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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

A R T I C L E I N F O

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Global Warming Potential (GWP)
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A B S T R A C T

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).

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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.)

a.

b.

c.

Fig. 2. a. Rooftop open-air farm on intensive green roof (image: ©Brooklyn Grange Rooftop Farm, New York, USA); b. Conditioned rooftop greenhouse farm (image: ©Gotham Greens, New York, USA); c. BIPV, roof system (image: ©BIPVco, UK). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

structures with a plastic film cover, with no supplemental lighting, and no climate control system besides natural ventilation. The integration of such facilities into the urban fabric requires the enhancement of their structures in order to satisfy building codes and safety standards. In *Scenario 2*, we consider this type of "low-tech" RG farm, with an enhanced envelope but no climate control nor supplemental lighting.

Building upon the low-tech system envisioned in *Scenario 2*, in *Scenario 3* we consider a more advanced "high-tech" RG farm. Controlled-Environment Agriculture (CEA) has recently become a viable approach for the large-scale and year-round production of a wide variety of crops within the built environment. Technology developments such as highly efficient spectrum-specific grow lights and computer-assisted climate and crop control systems have allowed the emergence of the world's first commercial BIA facilities over the past decade. "High-tech" RG farms consist of state-of-the-art greenhouses with recirculating hydroponic systems and structures made of metal and aluminum, with glass or polycarbonate covers, typically set on service buildings (e.g., warehouses, offices, markets, etc.). The installations are usually equipped with backup lighting, rainwater-harvesting systems, thermal screens, and climate control systems. Whereas higher energy requirements and higher investment costs in comparison with conventional industrial horticulture facilities were identified as major limitations to the widespread implementation of conditioned RG farms (Specht et al., 2014b; Goldstein et al., 2016), crop productivity was shown to have a decisive role to play in achieving environmental and economic viability of such facilities (Sanye-Mengual, Oliver-Sola, Montero, & Rieradevall, 2015).

1.3.2. Energy generation

In *Scenario 4*, we envision a Roof-integrated BIPV system (see Fig. 2c). Faced with limited fossil fuel supplies and with the necessity to mitigate the environmental impacts of urbanization, worldwide research and development has been recently looking at ways of turning buildings from energy consumers to net energy producers. Solar energy is an infinite and clean resource, and scientists have been assessing systems such as Building-Integrated Photovoltaics (BIPV), which consist of the application of photovoltaic materials, in replacement of conventional construction materials in parts of the building's envelope (e.g., roof, facade, window, skylight). Among existing applications for BIPV, rooftops are considered to be the ideal option, since pitched roofs with a proper angle and orientation provide the highest energy harvesting (Heinstein et al., 2013). Experts at the United States Energy Department's National Renewable Energy Laboratory (NREL) have estimated the potential of rooftop PV systems nationwide, concluding that buildings' rooftops can generate almost 40% of electricity needs in the United States (Gagnon et al., 2016).

2. Methodology

2.1. Cost-Benefit Analysis

Cost-Benefit Analysis (CBA) is a widely-used method for systematically assessing the advantages and disadvantages of a particular intervention and its alternatives. It has previously been used for the assessment of several green building technologies, such as green facades and living wall systems (Perini & Rosasco, 2013), green roofs (Nurmi, Votsis, Perrels, & Lehvavirta, 2016; William et al., 2016), alternative thermal insulation materials (Mahlia & Iqbal, 2010; Shekarchian, Moghavvemi, Rismanchi, Mahlia, & Olofsson, 2012), and BIPV (Delisle & Kummert, 2016). It is used here, as a cohesive method for comparing the costs and benefits of the following productive use of rooftops, as an alternative to the conventionally unused flat roofs: (1) Rooftop farms for open-air food production (on intensive green roofs); (2) "Low-tech" Rooftop Greenhouse (RG) farms (unconditioned); (3) "High-tech" RG farms for controlled-environment food production; and (4) Building-Integrated Photovoltaic (BIPV) energy systems.

This CBA includes two levels: (a) direct effects incurred by the operators of the systems, i.e., investment costs, operation costs, carbon costs, and profits generated from yields; and (b) societal effects on local community, such as market impacts (households' savings in food expenses, local jobs creation) and environmental impacts (carbon mitigation) (see Fig. 3). By quantifying these effects, this analysis aims to not only assess the economic sustainability of each option, but also reflect the societal value attached to the associated effects. This assessment provides decision-makers a holistic picture of the potential impacts of alternative project options, and can thereby assist in policy decision making to implement the productive use of rooftops.

A 50-year Discounted Cash Flow (DCF) was evaluated for the systems, accounting for all equipment upgrades, operations and maintenance costs, as well as revenue received over time. A DCF is a measure of the projected future cash flows (both costs and earnings) of an investment discounted to the present day. We assumed a 6% discount rate based on similar cost evaluations for sustainable construction schemes in Portugal (Real, 2010; Mendes, 2011), and a 2.5% annual inflation based on Portuguese conditions (Braganca et al., 2007) and a similar

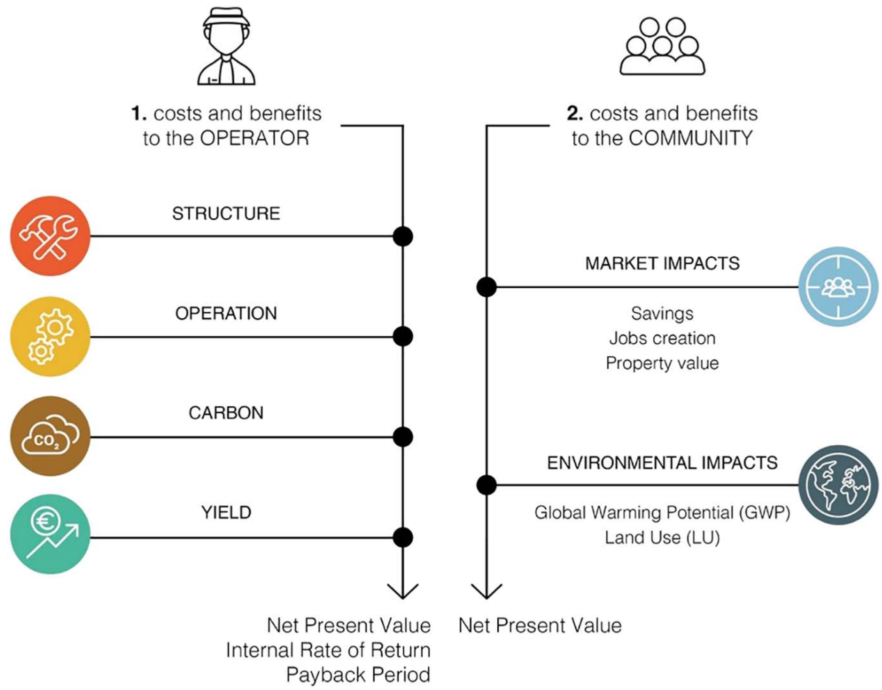

Fig. 3. Two-level CBA, considering costs and benefits to the systems' operator and to the community.

study conducted in an Italian context for a green façade installation (Perini & Rosasco, 2013). The economic viability of each scenario was assessed through: (i) the Net Present Value (NPV), i.e., the sum of all cash inflows and outflows for the project over the 50-year period, discounted to the present; (ii) the Internal Rate of Return (IRR), i.e., the annual percentage rate of return on investment based on the 50-year projected cash flows; and (iii) the payback period, i.e., the period of time required before total revenues equal or surpass total costs for the first time.

The following sections describe the cash flows and the sources and calculations that were used to collect respective life cycle data and costs. The functional unit is one square meter of rooftop. The case-study is an integrated mixed-use neighborhood for 17,500 occupants, designed on a 27-ha decommissioned industrial urban site in Lisbon, Portugal. Tomatoes were selected here as the crop produced in the rooftop farms since tomatoes are (a) among the most widespread indoor-grown horticultural species and (b) a large body of literature is available that describes growing requirements and crop yields.

