ROOFTOP GREENHOUSES: LCA AND ENERGY SIMULATION

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ABSTRACT

Building-Integrated Agriculture (BIA) has the potential to offer a new dimension to our buildings, providing locally grown food that increase urban resilience. There are two main forms of BIA: Rooftop Greenhouses (RG) and Vertically Integrated Greenhouses (VIG). This paper focuses on RG, i.e. setting up hydroponic greenhouses on top of flat roofs. With 85% of Lisbon's building stock built before 1980, when there were no insulation requirements, there is a strong retrofitting potential using RGs. This should be considered together with the energy requirements of hydroponic environments, particularly for indoor temperature control.

This work combines Life Cycle Assessment (LCA) and energy simulation of a RG implemented on a residential building located in Lisbon. The analysis is aimed at quantifying the environmental impact, but also the energy requirements of the RG through its operation phase. The effect of the RG on the indoor temperature of the last floor apartments was analyzed. The first results show an improvement of the indoor temperature in the winter period and an undesirable increase in the indoor temperature during summer. These results highlight the need to evaluate different scenarios such as recovering part of the cooling loads used in the greenhouse and transferring them to the building, the application of insulation in the rooftop slab and the evaluation of night ventilation.

The aim of this study is to constitute a first step towards a quantitative basis for decision-making in the implementation of RGs in building retrofit interventions, by showing what alternatives would be most effective in delivering CO_2 emissions reductions, along with their respective costs and amounts of saved energy —thus offering an indication of which option is to be favored to guarantee sustainability and cost-effectiveness.

Keywords: Building-Integrated Agriculture, Rooftop Greenhouse, LCA, energy simulation, indoor temperature, controlled environment

INTRODUCTION

Building Integrated Agriculture (BIA) consists of the application of hydroponic greenhouse methods adapted for use on top of or in buildings [1]. This study analyzes the implementation of a RG for lettuce and leafy greens production on a low-rise multi-family dwelling located in Lisbon, with 18 apartments and 60 estimated inhabitants.

Lettuce production systems use Nutrient Film Technique (NFT), a system where re-circulated nutrient solution is pumped from a reservoir to slopping polyethylene or PVC channels, in which plant roots are placed in planting holes separated by a distance of 15 to 30 cm.

The RG occupies the whole area of the flat rooftop (i.e., 270m^2 with a production area of 225m^2) with 26 plant sites per m^2, which provide a yearly yield of 16,85 tons (threefold of the demand of the building's inhabitants). Sizing characteristics were adapted from information provided by local growers. The 21 identical existing buildings in the neighborhood offer the possibility of diversifying hydroponic cultures to cover local needs.

LIFE CYCLE ASSESSMENT

Goal and Scope

The goal of this LCA is to quantify the environmental impacts of rooftop greenhouse hydroponics production systems in a residential building in the city of Lisbon. The functional unit is 1 ton of greenhouse food produced (lettuce and leafy greens). The system boundary was defined as in Figure 1 (cradle-to-gate). The LCA was modeled on *SimaPro*, using the *EcoInvent 3.1* database. The model includes five main processes: (1) *greenhouse structure*; (2) *electricity*; (3) *water use*; (4) *growing process*; (5) *waste management*.

