Journal of Cleaner Production 196, 635–643. doi:10.1016/j.jclepro.2018.06.087

Boulard, T., Raeppel, C., Brun, R., Lecompte, F., Hayer, F., Carmassi, G., Gaillard, G., 2011. Environmental impact of greenhouse tomato production in France. Agron. Sustain. Dev. 31, 757–777. doi:10.1007/s13593-011-0031-3

Cabeza, L.F., Rincón, L., Vilariño, V., Pérez, G., Castell, A., 2014. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. Renewable and Sustainable Energy Reviews 29, 394–416. doi:10.1016/j.rser.2013.08.037

Caputo, S., Iglesias, P., Rumble, H., 2017. Elements of Rooftop Agriculture Design 39–59.

Castleton, H.F., Stovin, V., Beck, S.B.M., Davison, J.B., 2010. Green roofs; building energy savings and the potential for retrofit. Energy & Buildings 42, 1582–1591. doi:10.1016/j.enbuild.2010.05.004

CEN, 2019. EN 13031-1: Greenhouses: Design and Construction—Part 1: Commercial Production Greenhouses. European Committee for Standardization, Brussels, Belgium.

CEN, 1991. EN 1991-1-3. Eurocode 1: Actions on structures—General actions—Snow loads. European Committee for Standardization.

Cerón-Palma, I., Sanyé-Mengual, E., Oliver-Solà, J., Montero, J.I., Rieradevall, J., 2012. Barriers and Opportunities Regarding the Implementation of Rooftop Eco.Greenhouses (RTEG) in Mediterranean Cities of Europe. Journal of Urban Technology 19, 87–103. doi:10.1080/10630732.2012.717685

Chau, C.K., Leung, T.M., Ng, W.Y., 2015. A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings. Applied Energy 143, 395–413. doi:10.1016/j.apenergy.2015.01.023

Cowcher, D.T., 2015. Design and analysis of geodesic tensegrity structures with agriculture applications.

CYPE Ingenieros, 2018. CYPE Metal 3D. Software para Arquitectura, Ingeniería y Construcción.

European Union, 2018. Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency.

FAO, F.A.A.O.O.T.U.N., 2002. El Cultivo Protegido En Clima Mediterrneo. Food & Agriculture Org.

Goldstein, B., Hauschild, M., Fernández, J., Birkved, M., 2016. Urban versus conventional agriculture, taxonomy of resource profiles: a review. Agron. Sustain. Dev. 36, 1–19. doi:10.1007/s13593-015-0348-4

Grard, B.J.P., Bel, N., Marchal, N., Madre, F., Castell, J.F., Cambier, P., Houot, S., Manouchehri, N., Besancon, S., Michel, J.C., Chenu, C., Frascaria-Lacoste, N., Aubry, C., 2015. Recycling urban waste as possible use for rooftop vegetable garden. Future of Food: Journal on Food, Agriculture and Society 3, 21–34.

Hossain, M.U., Ng, S.T., Antwi-Afari, P., Ben Amor, 2020. Circular economy and the construction industry: Existing trends, challenges and prospective framework for sustainable construction. Renewable and Sustainable Energy Reviews 130, 109948. doi:10.1016/j.rser.2020.109948

International Organization for Standardization, 2006. Environmental Management - Life Cycle Assessment - Principles and Framework (ISO 14040:2006).

IPCC, 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

ITeC, 2020. ITeC metabase: prices, technical details, companies, certificates, product pictures and environmental data.

Kortright, R., 2001. Evaluating the potential of green roof agriculture. City Farmer. Report on MSc Thesis available at http://www. cityfarmer. org/greenpotential. html.

Maunder, M., 2008. Beyond the greenhouse. Nature 455, 596–597. doi:10.1038/455596a

Max, J.F., Schurr, U., Tantau, H.-J., Mutwiwa, U.N., Hofmann, T., Ulbrich, A., 2012. Greenhouse Cover Technology. John Wiley & Sons, Inc., Hoboken, NJ, USA. doi:10.1002/9781118351871

Mok, H.-F., Williamson, V.G., Grove, J.R., Burry, K., Barker, S.F., Hamilton, A.J., 2013. Strawberry fields forever? Urban agriculture in developed countries: a review. Agron. Sustain. Dev. 34, 21–43. doi:10.1007/s13593-013-0156-7

Montero, J.I., 2012. Desarrollo de estructuras para invernaderos. Cuadernos de Estudios Agroalimentarios 45–70.