2.2. Costs and benefits to the system operator

To model costs and benefits incurred by the owners of the systems, the following cash flows were considered: (1) Structure; (2) Operation; (3) Carbon costs; and (4) Yields (see Table 1).

2.2.1. Structure

The *Structure* cash flow represents the costs associated with the roof-integrated system, including: (i) the installation of the structure; (ii) its maintenance (i.e. the upkeep and replacement of materials and equipment in the system); and (iii) the end-of-life treatment of its components. Lifecycle costs were collected through market research, by consulting local manufacturers and suppliers, and using a Portuguese database of market prices (CYPE, 2017).

As previously mentioned, literature on the use of green roofs for urban agriculture is emerging, showing that intensive green roofs can be adapted for food production (Proksch, 2011; Whittinghill & Rowe, 2011). Therefore, in *Scenario 1* the Life Cycle Inventory (LCI) data for intensive green roof layers was based on a study on Life Cycle Assessment (LCA) of green roof layers (Chenani, Lehvävirtaa, & Häkkinenc, 2014), which are conventionally composed of: (1) a waterproofing membrane and a root barrier that separate the wet layers from the underlying building rooftop; (2) a drainage layer that enables the removal of excess water; (3) a filter fabric that prevents the drainage layer from clogging with media; (4) a water retention layer; (5) a substrate; (6) and a vegetation layer. Costs of intensive green roofs found in the industry vary around 130 €/m^2, for a lifespan of 40 years (CYPE, 2017).

Since there are currently no RG farms in Lisbon, life cycle data of *Scenarios 2* and *3* was based on an LCA of state-of-the-art rooftop greenhouses in Mediterranean cities (Sanye-Mengual et al., 2015), with a steel structure, a rigid polycarbonate cover, and an internal shading film made of a UV-treated polyethylene. Costs were adapted to Lisbon by consulting local suppliers of the greenhouse components; a cost of 590 €/m^2 over a lifespan of 50 years was estimated.

As for BIPV, single-crystalline silicon-based PV modules were considered in *Scenario 4*, being a well-established and widely used technology for which up-to-date LCI data is available. Data from a recently published LCA of roof-integrated PV laminates (Frischknecht et al., 2014) was used as a basis. Similarly, unframed roof-integrated PV laminates were considered here, and the construction of a pitched roof was included in the LCI. Costs for the BIPV system were found to vary around 250 €/m^2 over a lifespan of 25 years (Frontini et al., 2015), while a cost of around 52 €/m^2 over a lifespan of 50 years was estimated for the pitched roof, according to local construction companies (CYPE, 2017).

2.2.2. Operation

The *Operation* cash flow quantifies the inputs required for the productive use of rooftops, i.e., for food production or for energy generation.

Operation of the open-air farm in *Scenario 1* includes resources required for tomato cultivation, i.e., inputs for organic field production (organic fertilizers, compost, etc.); water and energy needs; and labor (farmers). Data inventory was adapted from a study on Global Warming Potential (GWP) of tomato cultivation in Spain and Italy (Theurl, Haberl, Erb, & Lindenthal, 2014), and costs were adapted to Lisbon.

Table 1
a. Costs and benefits to the system operator: data inventory; b. Assumptions.

Scenario	Cash flow	Materials inventory	Lifespan	Cost	GWP	Carbon cost	Carbon cost
						Before 2030	After 2030
			(Years)	(€/m^2)	(kgCO_2eq/m^2)	(€/m^2) (n)	(€/m^2) (o)
SC 1: GR	Structure	Intensive green roof	40	131.45	21.712	0.22	0.76
	Operation	Organic fertilizer	Yearly	0.17	0.0006	0.00001	0.00002
		Manure compost	Yearly	0.02	0.0002	0.000002	0.00001
		Water (*a*)	Yearly	0.37	3.9380	0.039	0.138
		Energy (*b*)	Yearly	0.54	0.2695	0.003	0.009
		Labor (farmers) (*c*) (*g*)	Yearly	2.46	//	//	//
	Yield	Crop yield, LFSC (j_1)	Yearly	5.50	//	//	//
		Crop yield, SFSC (j_2)	Yearly	19.80	//	//	//
SC 2: LTBIA	Structure	Steel	25	78.00	17.723	0.177	0.62
		Polycarbonate	10	13.21	2.734	0.027	0.096
		Polyethylene	4	5.84	0.061	0.0006	0.002
		Climate screen	4	22.48	0.053	0.0005	0.0019
		Concrete	50	0.25	4.080	0.408	0.143
	Operation	Growing equipment	3	4.31	0.026	0.0003	0.0009
		Substrate	Yearly	0.70	0.011	0.0001	0.0004
		Fertilizers	Yearly	0.91	0.027	0.0003	0.001
		Pesticides	Yearly	0.53	0.0005	0.00001	0.00002
		Water (*a*)	Yearly	1.88	8.088	0.0809	0.2831
		Energy (*b*)	Yearly	0.84	2.044	0.0204	0.0715
		Labor (farmers) (*d*) (*g*) (*h*)	Yearly	4.66	//	//	//
	Yield	Crop yield, LFSC (k_1)	Yearly	22.40	//	//	//
		Crop yield, SFSC (k_2)	Yearly	55.72	//	//	//
SC 3: HTBIA	Structure	Steel	25	78.00	17.723	0.177	0.62
		Polycarbonate	10	13.21	2.734	0.027	0.096
		Polyethylene	4	5.84	0.061	0.0006	0.002
		Climate screen	4	22.48	0.053	0.0005	0.0019
		Concrete	50	0.25	4.080	0.408	0.143
	Operation	Growing equipment	3	11.71	0.071	0.0007	0.0025
		Substrate	Yearly	1.71	0.026	0.0003	0.0009
		Fertilizers	Yearly	2.23	0.067	0.0007	0.0023
		Pesticides	Yearly	1.31	0.0013	0.00001	0.00004
		Water (*a*)	Yearly	1.11	4.788	0.0479	0.1676
		Energy (*b*)	Yearly	7.43	18.058	0.1806	0.623
		Labor (farmers) (*e*) (*h*)	Yearly	5.74	//	//	//
	Yield	Crop yield, LFSC (k_1)	Yearly	54.72	//	//	//
		Crop yield, SFSC (k_2)	Yearly	136.12	//	//	//
SC 4: BIPV	Structure	Sloped roof	50	52.00	2.160	0.02	0.08
		BIPV system	25	250.00	21.840	0.22	0.76
	Operation	Labor (O&M) (*f*) (*i*)	Yearly	0.02	//	//	//
	Yield	FiT period (*l*)	15	28.50	//	//	//
		After FiT period (*m*)	10	13.47	//	//	//