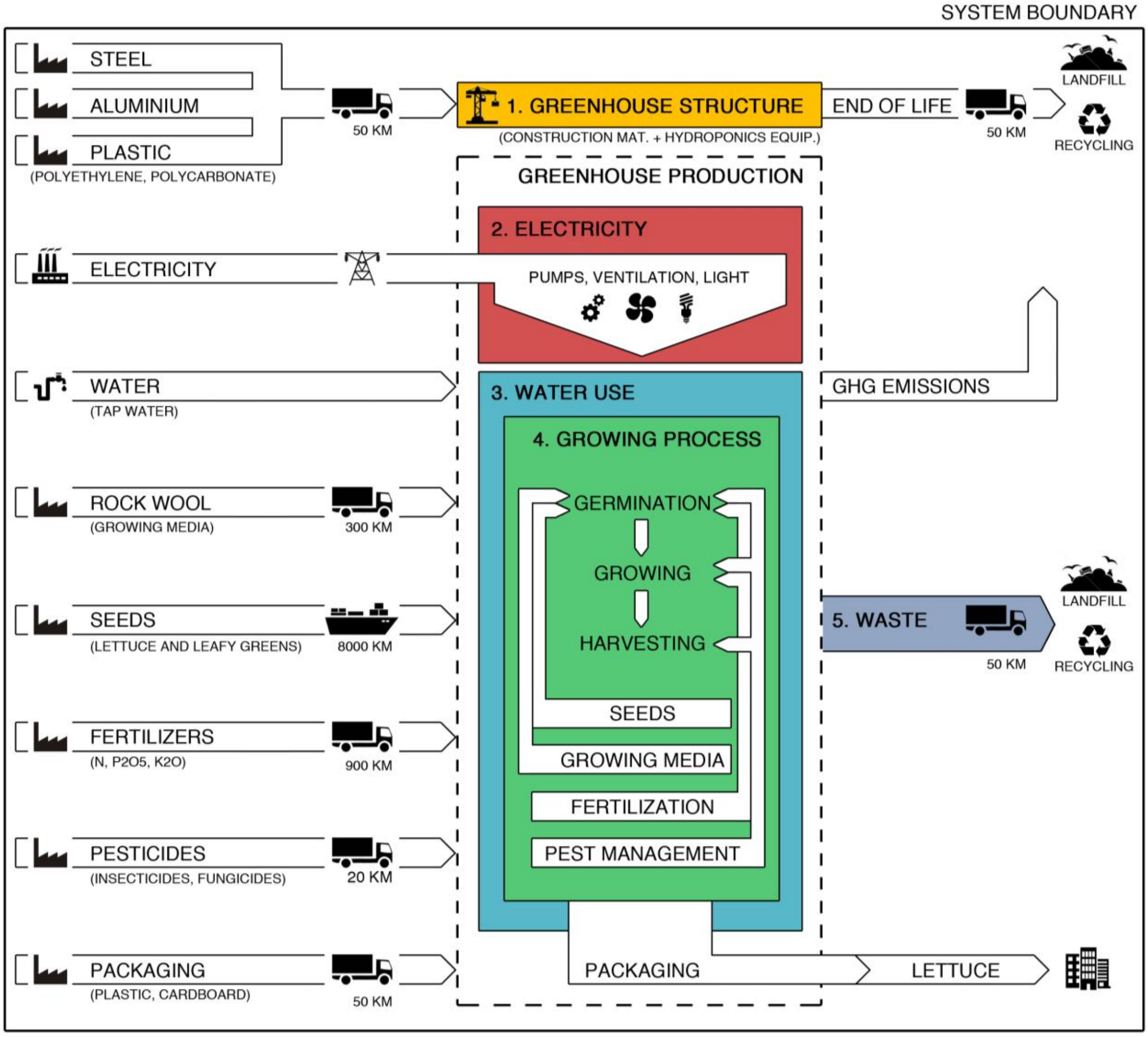

Figure 1: Life Cycle Inventory of greenhouse lettuce production system (hydroponics)

Life Cycle Inventory

The *greenhouse structure* is made from steel, aluminum and polycarbonate. Hydroponics growing channels are made of polyethylene. For this study, a leading Portuguese greenhouse manufacturer provided information concerning the characteristics and quantities of materials used in a “standard” greenhouse, which were adapted to this particular case. Local growers provided the specific dimensions and quantities of hydroponic equipment for growing lettuce.

The *electricity* process includes total electricity consumption (kWh) for the entire greenhouse activities (i.e., pumping systems, ventilation and lighting).