Montero, J.I., Antón, M.A., Torrellas, M., Ruijs, M., Vermeulen, P., 2010. EUPHOROS Deliverable 5. Report on Environmental and Economic Profile of Present Greenhouse Production Systems in Europe.

Montero, J.I., Baeza, E., Muñoz, P., Sanyé-Mengual, E., Stanghellini, C., 2017. Technology for Rooftop Greenhouses 83–101.

Montero, J.I., Van Henten, E.J., 2011. Greenhouse engineering: new technologies and approaches 51–63. doi:10.17660/ActaHortic.2011.893.1

Monticelli, C., 2010. Environmental assessment of ultralight roof structures built with new materials: The case of the ETFE cushions. Proceedings of IASS Colloquium WG.

Monticelli, C., Zanelli, A., Centrulli, M., 2017. Application and validation of eco-efficiency principles to assess the design of lightweight structures: case studies of ETFE building skins. Proceedings of the IASS Annual Symposium 2017.

Muñoz, P., Anton, Á., Nuñez, M., Paranjpe, A., Ariño, J., Castells, X., Montero, J.I., Rieradevall, J., 2008. Comparing the environmental impacts of greenhouse versus open-field tomato production in the Mediterranean region, in:. Presented at the Acta Horticulturae, International Society for Horticultural Science (ISHS), Leuven, Belgium, pp. 1591–1596.

Muñoz-Liesa, J., Royapoor, M., López-Capel, E., Cuerva, E., Gassó-Domingo, S., Josa, A., 2020a. Rooftop Greenhouses: Energy And Environmental Synergies Of Bidirectional Integration With The Building., in:. Presented at the Building Simulation 2019, IBPSA, Rome, pp. 5097–5104. doi:10.26868/25222708.2019.211264

Muñoz-Liesa, J., Royapoor, M., López-Capel, E., Cuerva, E., Rufí-Salís, M., Gassó-Domingo, S., Josa, A., 2020b. Quantifying energy symbiosis of building-integrated agriculture in a mediterranean rooftop greenhouse. Renewable Energy 156, 696–709. doi:10.1016/j.renene.2020.04.098

Nadal, A., Alamús, R., Pipia, L., Ruiz, A., Corbera, J., Cuerva, E., Rieradevall, J., Josa, A., 2017a. Urban planning and agriculture. Methodology for assessing rooftop greenhouse potential of non-residential areas using airborne sensors. Science of the Total Environment 601-602, 493–507. doi:10.1016/j.scitotenv.2017.03.214

Nadal, A., Cuerva Contreras, E., Cerón, I., Josa Garcia-Tornel, A., Rieradevall Pons, J., 2016. Agricultura en edificios urbanos: metodología para la implementación de invernaderos en azoteas de areas no residenciales urbanas 429–438.

Nadal, A., Llorach-Massana, P., Cuerva, E., López-Capel, E., Montero, J.I., Josa, A., Rieradevall, J., Royapoor, M., 2017b. Building-integrated rooftop greenhouses: An energy and environmental assessment in the mediterranean context. Applied Energy 187, 338–351. doi:10.1016/j.apenergy.2016.11.051

Population Division, U.N.D.O.E.A.S.A., 2018. World Urbanization Prospects: The 2018 Press Release. United Nations Publications.

Röös, E., Karlsson, H., 2013. Effect of eating seasonal on the carbon footprint of Swedish vegetable consumption. Journal of Cleaner Production 59, 63–72. doi:10.1016/j.jclepro.2013.06.035

Rufí-Salís, M., Petit-Boix, A., Villalba, G., Ercilla-Montserrat, M., Sanjuan-Delmás, D., Parada, F., Arcas, V., Muñoz-Liesa, J., Gabarrell, X., 2020a. Identifying eco-efficient year-round crop combinations for rooftop greenhouse agriculture 41, 89–576. doi:10.1007/s11367-019-01724-5

Rufí-Salís, M., Petit-Boix, A., Villalba, G., Sanjuan-Delmás, D., Parada, F., Ercilla-Montserrat, M., Arcas-Pilz, V., Muñoz-Liesa, J., Rieradevall, J., Gabarrell, X., 2020b. Recirculating water and nutrients in urban agriculture: An opportunity towards environmental sustainability and water use efficiency? Journal of Cleaner Production 261, 121213. doi:10.1016/j.jclepro.2020.121213