	Assumptions			Sources
(*a*)	Water for industry and agriculture (Portugal)	*€/m^3*	1.6749	(EPAL, 2017)
(*b*)	Electricity for industry (Portugal)	*€/kWh*	0.1402	(PORDATA, 2015a)
(*c*)	Labor SC.1: Open-air farming	*ppl/m^2*	0.00031	(de Mourao, 2007; Instituto Nacional de Estatística, 2002)
(*d*)	Labor, SC.2: Greenhouse farming, low yields	*ppl/m^2*	0.0005	(Resh, 1978)
(*e*)	Labor, SC.3: Greenhouse farming, high yields	*ppl/m^2*	0.0005	(Resh, 1978)
(*f*)	Labor, SC.4: BIPV system maintenance	*ppl/m^2*	0.0001	(IEA, 2002)
(*g*)	Agriculture, non-qualified workers	*€/y*	7898.80	(PORDATA, 2015b)
(*h*)	Agriculture, qualified workers	*€/y*	11,473.00	(PORDATA, 2015b)
(*i*)	Energy industry, qualified workers	*€/y*	1393.10	(PORDATA, 2015b)
(j_1)	Organic tomato, farmer to retailer	*€/kg*	1.00	(Arsenio, 2014)
(j_2)	Organic tomato, retailer to consumer	*€/kg*	3.60	Local grocery stores
(k_1)	Non-organic tomato, farmer to retailer	*€/kg*	0.80	(Silva, 2015)
(k_2)	Non-organic tomato, retailer to consumer	*€/kg*	1.99	Local retailers
(*l*)	PV Feed-in Tariff (Portugal), 15 years	*€/kWh*	0.0950	(Ordinance 20, 2017)
(*m*)	Average market electricity price	*€/kWh*	0.0499	(SIMEE, 2015)
(*n*)	Carbon tax, before 2030	*€/kg*	0.010	(Pereira, Pereira, & Rodrigues, 2016)
(*o*)	Carbon tax, after 2030	*€/kg*	0.035	(Pereira et al., 2016)

Similarly, in *Scenarios 2* and *3*, operation of RG farms includes: inputs required for hydroponic cultivation (PVC channels, seeds, growing media, etc.); water and energy needs; and labor (farmers). In *Scenario 2*, while the envelope materials were enhanced (in comparison with conventional rural greenhouses) in order to satisfy municipal regulations, these "low-tech" RG farms were assumed to have no supplemental lighting system and no climate control. Energy needs are therefore significantly lower than in *Scenario 3*.

Costs of farming materials and equipment were provided by local suppliers. We assumed a price of 1.6749 €/m^3 for water, according to the water sell price for industry and agriculture from the water supply concessionaire of Lisbon (EPAL, 2017). We assumed an electricity price of 0.1402 €/kWh, based on national statistics on electricity prices for industrial consumers (PORDATA, 2015a). Respective labor requirements were defined for each cultivation system, based on existing statistical data and literature (Instituto Nacional de Estatística, 2002; de Mourao, 2007; Resh, 1978). Wages for qualified and non-qualified workers in the agriculture sector were found in national statistics on employment and labor market (PORDATA, 2015b).

Finally, in *Scenario 4*, BIPV operation requires workers for the maintenance of the system. Labor requirements were obtained from a study on economic evaluation of BIPV systems (IEA, 2002); wages of qualified workers in the energy industry were found in national statistics (PORDATA, 2015b).

2.2.3. Carbon

The *Carbon* cash flow accounts for the environmental impacts associated with the structure and operation of each alternative rooftop system. Lifecycle GWP was modeled for each system. A carbon tax was then assumed, in order to estimate carbon costs for each scenario.

As a member state of the European Union (EU), Portugal is subject to the EU climate-energy policy regulation. In 2014, the Portuguese government designated a Commission for Environmental Tax Reform (CFRV) that formulated a carbon tax proposal to help the country meet the EU's target for emissions reductions by 2030 (CFRV, 2014). An important part of carbon emissions in the Portuguese economy are covered by the EU's Emissions Trading System (EU-ETS). In order to prevent distorting market incentives across EU-ETS covered and non-covered sectors, the CRFV Commission indexes the carbon tax to the EU-ETS (Pereira et al., 2016).

Therefore, following the official EU projections for the EU-ETS carbon prices (i.e., a carbon tax of 10 €/tCO_2 by 2020, leveling off at 35 €/tCO_2 from 2030 onwards) (European Commission, 2014b), we assumed a carbon tax of 10 €/tCO_2 from 2017 to 2030, and of 35 €/tCO_2 for the remaining years of the project's lifespan.

2.2.4. Yield

The *Yield* cash flow quantifies the economic value of the outputs of rooftops' productive use, i.e., of food harvested or energy generated. In the food production scenarios, two distribution alternatives were modeled:

(A) Long Food Supply Chains (LFSC), where crops are sold from farmer to retailer, at the average producer sell price;

(B) Short Food Supply Chains (SFSC), where crops are sold at farmers' markets directly to the consumer, at the average retail price.

In *Scenario 1*, a potential annual crop yield of 5.5 kg/m^2/y and an average sell price of 1 €/kg from producers to retailers were assumed, based on a recent study on organic field tomato in Portugal (Arsenio, 2014); an average retail price of 3.60 €/kg was obtained from local organic grocery stores.

In *Scenario 2*, a potential annual crop yield of 28 kg/m^2/y was assumed, based on existing literature on "low-tech" greenhouse tomato production under Mediterranean climates (Peet & Welles, 2005). In *Scenario 3*, a potential annual crop yield of high-tech RG farms of 68 kg/m^2/y was assumed, based on simulation results from a recently published study on BIA farms in Lisbon (Benis, Reinhart, & Ferrao, 2017) – 10% of the simulated yield of 76 kg/m^2/y was conservatively assumed here to be non-marketable. An average tomato sell price from producers to retailers of 0.80 €/kg was assumed, based on a recent publication of the Portuguese Association of Horticulture (Silva, 2015); and a retail price to consumers of 1.99 €/kg was assumed, based on data collected from local retailers.

For BIPV, the annual energy yield was modeled for the site with DIVA-FOR-RHINO v4 (Solemma, 2016) which uses the EnergyPlus photovoltaic model to simulate solar energy generation potential; a yield of 300 kWh/m^2/y was obtained. It was assumed that the system feeds all the generated energy to the grid. In Portugal, electricity producers receive Feed-in Tariffs (FiT), through a reverse auction process that is capped at the reference tariff set at 0.095 €/kWh in 2015 (Ordinance 15, 2015) and is still applied in 2017 (Ordinance 20, 2017). Solar systems receive 100% of this reference tariff for a period of 15 years. After that period, the produced electricity is remunerated through the energy market, receiving 90% of the market price (Decree-Law 153, 2014). The average market price of 2015 was considered here, i.e., 0.0499 €/kWh (SIMEE, 2015). While this CBA considers current prices, it is important to note that energy prices are expected to grow throughout the coming years, driven by the increase of fossil fuel prices coupled with needed investment into infrastructure and generation capacity, before stabilizing and then decreasing as fossil fuels are replaced by renewable energy sources (European Commission, 2014a).

2.3. Costs and benefits to the community

The societal effects that were considered are separated into two categories: (1) market impacts, including food cost savings to the local households, local jobs creation, and impacts on the surrounding real estate value; and (2) environmental impacts, namely global warming potential and land use (see Table 2).

2.3.1. Market impacts

2.3.1.1. Savings. The *Savings* cash flow estimates the savings to the local residents resulting from the productive use of rooftops within their own neighborhood.

Previous research has shown that urban agriculture saves consumers money on their food expenditures (Blair, Giesecke, & Sherman, 1991). Short supply chains through partnerships between farmers and consumers, such as Community-Supported Agriculture (CSA), are increasingly acknowledged in Europe as an alternative to the unsustainable global food system. CSA consists of a network of consumers that support a local farm by sharing operation costs (i.e., production inputs and labor) and periodically receiving a share of the harvest in return. Researchers showed that CSA subscribers could save up to 150% of share prices compared to equal quantities of produce purchased at conventional retailers (Cooley & Lass, 1998). For *Scenarios 1, 2 and 3*, savings to the local community in food expenditure were accounted for by comparing the share to be paid by potential CSA members per square meter of rooftop area, to the expenditure for the same amount of tomato over the 50-year project lifespan if the tomatoes were purchased at conventional suppliers. Average conventional retail prices were obtained from local suppliers – 3.60 €/kg for organic tomato (*Scenario 1*), and 1.99 €/kg for non-organic tomato (*Scenarios 2 and 3*).