The *water use* process includes total water consumption (m^3). Whereas conventional agricultural production requires 120 liters of water per kg of lettuce, water use efficiencies in hydroponics are usually around 20 liters per kg of lettuce [2]. Based on data provided by local growers, the calculations for this case study led to a result of 19,23 liters of water per kg of lettuce.

In the *growing process*, the production of *seeds* was not considered because of lack of data. The *growing medium* process includes material and energy inputs for the manufacturing of substrate (i.e. rock wool), and its *packaging* (plastic and cardboard). The *fertilizers* process includes building infrastructure and electricity needed for the production of fertilizers. The *pesticides* process considers the production of pesticides including materials, energy use, and infrastructure.

Electricity consumption rates, *water use*, and quantities of *seeds*, *growing medium*, *fertilizers* and *pesticides* used per kg of production were also obtained from local growers. The Portuguese electricity mix was used in the model.

Different *waste scenarios* were modeled depending on the nature of the waste: (1) *greenhouse structure*, namely construction materials and hydroponics equipments (steel, aluminum and plastic); (2) *organic* (plant roots and waste); (3) *inorganic* (rock wool); (4) *plastic and cardboard packaging*. The RG construction materials, excluding plastic, were assumed to have a lifespan of 25 years. For the roof and walls composed of polycarbonate, the lifespan considered was 10 years. For hydroponic polyethylene equipment (i.e. channels and pipes), the lifespan considered was 4 years. Distances of transportation were considered, as well as GHG emissions from the waste treatment process. In LCA studies of greenhouse food production, the *cut-off method* [3] is the most commonly applied for the allocation of compost and recycling process: only loads directly caused by a product are allocated to it. Thus, composting of organic waste and recycling processes (for metals and plastics) were excluded.

All processes required transportation from production sites to the greenhouse, and were calculated using the formula: t x km. Distances traveled were based on the discussions with local hydroponic lettuce producers, regarding the locations of their suppliers.

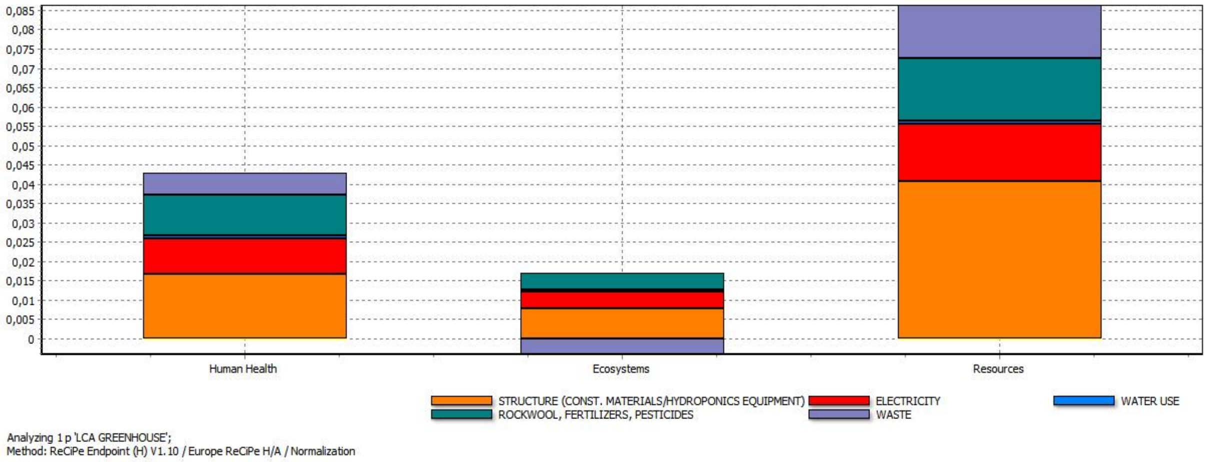

Figure 2: Life Cycle Inventory of greenhouse lettuce production system (hydroponics)

Life Cycle Impact Assessment

Environmental impacts of hydroponic production of lettuce and leafy greens in the RG are shown in Figure 2. The production process (i.e. *electricity*, *water use* and *growing process*) has a significant share in most of the categories (*ReCiPe Endpoint (H)* Assessment Method, Europe). Among the *growing process* components, *pesticides* are the major contributors to the impacts. *Greenhouse structure* and *waste* have less environmental impacts, since most of the materials are to be recycled at their end of life.

