ARTICLE IN PRESS

Cities xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Cities

journal homepage: www.elsevier.com/locate/cities

Putting rooftops to use – A Cost-Benefit Analysis of food production vs. energy generation under Mediterranean climates

Khadija Benis[a,*], Irmak Turan[b], Christoph Reinhart[b], Paulo Ferrão[a]

[a] IN+ Center for Innovation, Technology and Policy Research, Instituto Superior Técnico, Avenida Rovisco Pais 1, 1049-001 Lisbon, Portugal

[b] Building Technology, Massachusetts Institute of Technology (School of Architecture + Planning), 77 Massachusetts Avenue, Cambridge, MA 02139, USA

ARTICLE INFO

Keywords:
Cost-Benefit Analysis (CBA)
Productive rooftops
Building-Integrated Agriculture (BIA)
Building-Integrated Photovoltaics (BIPV)
Global Warming Potential (GWP)
Discounted Cash Flow (DCF)

ABSTRACT

In today's growing cities, where land is an expensive commodity and direct exposure to sunlight is a valuable asset, rooftops constitute vast underexploited areas. Particularly with growing urban environmental concerns, the potential of transforming these areas into productive spaces – either for food cultivation or energy generation – has emerged as a viable option in recent years. Both food production and energy generation have benefits in the urban environment. Rooftop farming is an environmentally and economically sustainable way of exploiting urban rooftops, reducing "food miles" and providing local jobs, while roof-integrated solar photovoltaic (PV) modules provide clean energy, are increasingly cost-effective, and offer job opportunities. In both cases, a rooftop network of production could directly supply a portion of a necessary resource – either food or electricity – to the local community while concurrently reducing the burden on the environment. To provide a basis for comparing the implementation of these productive uses of rooftops in Mediterranean cities, this article applies a Cost-Benefit Analysis (CBA) to a mixed-use neighborhood located in Lisbon to assess the following uses: (1) open-air rooftop farming on intensive green roofs; (2) food production in low-tech unconditioned Rooftop Greenhouse (RG) farms; (3) Controlled-Environment Agriculture (CEA) in high-tech RG farms; and (4) solar PV energy generation. Relative costs, cost-saving benefits and added value of these four alternative productive uses of rooftops were modeled over 50 years and deducted from present value, considering two levels of analysis: (a) effects directly incurred by the operator of the systems; and (b) societal effects on the local community. To the authors' knowledge, this is the first comprehensive comparison of rooftop PV versus rooftop farming technologies. The results have shown food production to be more beneficial than energy generation, for both the owner of the system and the local community, under the modeled conditions and given the selected items of comparison. In particular, the results show that rooftop greenhouse farming can provide significant benefits over rooftop green roof and solar PV systems when assessed from a holistic perspective that accounts for impacts on both the operator and the local community.

1. Introduction

1.1. Background

The world is witnessing an unprecedented urban growth, with more than half of its population living in urban areas. This proportion is only growing larger, expected to exceed two-thirds by 2050 (United Nations, 2014). At this pace, and in lack of specific planning for food systems, urbanization will exacerbate pressures on food and nutrition security. Competition for land between agriculture and other urban uses will escalate in urban and periurban areas; food supply needs of cities will further grow, leading to greater environmental impacts and placing stress on overloaded food distribution systems; and distances of low-income households from markets will increase, resulting in supplementary environmental and economic costs to access food (FAO, 2011). Furthermore, cities account for 60 to 80% of energy consumption, generating 70% of total anthropogenic greenhouse gas (GHG) emissions through the use of fossil fuels for energy supply and transportation; and similarly to food supply needs, energy needs of urban areas are expected to increase (UN-Habitat, 2016).

In the current context of climate change, cities have therefore a critical role to play in building resilient communities. Over the past years, scientific literature on the assessment of sustainable urban solutions addressing both food supply and energy supply issues has been expanding. While some researchers have measured the potential of cities for self-reliance in food (Grewal & Grewal, 2012; Haberman et al.,

* Corresponding author.
E-mail address: khadija.benis@tecnico.ulisboa.pt (K. Benis).

https://doi.org/10.1016/j.cities.2018.02.011
Received 29 June 2017; Received in revised form 15 February 2018; Accepted 20 February 2018

Please cite this article as: Benis, K., Cities (2018), https://doi.org/10.1016/j.cities.2018.02.011

2014; Orsini et al., 2014) and for mitigating environmental impacts of food systems through urban agriculture (Benis & Ferrao, 2016); others have estimated the potential of renewable energies, such as solar photovoltaic (PV) systems, to fulfill urban energy needs (Hofierka & Kanuk, 2009; Amado & Poggi, 2014; Byrne, Taminiau, Kurdgelashvili, & Nam, 2015). Both food production and solar energy generation require large areas of one of the most coveted urban resources – land – and large amounts of a valuable urban asset – sunlight. At the same time, buildings' rooftops represent considerable unutilized urban areas with direct exposure to sunlight, and are therefore suitable for both food production (Orsini et al., 2014; Rodriguez, 2009; Proksch, 2011; Ackerman, Plunz, Katz, Dahlgren, & Culligan, 2012; NYSERDA, 2013; Specht et al., 2014b; Goldstein, Hauschild, Fernández, & Birkved, 2016) and energy generation (Byrne et al., 2015; Heinstein, Ballif, & Perret-Aebi, 2013; Gagnon et al., 2016; Yang & Zou, 2016). As cities are densifying, rooftops are becoming increasingly valuable urban commodities and city governments and owners are confronted with the choice to either use their rooftops for urban agriculture or electricity generation. This manuscript addresses this question, offering – to the authors' knowledge, the first quantitative comparison between the two uses in terms of environmental performance and job creation.