No savings to the community were considered in *Scenario 4*, since there are no additional energy savings associated with local PV generation beyond the ones already captured by the LCA. An exception would be if municipalities provide a specific incentive for community owned PV installations which is currently not the case in Portugal.

2.3.1.2. Jobs creation. The *Jobs Creation* cash flow estimates the impact of productive uses of rooftops on employment within the local community, i.e., jobs created if conventional unused flat roofs of the neighborhood were to be replaced by RG farms or BIPV systems. Based on existing literature (Marrana, Silvestre, De Brito, & Gomes, 2017), maintenance labor costs of conventional flat roofs over 50 years were assumed to be negligible. Therefore, *jobs creation* benefits to the community correspond to the jobs quantified in Section 2.2.2. for the operation and maintenance of the four alternative systems.

2.3.1.3. Property value. Another relevant effect is the impact of the

Table 2
a. Costs and benefits to the community: data inventory; b. Assumptions.

Scenario	Cash flow		Lifespan (Years)	Cost (€/m^2)
SC 1: GR	Savings	(*p*) (*q*)	Yearly	16.24
	Jobs creation	Jobs (agriculture)	Yearly	2.46
	GWP mitigation	Before 2030 (*t*) (*v*)	Yearly	0.13
		After 2030 (*u*) (*v*)	Yearly	0.45
SC 2: LTBIA	Savings	(*r*) (*s*)	Yearly	44.75
	Jobs creation	Jobs (agriculture)	Yearly	4.66
	GWP mitigation	Before 2030 (*t*) (*v*)	Yearly	0.07
		After 2030 (*u*) (*v*)	Yearly	0.25
SC 3: HTBIA	Savings	(*r*) (*s*)	Yearly	112.69
	Jobs creation	Jobs (agriculture)	Yearly	5.74
	GWP mitigation	Before 2030 (*t*) (*v*)	Yearly	−0.06
		After 2030 (*u*) (*v*)	Yearly	−0.20
SC 4: BIPV	Savings	//	//	//
	Jobs creation	Jobs (energy)	Yearly	0.02
	GWP mitigation	Before 2030 (*t*) (*w*)	Yearly	1.14
		After 2030 (*u*) (*w*)	Yearly	3.98

	Assumptions			Sources
(*p*)	Organic tomato, farmer to retailer	*€/kg*	1.00	(Arsenio, 2014)
(*q*)	Organic tomato, farmer to consumer	*€/kg*	3.60	Local grocery stores
(*r*)	Non-organic tomato, farmer to retailer	*€/kg*	0.80	(Silva, 2015)
(*s*)	Non-organic tomato, farmer to consumer	*€/kg*	1.99	Local retailers
(*t*)	Carbon tax, before 2030	*€/kg*	0.010	(Pereira et al., 2016)
(*u*)	Carbon tax, after 2030	*€/kg*	0.035	(Pereira et al., 2016)
(*v*)	GWP tomato supply (farm operation + transport)	*$kgCO_2eq/kg$*	1.042	(Benis et al., 2017)
(*w*)	Emission factor Portuguese electricity mix	*$kgCO_2eq/kWh$*	0.379	(IEA, 2015)

productive use of rooftops on real estate value of the surrounding properties. In other words, does the presence of either localized rooftop food or energy production systems add to the desirability of the neighborhood? To our knowledge there have been no empirical studies to date assessing the impact of BIA or onsite energy production facilities on the market value of surrounding real estate properties. Therefore, the impact on property value was not included here in quantitative terms, but only considered qualitatively.

2.3.2. Environmental impacts

2.3.2.1. Global Warming Potential (GWP). The *GWP* cash flow is a quantification of the added GHG emissions associated with each scenario as a result of the onsite production in comparison to conventional production of either produce or energy. Operation-related GWP of the alternative productive uses of rooftops (previously modeled to estimate carbon costs in Section 2.2.3.), were assessed against GWP of the existing supply chain of the tomato that is imported to Lisbon for *Scenarios 1*, *2* and *3*, and against GWP of the current Portuguese electricity mix for *Scenario 4*.

Currently, 70% of the fresh tomatoes consumed in Lisbon come from domestic production while the remaining 30% are imported, mainly from Spain (over 90%) and Northern Africa, reaching the city through road transportation (Instituto Nacional de Estatística, 2014). In these Mediterranean countries, it is mostly produced in unconditioned rural greenhouses. A GWP of 1.042 $kgCO_2eq/kg$ was estimated for the Lisbon supply chain for tomatoes (Benis et al., 2017). Considering a carbon tax of 10 €/ton until 2030, and of 35 €/ton from 2030 onwards (see Section 2.2.3.), annual benefits to the society from GWP mitigation were estimated.

2.3.2.2. Land use. In addition to GWP, other local environmental indicators such as land use should be considered, in order to measure environmental impacts of the alternative scenarios in a comprehensive way.

Land is a vital part of ecosystems. It is crucial for biodiversity and the carbon cycle, and essential to most human activities, which use it as a natural and/or economic resource. One can hypothesize that putting rooftops to use for food production and energy generation will reduce, to some degree, the demand for rural open land parcels to grow food. While urban agriculture is not likely to replace rural farming altogether, it will allow some open space areas to be used for other purposes or restored into critical ecological habitats. However, as environmental services provided by soils are not priced in the markets, effects related to land use were not quantified here, but only considered in a qualitative way.

3. Results

3.1. Economic sustainability of food production vs. energy generation

The economic sustainability of alternative productive uses of rooftops depends on yields and prices. Here, optimal yields were modeled, assuming unshaded rooftops with optimal solar radiation conditions. In reality, these yields can fluctuate due to shadings on the rooftops from surrounding buildings or structures, or variations in weather conditions. As for prices, current average market prices for tomatoes and for electricity were considered. In *Scenarios 1*, *2* and *3*, tomato crops were assumed to be sold at current producer and retailer prices; in *Scenario 4*, the electricity generation system was assumed to receive a Feed-in-Tariff, according to the latest Portuguese regulation.

Table 3 summarizes the results of the CBA to the system operator. While BIPV led to a positive NPV, results of the food production scenarios varied according to the supply chains considered. Due to the very high productivity of conditioned RG farms, *Scenario 3* led to a positive NPV both in long and short food supply chains. On the other hand, organic field farming and soilless cultivation in unconditioned RG farms only led to a positive NPV in the case of short food supply chains, where the yield is sold directly to the final consumer, providing a larger margin of profit to the producer.

The disaggregation of NPV for all the scenarios provides some

Table 3
Economic performance indicators of the four productive uses of rooftops.

		NPV (€/m^2)	IRR (%)	First payback year
SC. 1. GR	*A. Long food supply chain (LFSC)*	−96.44	0	30
	B. Short food supply chain (SFSC)	233.29	16	8
SC. 2. LTBIA	*A. LFSC*	−77.99	1	//
	B. SFSC	690.30	36	4
SC. 3. HTBIA	*A. LFSC*	360.62	23	6
	B. SFSC	2237.46	96	3
SC. 4. BIPV		163.40	11	10

insights into the relative contribution of each cash flow to the overall result (see Fig. 4). Over 50 years, while BIA structure costs represent half of BIPV structure costs, operation costs of the RG farms are much higher. This is the case because BIPV systems only require periodic cleaning and maintenance, while the farms require workers on a daily basis. However, profits generated by BIA yields largely compensate for this difference. Moreover, high operation costs of BIA are also due to the short lifespan of hydroponic cultivation equipment, which needs to be replaced every three years (see Table 1), and to the energy needs for climate control (i.e., lighting, heating and cooling) in order to achieve year-round high productivity levels in the greenhouse (Benis et al., 2017).