BUILDING AND GREENHOUSE SIMULATION

The building energy modelling allows performing an initial assessment of the thermal needs of the building and of the greenhouse during the operating phase and the possibility to evaluate different solutions for its acclimatization.

Simulation inputs of the building

The energy simulation of the building was performed using the software *Energy Plus version 8* and the geometry was defined using *Google Sketchup*. It is important to note that this simulation needs to be calibrated with *in situ* measurements to better represent the energy performance of the existing building. Therefore, the results presented here are a first analysis of the building thermal needs.

For this simulation, the building zoning was done considering spaces with different uses (i.e., kitchen, rooms and living rooms). The building was constructed in 1960 and the constructive solutions defined in the simulation were a double brick wall with air space for the exterior walls and a precast concrete joist and brick panel for the slabs.

The windows defined in the simulation are constituted by a clear 6mm glass installed in an aluminum frame, with external plastic shutters. Internal gains of the building were defined, namely occupation, lighting and equipment, considering predicted and reasonable values for the building typology. The air infiltration values were defined accordingly to specific bibliography [4] but are expected to have more accurate results in the future with *in situ* measurements.

Simulation inputs for the greenhouse

One main purpose for considering a greenhouse structure in a building rooftop is to create a controlled environment in terms of temperature and humidity for optimum growing conditions within a predictable and repeatable time schedule when compared to growing outside in a non-controlled environment. Considering the greenhouse structure, construction materials and design, it can become too warm in the summer and cold in the winter which could affect the crop production. The best indoor conditions control systems should not only be effective in providing the desired environment, but also be designed to be unobtrusive within the greenhouse system. Evaporative cooling is a common way to reduce indoor temperatures for greenhouses in dry climates [9] and basically consists of a process that reduces air temperature by water evaporation into the airstream. As water evaporates, it absorbs energy from the surrounding environment (greenhouse) decreasing the temperature of the air flow. Fan and pad evaporative systems consist of exhaust fans at one end of the greenhouse and a pump circulating water through and over a porous pad installed at the opposite end [5, 6, 7, 8]. The cooling efficiency is dependent of the pad wall material (corrugated cellulose, aspen pads or aluminum and plastic fibers) and air flow velocity and can vary between 70 to 80% [6, 9]. Additionally, the outside air conditions, namely the relative humidity and temperature, affect the cooling potential of the pad wall system [8, 9].

Evaporative pad cooling system

The ventilation sizing for the evaporative pad system considered in this greenhouse was performed considering the air flow value of 2.4 m^3 min^{-1} per m^2 of floor area [8]. Considering the greenhouse geometry it was considered that the system has three fans, one for each zone considered in the simulation of the greenhouse. The pad wall considered is constituted by corrugated cellulose since this is the most widely type used for evaporative pad walls [8]. The pad wall was considered to be in the north façade of each zone since this is the direction of the prevailing winds in Lisbon [11], increasing the efficiency of the pad system. For heating purposes it was considered an electric baseboard equipment to heat the greenhouse. The indoor temperature setpoint defined for the greenhouse was 24-28ºC.

Results

As it was expected considering the building typology and the constructive solutions, there are significant heating and cooling needs in all the apartments, as the number of annual hours with indoor temperatures above 26ºC in the summer period and below 18ºC in winter period is considerably high (considering no HVAC systems). The effect of the rooftop greenhouse in the building indoor temperature can be observed in the figure 3. As the temperature of the greenhouse was defined to be between 24 and 28ºC during all year it can be observed that the temperature of one room in the last floor increased with the implementation of the RG. This is a result from an increase of the heat gains from the greenhouse considering the low thermal resistance of the existing rooftop slab. Although this can be considered positive in the winter period, it represents a thermal comfort disadvantage in the summer period. One possibility to overcome this situation could be to improve the slab insulation or increase the night ventilation on the building.