1.2. Objective of the study

Concurrent with emerging sustainability concerns, the potential of transforming urban rooftops into productive spaces, such as for food cultivation or energy generation, has aroused interest in recent years, as both uses have benefits in the urban environment. Rooftop farming is claimed to be an environmentally and economically sustainable way of exploiting urban rooftops, reducing "food miles" and providing local jobs, while roof-integrated solar photovoltaic (PV) panels provide clean energy, are increasingly cost-effective, and offer job opportunities. To the best of our knowledge, the costs and benefits of these two alternative uses of buildings' rooftops have not been comparatively assessed.

This study aims to provide decision-makers with a basis for systematic and integrated comparison of these productive uses of rooftops, enabling the evaluation of economic sustainability and net social welfare of a set of options over a 50-year life cycle. A Cost-Benefit Analysis (CBA) approach was applied to assess the following scenarios, against conventional unused flat roofs (see Fig. 1):

(1) Rooftop farms for open-air food production (on intensive green roofs);
(2) "Low-tech" Rooftop Greenhouse (RG) farms;
(3) "High-tech" RG farms for controlled-environment food production;
(4) Building-Integrated Photovoltaic (BIPV) energy systems.

In this study, we chose to evaluate the proposed systems individually. There exists precedents in which rooftop food growing and solar energy generation technologies are combined into one synergistic system (ZinCo, 2017). We chose to evaluate the systems independently in this case to understand their individual impacts. Future studies may consider the effects of combined systems on a single rooftop.

The following section describes these productive uses of rooftops.

1.3. Productive uses of rooftops in urban areas

1.3.1. Food production

Today, numerous cities have developed policies and programs on urban food security, nutrition and urban agriculture (Baker & de Zeeuw, 2015). Sustainable food systems are on the political agenda of over 100 cities worldwide, all of which have committed to The Milan Urban Food Policy Pact, the first international protocol that calls for municipalities to develop food systems that grant healthy and accessible food to all, protect biodiversity and reduce food waste. Among its recommended actions, local food systems are highlighted, through the promotion of urban and periurban agriculture and its integration into city resilience plans (Milan Expo, 2015).

1.3.1.1. Open-air rooftop farming on intensive green roofs. In *Scenario 1*, we consider the use of intensive green roofs for horticultural cultivation in urban areas (see Fig. 2a). The integration of green spaces into the urban fabric has been gaining importance in recent years, as a way of restoring ecosystems and mitigating the effects of soil sealing (European Commission, 2011). Farming in vacant lots, backyards or urban parks establishes patches of unsealed urban areas that can help reduce run-off, mitigate the risk of urban flooding and replenish groundwater stocks by allowing the infiltration of rainwater. Farming on rooftops, in particular, can reduce run-off from building roofs, moderate the Urban Heat Island (UHI) effect and the building temperatures, reduce pollution, neutralize acid rain, and increase the area available for biodiversity by offsetting the green area that is lost in building construction (Sabeh, 2016; Whittinghill, Hsueh, Culligan, & Plunz, 2016). In this context, researchers are addressing benefits and barriers of integrating green roofing technology into urban horticulture (Proksch, 2011; Whittinghill & Rowe, 2011), arguing that it can maintain the economic and food security benefits of Urban and Periurban Agriculture (UPA).

1.3.1.2. Rooftop Greenhouse (RG) farming. Building-Integrated Agriculture (BIA) is another form of horticultural production in the cities, consisting of the application of high-performance soilless cultivation methods adapted for use on top of or in buildings (Puri & Caplow, 2009). Particularly, Rooftop Greenhouse (RG) farming has been gaining popularity recently, in large cities such as New York, Singapore and Montreal (see Fig. 2b).

Mild conditions of Mediterranean climates allow for the cultivation of crop species with medium thermal requirements (i.e., crops that can adapt to temperatures ranging from 17 to 28 °C) in unconditioned greenhouses, during 9 months per year (Castilla & Baeza, 2013). Conventional Mediterranean greenhouses are usually made of wooden

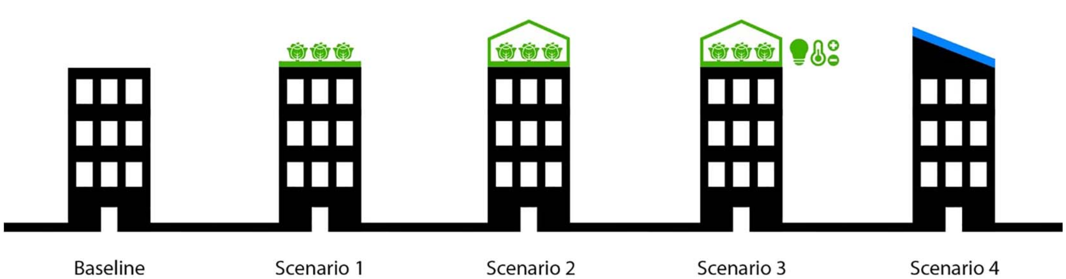

Fig. 1. Alternative productive uses of rooftops considered in the Cost-Benefit Analysis. Baseline: unused flat roofs; Scenario 1: rooftop farming on intensive Green Roofs (GR); Scenario 2: Unconditioned Rooftop Greenhouse (RG) farms; Scenario 3: Conditioned RG farms; Scenario 4: roof-integrated PV system (BIPV). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)