3.1.1. Open-air farming on intensive green roof

Scenario 1 considered organic field production. Such systems lead to lower yields, in comparison with indoor soilless cultivation systems (5 to 12 times lower for tomatoes, specifically). On the other hand, organic produce is sold at a higher market price than its non-organic counterpart. As soilless-grown crops cannot be awarded organic certification,[1] this price difference can contribute to compensating for the lower yields, turning organic cultivation more attractive to producers.

On the consumption side, researchers have identified that Portuguese consumers are increasingly dissatisfied with conventional foods (as opposed to organic), and growing more concerned about environmental and health issues associated with food. At the same time, they are showing higher levels of trust in organic processes and certification labels (Ventura-Lucas & Marreiros, 2013). Studies of Portuguese consumer behavior show that people have a positive opinion of organic food and some are willing to pay a premium for healthier food (Ventura-Lucas & Marreiros, 2013; Tranter et al., 2009).

Therefore, in the case of open-air farming on green roofs, higher prices of the locally produced organic tomato can be considered, assuming a short supply chain where the consumer buys the produce directly from the urban farmer, allowing a larger profit margin for the latter, and a positive NPV, i.e., the economic viability of such a system.

3.1.2. “Low-tech” RG farming

Scenario 2 modeled unconditioned greenhouses, considering a yearly crop period of only nine months since it is more difficult to grow tomatoes in such greenhouses through the warm summer months in Mediterranean regions (Sanye-Mengual et al., 2015). These “low-tech” RG farms are common in Mediterranean countries, where climate is mild and solar radiation conditions are favorable for greenhouse horticultural production. Since yields cannot be enhanced through controlled-environment, higher tomato prices can help increase the profit margin. Here, the economic sustainability of unconditioned rooftop farms has been shown to be achievable in SFSC.

When considering LFSC, the analysis led to a negative NPV, even when assuming an optimal yield of 28 kg/m^2/y. The non-viability of such structures is mainly due to the high initial investment costs. Urban rooftop greenhouses are exposed to greater wind forces than similar ground-based rural greenhouses. Therefore, they are required to be heavier to create a stable structure that satisfies building codes and safety requirements. The greater material input in the construction makes them more expensive to build. In addition to higher initial construction costs, the materials of the greenhouse envelope, such as the polycarbonate cover or the polyethylene climate screen, have shorter lifespans and therefore need to be replaced more frequently. This is important because the quality of the material impacts the solar radiation penetration of the facility, which directly impacts the Photosynthetically Active Radiation (PAR) that reaches the plants, ultimately affecting the crop yields.

3.1.3. “High-tech” RG farming

In Scenario 3, *the* very high productivity of conditioned greenhouses has led to a positive NPV in both LFSC and SFSC cases. This outcome has to be analyzed cautiously, as distributing such large amounts of produce might require widening the disposal area, leading to a “not-so-local” food system where food would travel longer distances, requiring conditioned storage, and eventually ending-up being more harmful to the environment than rural produce that travels to the city. To avoid this pitfall, crop diversification can be a solution. Large-scale commercial BIA farms in cities like New York and Montreal have adopted this strategy, selling food baskets – containing different types and quantities of fresh local produce – to their subscribers. Ultimately, this model has the potential to locally meet a substantial share of the demand of urban dwellers in vegetables.

3.1.4. BIPV

On south-oriented unshaded rooftops, BIPV is economically viable under Mediterranean climates (where solar radiation conditions allow for high yields), current state of technology, and market prices. However, determining whether BIPV is more profitable than BIA requires site-specific assessments.

3.2. Social impacts of food production vs. energy generation

Quantification of societal impacts can be challenging, and requires expanding the scope of analysis to be accurately accounted for all the resultant community costs and benefits. Our analysis shows that when comparing overall benefits provided by each scenario to the local community – in this case, the neighborhood – benefits provided by BIA can be substantially higher than benefits provided by BIPV (see Fig. 5).

3.2.1. Savings

The primary benefit is in the form of savings resulting from local food availability. To account for savings allowed by a short food supply chain, CSA was considered here, where subscribers pay a share of the rooftop farm costs and receive a share of the harvest in return. While determining the price of CSA shares is essential to the viability of the farm, it can be challenging task, as it depends on the willingness to pay of the shareholders.

The annual demand for fresh tomatoes in Portugal is 10.4 kg/capita (Instituto Nacional de Estatística, 2014). Considering average retail values (i.e., retail prices that consumers would pay for their produce at conventional suppliers of organic and non-organic tomatoes) annual expenditures for fresh tomatoes were calculated and the NPV over 50 years was estimated for these expenditures. If this demand was to be met through rooftop farming, for each of the farming systems – organic field cultivation (*Scenario 1*), soilless cultivation in unconditioned greenhouse (*Scenario 2*), or soilless controlled-environment agriculture (*Scenario 3*) – it would require areas of 1.89, 0.37 and 0.15 square meters, respectively. Assuming that CSA shares cover the previously

[1] European regulation 889/2008/EC defines organic cultivation as a process consisting of nourishing the plants through the soil ecosystem, and therefore does not allow soilless cultivation to receive organic certification (European Commission, 2008).

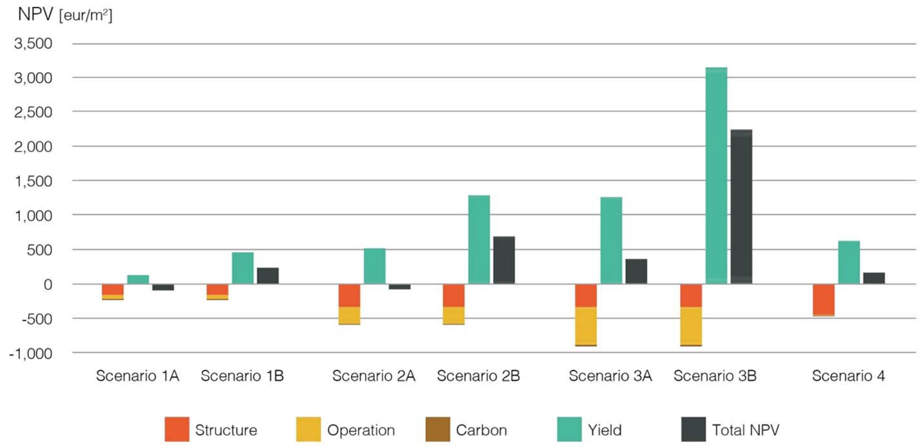

Fig. 4. NPV of the four productive uses of rooftops. For scenarios 1–3, the results are presented for both (A) long food supply chain and (B) short food supply chain.

calculated structure, operation, and carbon costs, share prices were determined for these areas. Furthermore, seasonality was taken into account in *Scenario 1*, where open-air field farming only allows for 6-month crop seasons; and in *Scenario 2*, where unconditioned greenhouses only allow tomato cultivation for 9 month per year. In these cases, CSA only meets partially the demand of shareholders, who have to purchase their produce at conventional retailers for the remaining months of the year.

It was found that CSA can lead to savings of 27 to 72% of current retail values (see Table 4). Seasonality resulting in substantially lower savings in *Scenarios 1* and *2* in comparison with *Scenario 3*, where the controlled environment allows for year-round crop cultivation.

Going further, this analysis can be extended to a larger set of crops, to assess savings provided by CSA if baskets of diversified produce were provided to the shareholders. Prices, yield productivity, and seasonality of crops will play an essential role in determining to what extent can open-air field farming or soilless cultivation in unconditioned greenhouses provide savings to the CSA members, in comparison with controlled-environment agriculture.