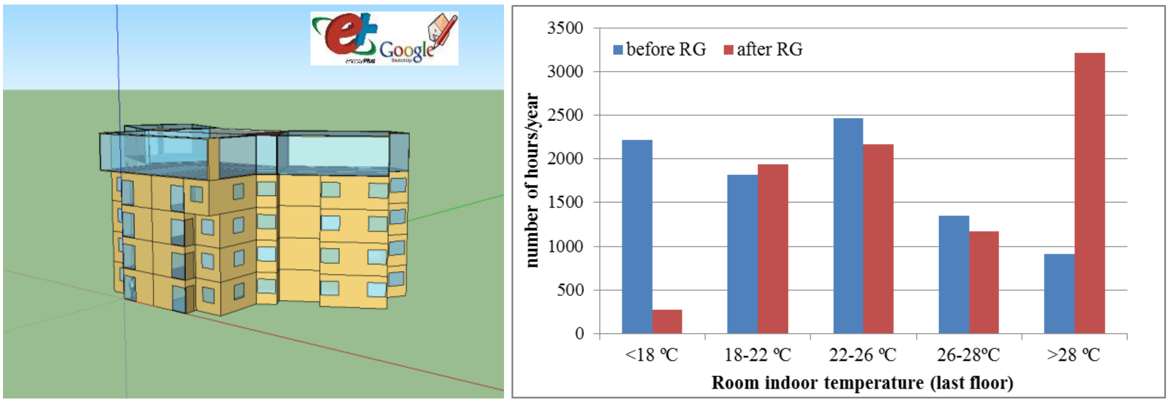

Figure 3: Building simulation model (southeast view) and annual indoor temperature in one room of the last floor before and after the rooftop greenhouse

Simulation limitations

Several limitations regarding the simulation of the building and of the greenhouse can be highlighted. The calibration of the model with *in situ* measurements in the existing building, energy audits, occupation patterns evaluation and other relevant parameters, will contribute to a more accurate building simulation and a better analysis of the operative phase of the building with and without the greenhouse. Regarding the greenhouse, it is relevant to highlight the possibility of the existence of a gradient of air temperature between the pad wall and the fans (not considered in the simulation). In fact it is expected that the temperature near the fans will be higher than on the opposite side of the greenhouse. Other relevant aspect to be analyzed is the effect of the wind on the pad evaporative system. The wind profile specific from the building location will contribute to this analysis.

ONGOING AND FUTURE WORK

In a next step, the energy modeling of the greenhouse will allow for the assessment of its heating and/or cooling energy consumptions, which will constitute an additional process of this LCA model, increasing the environmental impact of the use phase of the RG. A sensitivity analysis looking at reducing the impacts of the major contributors to the environmental impacts will be performed. This assessment will rely on the analysis of different scenarios such as the evaluation of different greenhouse acclimatization solutions, building insulation application, and passive solutions in order to reduce LCA impact of the greenhouse together with existing building. For all the scenarios, the energy savings will be calculated but will also be considered the input material such as ducts, fans, heat recover units and other materials and construction works. Also, the possibility of implementing a photovoltaic system to provide energy to the greenhouse will be considered and analyzed from a LCA perspective.

Besides, the size of the greenhouse and consequently the crop production should be evaluated in order to define the most suitable solution regarding global environmental impact. The main goal is to achieve the best scenario that includes solutions for the building as well as for the greenhouse.

A Life Cycle Cost (LCC) analysis performed in parallel to the energy flows scenarios will lead to the constitution of a quantitative basis for decision-making, by showing what alternative would be most effective in delivering CO2 emissions reductions, along with their respective costs and amounts of saved energy —thus offering an indication of which option is to be favored to guarantee sustainability and cost-effectiveness.

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