Sanjuan-Delmás, D., Llorach-Massana, P., Nadal, A., Ercilla-Montserrat, M., Muñoz, P., Montero, J.I., Josa, A., Gabarrell, X., Rieradevall, J., 2018. Environmental assessment of an integrated rooftop greenhouse for food production in cities. Journal of Cleaner Production 177, 326–337. doi:10.1016/j.jclepro.2017.12.147

Sanyé-Mengual, E., Anguelovski, I., Oliver-Solà, J., Montero, J.I., Rieradevall, J., 2015a. Resolving differing stakeholder perceptions of urban rooftop farming in Mediterranean cities: promoting food production as a driver for innovative forms of urban agriculture. Agric Hum Values 33, 101–120. doi:10.1007/s10460-015-9594-y

Sanyé-Mengual, E., Cerón-Palma, I., Oliver-Solà, J., Montero, J.I., Rieradevall, J., 2015b. Integrating Horticulture into Cities: A Guide for Assessing the Implementation Potential of Rooftop Greenhouses (RTGs) in Industrial and Logistics Parks. Journal of Urban Technology 22, 87–111. doi:10.1080/10630732.2014.942095

Sanyé-Mengual, E., Cerón-Palma, I., Oliver-Solà, J., Montero, J.I., Rieradevall, J., 2012. Environmental analysis of the logistics of agricultural products from roof top greenhouses in Mediterranean urban areas. J. Sci. Food Agric. 93, 100–109. doi:10.1002/jsfa.5736

Sanyé-Mengual, E., Llorach-Masana, P., Sanjuan-Delmás, D., Oliver-Solà, J., Josa, A., Montero, J.I., Rieradevall, J., 2014. The ICTA-ICP Rooftop Greenhouse Lab (RTG-Lab): closing metabolic flows (energy, water, CO 2) through integrated Rooftop Greenhouses, in: Finding Spaces for Productive Cities. Proceedings of the 6th AESOP Sustainable Food Planning Conference. pp. 693–701. doi:10.13140/RG.2.1.5016.7206

Sanyé-Mengual, E., Oliver-Solà, J., Montero, J.I., Rieradevall, J., 2015c. 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. Int J Life Cycle Assess 20, 350–366. doi:10.1007/s11367-014-0836-9

Sastre, R., Gimferrer, X., Martí, A., Coris-Veray, J., 2014. Wineva version 8.01.

Specht, K., Sanyé-Mengual, E., 2017. Risks in urban rooftop agriculture: Assessing stakeholders' perceptions to ensure efficient policymaking. Environmental Science and Policy 69, 13–21. doi:10.1016/j.envsci.2016.12.001

Specht, K., Siebert, R., Hartmann, I., Freisinger, U.B., Sawicka, M., Werner, A., Thomaier, S., Henckel, D., Walk, H., Dierich, A., 2013. Urban agriculture of the future: an overview of sustainability aspects of food production in and on buildings. Agric Hum Values 31, 33–51. doi:10.1007/s10460-013-9448-4

Swiss Center for Life Cycle Inventories, 2018. Ecoinvent version 3.5 Life Cycle Inventory Database.

Toboso Chavero, S., Nadal, A., Petit-Boix, A., Pons, O., Villalba, G., Gabarrell, X., Josa, A., Rieradevall, J., 2018. Towards Productive Cities: Environmental Assessment of the Food-Energy-Water Nexus of the Urban Roof Mosaic. Journal of Industrial Ecology 23, 767–780. doi:10.1111/jiec.12829

Torrellas, M., Antón, A., Ruijs, M., Victoria, N.G., Stanghellini, C., Montero, J.I., 2012. Environmental and economic assessment of protected crops in four European scenarios. Journal of Cleaner Production 28, 45–55. doi:10.1016/j.jclepro.2011.11.012

Vadiee, A., Martin, V., 2013. Thermal energy storage strategies for effective closed greenhouse design. Applied Energy 109, 337–343. doi:10.1016/j.apenergy.2012.12.065

van Beveren, P.J.M., Bontsema, J., van Straten, G., Van Henten, E.J., 2015. Optimal control of greenhouse climate using minimal energy and grower defined bounds. Applied Energy 159, 509–519. doi:10.1016/j.apenergy.2015.09.012

Wallgren, C., Höjer, M., 2009. Eating energy—Identifying possibilities for reduced energy use in the future food supply system. Energy Policy 37, 5803–5813. doi:10.1016/j.enpol.2009.08.046