However, it is important to note that while small-scale urban farming has been widely recognized to provide social benefits to local communities (Proksch, 2011; Eigenbrod & Gruda, 2015), such a statement cannot be systematically extrapolated to BIA, which usually involves large-scale profit-oriented ventures, that can have difficulties finding a place in the urban space due to their novelty. For instance, a survey on social acceptance of different types of urban agriculture businesses by urban dwellers in Berlin, has led to the conclusion that residents are more likely to reject the implementation of high-tech commercial-scale BIA projects in their neighborhoods and to perceive hydroponically-grown fruits and vegetables as unnatural and unhealthy products, due to their growing environment, without soil and surrounded by urban pollution (Specht, Weith, Swoboda, & Siebert, 2016). At the same time, flourishing examples of high-tech commercial rooftop farms in major cities worldwide are leading the way towards social acceptance of large-scale BIA (Buehler & Junge, 2016).

3.2.2. Jobs creation

As for local jobs creation, BIA requires year-round full-time workers in the greenhouses, while BIPV only involves periodic interventions for the maintenance of the system. Therefore, BIA potentially leads to the creation of up to five times as many jobs as compared to BIPV.

The creation of jobs has additional community benefits that are unquantified in this CBA, but still worth considering. For example, partnerships with social service organizations can be forged to create job training programs. Similarly, the greenhouses can work with local schools, and provide opportunities for youth to get involved in the facility and learn about growing. In other words, the greenhouses can serve as an amenity in the neighborhood where residents can actively engage.

3.2.3. Property value

Studies show that sustainable design features, in addition to being environmentally beneficial, increase the property value of real estate. Buildings with sustainability certifications (such as LEED and BREEAM) or energy efficiency certifications (like EnergyStar) command a financial premium over conventional buildings in both the commercial and residential sectors (Deng & Wu, 2014). Empirical studies of certified buildings show that the sales transaction price of commercial properties increases by 5–25% (Eichholtz, Kok, & Quigley, 2010; Fuerst & Mcallister, 2011; Chegut, Eichholtz, & Kok, 2014). Similarly, in the residential sector, the sales transaction price for certified buildings are 2–17% higher than their non-certified counterparts (Deng, Li, & Quigley, 2012; Zheng, Wu, Kahn, & Deng, 2012; Kahn & Kok, 2014).

Sustainability certifications represent the culmination of many individual sustainable design features, from the energy and water saving measures to the ecological design. Therefore, one can posit that the premium associated with a sustainability certification is, in fact, attributed to the individual design features – such as BIA and BIPV – that it represents.

While we are not aware of any studies conducted on the real estate value associated with BIA, for community gardens we know this to be true. Studies investigating the relationship between urban farming and

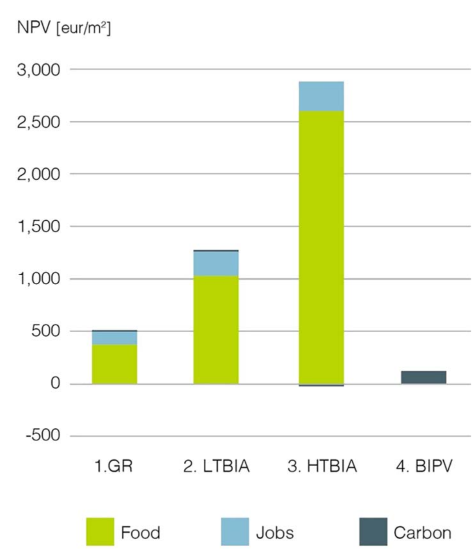

Fig. 5. Benefits to the community, allowed by the productive use of rooftops.

Table 4
Savings to the community in food expenditure, allowed by CSA.

Demand for fresh tomato	*kg/cap/y*	10.40		To meet the demand…				
		Organic	Non-organic			*SC 1*	*SC 2*	*SC 3*
Yearly expenditure	*€/cap/y*	34.77	20.70	Rooftop area needed	*m^2/cap*	1.89	0.37	0.15
NPV over 50 years	*€/cap*	−900.74	−497.91	CSA subscription share*	€	−211.08	−165.61	−137.01
				Savings	%	27	42	72

* Structure + operation + carbon costs.

real estate value have found a positive correlation between the presence of urban farming and the economic value of surrounding properties (Tranel & Handlin, 2006; Voicu & Been, 2008). According to a study on a sample of 636 community gardens in the city of New York, the establishment of a community garden increased nearby property values (those within 300 m of the garden) by up to 9.4% within five years after the opening of the garden (Voicu & Been, 2008).

To our knowledge there have been no similar empirical studies to date assessing the impact of enclosed BIA or onsite energy production facilities on the market value of surrounding real estate properties as they add to the desirability of a neighborhood. We hypothesize that a similar increase in value can be associated with BIPV given the generally positive perception that the public has of sustainable technology. However, we suspect that the agricultural system might have a greater premium compared to BIPV systems because residents of the area can participate actively in the growing activities, it may be seen as an amenity for the community.

While urban economic growth and increasing property values have a complex impact on a neighborhood, the inherent neighborhood effect of changing property value is beyond the scope of this paper. In this study, we understand increased property value to be an index of desirability. Thus, when property values go up, it indicates a general positive perception of the added amenity.

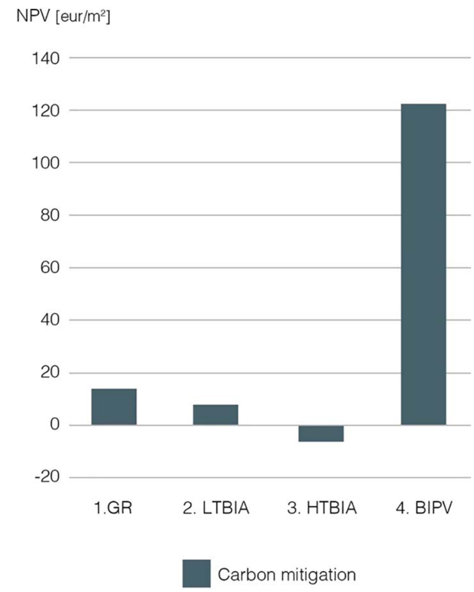

Fig. 6. GWP mitigation, allowed by the productive use of rooftops.

3.2.4. GWP

The carbon savings, representing the emissions reductions of each scenario as compared to conventional production of either produce or energy, represent the smallest share of the societal benefits.

While GWP mitigation per square meter of rooftop is positive in *Scenarios 1* and *2*, in *Scenario 3* the result is negative, meaning that "high-tech" RG farms are more harmful to the environment when compared – in terms of area – to other productive uses of rooftops. This is due to the higher energy requirements of controlled-environment cultivation. In a previous article where different forms of BIA were compared to the current conventional supply chain for tomatoes in Lisbon (Benis et al., 2017), conditioned RG farms were found to potentially cut CO_2 emissions in half. It is important to note that while we are analyzing the production by area, the referenced work considers comparing carbon intensities per kilogram of produce.

Energy generation led to over tenfold greater savings per square meter of rooftop, in comparison with food production (see Fig. 6).

3.2.5. Land use

In a recently published LCA of the Lisbon Metropolitan Area (LMA) food system, the vegetables supply chain was estimated to be accountable for a Land Use (LU) of 23.4 m^2/cap/year (Benis & Ferrao, 2016). The integration of horticultural production into urban buildings requires no additional land than the land already occupied by the buildings. Similarly, BIPV does not require any additional land than the footprint of the host buildings. One can therefore hypothesize that both BIA and BIPV may lead to environmental benefits by alleviating the demand for fertile agricultural land and reducing land impacts from fossil fuel developments, consequently restoring habitats and improving biodiversity. Modeling an economic valuation of these trade-offs is a challenging task, since the environmental services provided by soils are not priced in the markets (Marta-pedroso, Domingos, Freitas, & De Groot, 2007).

4. Discussion and final considerations

This article has presented a comparative CBA of rooftop food production against roof-integrated solar PV energy generation, setting the foundation for systematic comparison of alternative productive uses of rooftops in urban contexts to understand their individual impacts. Here, the CBA was applied to Lisbon, as an example of Mediterranean cities. However, the method used could be applied to any other urban area worldwide, as long as the inputs of the model are known.

Under the modeled conditions and given the selected items of comparison, results have shown food production to be more beneficial than energy generation for both the owner of the system and the local community in terms of financial return and local job creation. In particular, the results show that rooftop greenhouse farming (envisioned in *Scenarios 2* and *3*) can provide significant benefits when assessed from a holistic perspective that accounts for impacts on both the operator and the local community. From the operator's perspective, the cost of these systems is greater than that of green roof and rooftop solar arrays (*Scenarios 1* and *4*, *respectively*). However, the produce yield is significantly higher and leads to more profit. Aside from the economic benefits to the operator, these systems are also more beneficial to the local community, serving as an abundant source of localized produce (saving the local consumers in terms of money and carbon as compared to conventionally-sourced produce) and creating local jobs. It should be noted that for all cases considered, the outcomes of the CBA are highly site-specific, depending on yields, which vary according to local conditions such as solar radiation; and technology-specific, depending on the efficiency of the system.

Going forward, additional indicators such as land use or impacts on energy and freshwater resources should be considered in order to measure environmental impacts of each system in a more comprehensive way. At the same time, it is critical that the societal impacts (sometimes characterized as externalities or secondary impacts) are assessed alongside direct economic impacts, in order to consider the full costs and benefits of the systems being assessed.

Whereas renewable energy integration has been widely addressed in planning and policy studies, BIA is an emerging field on which very few quantitative studies have been conducted so far to inform policy-making. The following sections focus therefore on BIA, highlighting its relevance and outlining policy recommendations for its implementation on urban rooftops.

4.1. BIA as an emerging opportunity to feed our growing cities

For millennia, agricultural areas and urban settlements have evolved hand in hand as two interconnected entities, with rural farmers supplying urban markets, turning waste into manure, and sustaining urban prosperity through innovations ranging from the complex underground canal irrigation systems of the Middle East to the Aztec's artificial productive lake islands. Historically placed close to the cities in order to facilitate access to crops and animals and enable waste management, agriculture started sprouting up within cities many centuries ago, in informal or planned forms, from the sumptuous gardens that fed the monarchs of Versailles to the allotment gardens that provided food to the working classes of the 19th and 20th century industrial cities. Yet whether informal or planned, agriculture had to permanently adapt to urban sprawl, sometimes resulting in innovative cultivation practices that intensified yields, such as the transformation of swampland into productive gardens in the Marais district of Paris as early as in the 12th century (Lawson, 2016). However, in spite of innovation and crop intensification, rising urban land costs, cheap fuel and improved transport infrastructure led farmers in Paris and elsewhere to relocate in the urban outskirts. Under current urbanization pace and climate change issues, available land is expected to decrease, while the demand for fresh and healthy fruits and vegetables will increase with growing populations. To meet the demand in an environmentally and economically sustainable way, horticultural production units will have to find creative ways of adapting again to urban environments, and this time more than ever tackling the challenge of achieving high productivity in (very) limited areas.

Urban planning will have an important role to play in optimizing the resource efficiency of urban farms by integrating them early in the planning process. From Ebenezer Howard's concept of the *Garden Cities* as self-contained communities surrounded by greenbelts (Howard, 1898), to Frank Lloyd Wright's unbuilt suburban utopia *Broadacre City* in which plots of land were allocated to residents for food production (Wright, 1932), a few attempts were made to integrate agriculture into urban planning. The most recent one, the Continuous Productive Urban Landscape (CPUL), is an urban design concept that promotes the introduction of interlinked productive landscapes into urban areas as an essential component of sustainable urban infrastructure. Linking existing open space and vacant sites into a linear landscape that connects to the countryside, the concept emerged in 2004 out of design research on the role of urban agriculture within urban design, conducted by the architects André Viljoen and Katrin Bohn at a time when connecting food and urban planning was unusual (André Viljoen & Bohn, 2005, 2009). While envisioning the city as a “farm” might sound anachronistic in our modern societies, the authors have been looking beyond our era of cheap oil, towards a future where expensive transportation and a damaged environment will exacerbate the challenge of feeding our growing cities. As a unique tangible example of surviving peak oil by building food resilience, Viljoen and Bohn have documented Cuba's urban agriculture experience. Whereas the country had developed a Western intensive agriculture model, such a system became unfeasible after the economic collapse in the early 1990s, and the Cuban agro-food system had to be fully redesigned. Today, it is more than 80% organic, and urban agriculture has largely contributed to national food security, almost two-thirds of Havana's fresh vegetables being now produced within the city's community gardens, balconies and rooftops. With all these food production landscapes woven into its urban fabric, Havana constitutes an unprecedented example of a holistic approach to rethinking unutilized urban space for productive means, achieved through the combination of top-down government support and bottom-up citizen participation.

Worldwide, contemporary urban constraints such as rising pressure on land, soil and air contamination, water scarcity, and *food deserts*, are shaping a new era where urban agriculture is expected to feed an urban future while coping with climate change. Whereas current perception of urban agriculture includes both conventional low-yield open-air cultivation practices and high-yield controlled-environment building integrated systems, the latter are likely to play an increasingly fundamental role in achieving food resilience, due to their potential to satisfy a larger share of the demand. It is therefore essential to integrate them into sustainable design practices. In this context, the idea of BIA as a viable solution to feed cities is gaining momentum among some of those who believe that current sustainable farming methods will not be sufficient or the most effective method to meet the demand for food of a growing global population (Despommier, 2013). At the same time, although it is a relatively embryonic area, numerous research questions are already emerging around BIA, from uncertainties about its environmental and economic sustainability (Goldstein et al., 2016; Sanye-Mengual et al., 2015; Specht et al., 2014a; Nadal et al., 2017) to its scalability and integration into urban planning strategies (Grewal & Grewal, 2012; Orsini et al., 2014; Buehler & Junge, 2016; Specht et al., 2015).

Only very recently has BIA been promoted as a means of generating economic value from otherwise unutilized urban space, like rooftops or decommissioned industrial or commercial sites, by turning them into productive spaces that can contribute to vitalize local economies (Specht et al., 2014b; Mandel, 2013; Thomaier et al., 2014). Seizing the opportunity, pioneer BIA farms have been sprouting up over the past decade in different types of urban areas, from American Rust Belt cities where urban farming movements have been integrated into the effort for urban regeneration, to vibrant cities like New York, London or Amsterdam, which populations are not only highly aware and supportive of initiatives that promote sustainability and healthy lifestyles, but do also have more purchasing power. However, neither the replicability of these start-ups nor the economic viability of BIA have been fully demonstrated yet, and this is mentioned in the literature as a major barrier to the large-scale implementation of BIA in urban contexts (Eigenbrod & Gruda, 2015). This article sets the stage for the holistic assessment of alternative solutions, integrating environmental and socio-economic dimensions, and putting BIA into perspective by comparing it to alternative uses of urban vacant space.

4.2. Policy recommendations

Building resilient urban systems will involve the development of urban standards that consider the integration of sustainable high-yield local food production and clean energy generation into urban projects. By evaluating the systems holistically, decision makers will recognize that our building rooftops can provide measurable benefits both to the operators and the community. In this way, the rooftops – currently an underused resource – can be activated as a valuable amenity for our cities. Based on CBA assessments, policy may include the following actions.

4.2.1. Including productive rooftops into urban resilience plans

With emerging sustainability concerns, the environmental footprint of food systems, including the energy bill of cultivation, processing and transport, have been increasingly considered by the scientific community over the past decade (Benis & Ferrao, 2016). At the same time, urban settlements being major contributors to GHG emissions, municipal governments' role is fundamental in influencing the metamorphosis of today's cities, not only by translating national strategies into locally implemented policies, but also by constituting an essential vehicle for innovation in climate policy and practice. As a part of their transition to a greener economy, cities are therefore progressively looking at ways of fostering Urban and Periurban Agriculture (UPA) as a means to lessen the demand for agricultural land elsewhere and cut food miles. Concurrently, urban agriculture experts are addressing the assessment of the level of self-sufficiency of cities, arguing that for a resilient future, cities of today's globalized world should aim to be as self-sufficient as possible for basic needs such as food (Grewal & Grewal, 2012; Haberman et al., 2014). However, in today's modern cities, a complex agenda focused on commercial value has been driving urban design towards increasingly dense cityscapes, while urban agriculture is not protected as a land use within the urban context and remains vulnerable against more profitable land uses such as housing. Improving the resilience of urban food systems will therefore involve introducing municipal zoning codes where minimum levels of self-sufficiency should be targeted by neighborhoods, according to their urban morphology, i.e., to available potential farming areas, built environment structural properties, etc. This study has shown that the integration of BIA (as a strategic area) and particularly of rooftops (as a network of productive spaces) into urban resilience plans and green growth strategies can enhance its importance for sustainable urban development through job creation, increased property values, and community empowerment.

4.2.2. Towards more flexible urban codes

Zoning codes in urban areas usually impose height limitations on buildings and area limitations on the use of rooftops. Yet due to their direct exposure to sunlight, rooftops constitute a prime location for productive uses such as greenhouse cultivation. Gauging the environmental and socio-economic benefits of such productive uses of rooftops in any given context through CBA brings valuable insights that can facilitate their integration within the urban built environment. For instance, estimating the extent to which high-yield commercial-scale rooftop farming can contribute not only to food security and access to healthy food but also to local community development through job creation and economic growth may lead municipalities to grant exemptions from height and area limitations to such uses, and establish streamlined permit processes for roof-integrated food production projects. Examples are sprouting up worldwide, such as the city of Cambridge (Massachusetts), that started supporting the implementation of green roofs through a zoning ordinance that excludes roof gardens from gross floor area calculations of new projects (City of Cambridge, 2017). In Singapore, one of the most densely populated cities of the world, agricultural land is scarce and the island relies heavily on overseas imports of food. In 2009, the city launched its Landscaping for Urban Spaces and High-Rises (LUSH) program, to incentivize developers and building owners to integrate greenery. The program was enhanced recently, encouraging them to use rooftops for productive uses – mainly for farming or energy generation – in lieu of mechanical and electrical equipment. The relocated equipment space is exempted from gross floor area calculation (Urban Redevelopment Authority, 2017). Other municipalities have recently started promoting high-yield urban farms and facilitating their integration. For example, the City of Atlanta's Office of Sustainability has an *Urban Agriculture Director* since 2015, whose function is to attract commercial-scale farming projects to the city and assist them to obtain funding and permits, under the city's overarching goal of putting local healthy food within 10 min for 75% of the city's residents by 2020.

4.2.3. Financial instruments

By demonstrating the positive effects of alternative uses of rooftops on local communities, CBA approaches can substantiate the integration of local food production and/or energy generation into city-scale planning strategies. This has been happening recently for green roofs, which were introduced as compulsory urban interventions in many European and North American cities, after being widely recognized as an effective measure for UHI effect mitigation and storm water management (UNECE, 2011). This acknowledgment of the benefits of green roofs has led some cities to offer subsidies for roof reinforcements and green roof implementation. For example, in Germany, Hamburg's Green Roof Strategy provides financial incentives to those that voluntarily install a green roof before 2020. After that date, the city of Hamburg will consider green roofs to be compulsory by law. Until then, building owners can receive non-refundable subsidies to cover up to 30–60% of the installation costs (European Environment Agency, 2017).

Similarly, when leading to positive impacts in a given urban context, productive rooftops could be supported by financial instruments for their large-scale implementation. In the case of rooftop food production, besides the elevated urban rents, high-tech commercial BIA is a capital-intensive industry, as it involves the adaptation of the host building for cultivation, in accordance with local municipal regulations and building codes. This urban constraint was identified as one of the major barriers to the large-scale implementation of BIA (Cerón-palma, Sanyé-mengual, Oliver-solà, & Rieradevall, 2012). For instance, a rooftop greenhouse was shown to require a higher investment per area than its conventional rural greenhouse counterpart, as more construction materials are needed to build a heavier structure that satisfies safety requirements on top of a building located in an urban neighborhood (Sanye-Mengual et al., 2015). Such costly retrofits may be offset by municipal subsidies or loans programs.

Furthermore, supportive programs may lower the barriers for property owners to invest in productive rooftop technologies by offering incentives, such as subsidized water and energy for rooftop food production, real estate tax reductions, or low-interest loans. For instance, the Lisbon case study assessed in this manuscript has shown that the use of rooftops for food production may yield higher local value than solar PV energy generation in the Portuguese context. This outcome can guide policy-making in the sense that is seems preferable to incentivize the installation of rooftop farms within the city, while solar PV can be implemented further from the urban core, as it is easier and less environmentally harmful to move electricity over long distances than food.

4.2.4. Fostering R&D and product quality certification

Rooftop farming, and BIA in general, is still an evolving field. While there is a high risk in starting up an urban BIA farm due to high initial and operation costs, CEA in urban contexts can be extremely profitable in the long run, with low cost of distribution, increased efficiency, and economies of scale. This approach of producing food closer to where it is consumed within controlled environments has aroused an increasing interest over the last years. Pioneers of BIA have been advocating the capacity of high-density building-integrated farming to attain environmental and socio-economic benefits on a citywide scale that would be unachievable otherwise, as it can considerably decrease fossil fuel consumption, improve food security, provide jobs locally, cut transportation costs and enhance energy efficiency in buildings. With technological advances, increased maturity of CEA industry, and price-competitive produce, urban BIA could one day provide fresh and affordable food for the masses.

In the meantime, on the one hand, initial investment cost and operating cost of urban rooftop greenhouses are significantly higher when compared to their rural counterparts. Urban BIA produce has therefore to be priced higher. As a consequence, crops grown in BIA farms are usually high-value, rapid-growing, small-footprint, and quick-turnover crops, whereas slower-growing horticultural produces, as well as grains, are not as profitable in a commercial urban BIA system as in conventional production systems. On the other hand, in high-yield rooftop greenhouses, crops are grown in soilless cultivation systems such as hydroponics. As previously mentioned, such farming practices can currently not be granted organic certification, as many agricultural specialists argue that a certified organic crop involves growing in an entire soil ecosystem, rather than just the lack of pesticides. These two facts should motivate decision makers to put efforts into fostering R&D and innovation activities around high-yield BIA farming systems, and into working towards the development of new certification as a measure of quality of the products.

Acronyms

BIA	Building-Integrated Agriculture
BIPV	Building-Integrated Photovoltaics
CBA	Cost-Benefit Analysis
CEA	Controlled-Environment Agriculture
CSA	Community-Supported Agriculture
DCF	Discounted Cash Flow
EU-ETS	European Union Emissions Trading System
GHG	Greenhouse Gas
GR	Green Roof
GWP	Global Warming Potential
HTBIA	High-Tech Building-Integrated Agriculture
LTBIA	Low-Tech Building-Integrated Agriculture
IRR	Internal Rate of Return
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LFSC	Long Food Supply Chain
SFSC	Short Food Supply Chain
LMA	Lisbon Metropolitan Area
NPV	Net Present Value
PV	Photovoltaic
RG	Rooftop Greenhouse
UHI	Urban Heat Island
UPA	Urban and Periurban Agriculture

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