Transforming rooftops into productive urban spaces in the Mediterranean. An LCA comparison of agri-urban production and photovoltaic energy generation

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Abstract

A key strategy towards sustainable urban development is designing cities for increased circular metabolism. The transformation of areas underused, such as urban rooftops, into productive spaces is being increasingly implemented as a result of associated multiple benefits. Rooftop greenhouses (RTGs) are an interesting option for exploiting urban rooftops with direct exposure to sunlight, reducing food miles and creating new agricultural spaces, while building-applied solar photovoltaic (BAPV) panels provide clean energy and reduce greenhouse gas emissions. However, a proper assessment of environmental costs and benefits related to both systems is vital for a successful implementation. By means of life cycle assessment method, this paper aims to compare the environmental performance of different productive uses of rooftops under Mediterranean climatic conditions. The results showed that, in the case of RTG systems, the operation and maintenance phase (i.e.tomato production) has more impacts than the infrastructure and end-of-life phases due to the use of fertilisers (impacts ranging from 21% to 62%). Concerning BAPV systems, the manufacturing phase is dominant in almost all impact categories (impacts ranging from 52% to 93%) due to the electricity used in producing materials for solar panels. The implementation of measures for material and energy efficiency in the assessed systems resulted crucial in lowering the environmental burdens, by avoiding food imports and fossil energy supply.

The main finding of this study was that urban planning will have an important role to play in optimizing the circular patterns in highly urbanized areas by integrating these technologies early into the planning process.

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Keyword: cities, LCA, agri-urban, photovoltaic energy, rooftop, circular economy

Acronyms

BAPV Building Applied Photovoltaic	**LCIA** Life Cycle Impact Assessment
BOS Balance of System	**MD** Metal Depletion
CC Climate Change	**OD** Ozone Depletion
c-Si crystallin Silicon	**POF** Photochemical Oxidant Formation
EoL End-of-Life	**RTG** Rooftop Greenhouse
FD Fossil Depletion	**TA** Terrestrial Acidification
FE Freshwater Eutrophication	**TE** Terrestrial Ecotoxicity
FU Functional Unit	**UA** Urban Agriculture
GHG Greenhouse Gas	**UAB** Autonomous University of Barcelona
GR Green Roof	**WD** Water Depletion
LCA Life Cycle Assessment	**Wp** Peak Watt
LCI Life Cycle Inventory	**WEEE** Waste Electrical and Electronic equipment

1. Introduction

Urban areas play a significant role in addressing the 21st century's challenges of sustainably realizing climate, energy and economic objectives. Currently, urban environments have proved to be unsustainable, as they heavily rely on imported resources and their environmental footprint exceeds their natural bio-capacity (Doughty and Hammond 2004). Cities host more than 50% of the global population (United Nation, 2014), consuming 60-80% of global primary energy and generating 70% of the world's total greenhouse gas (GHG) emissions, primarily through the consumption of fossil fuels for energy supply, transportation and food production (UN-Habitat, 2016). To transform modern cities into more sustainable environments, cities need to develop a more circular metabolism where more resources are recycled, reused or produced on-site whilst cleaner forms of energy are produced and consumed (Doughty and Hammond 2004). Additionally, there is a need to optimize land use in over-populated cities where land competition becomes a problem.

In this context, sustainable solutions for food, water, energy, and transport of food or waste are needed as integrated components of a city's climate change adaptation. Sustainable urbanization practices offer many opportunities for optimizing resource use efficiency and developing mitigation measures to deal with such problems, especially through urban planning (e.g., exploitation of unused areas for local resources production, efficient waste management) and design (e.g., green construction, use of recycled materials, upgraded technologies for material/energy recovery) (UN-Habitat, 2016). Urban deployment of such strategies is often amalgamated under concepts such as the ‘eco-city’, ‘circular city’ or ‘sustainable city’, and have found wide spread local, regional, and national acceptance (Castán Broto and Bulkeley, 2013; Petit-Boix and Leipold, 2018). In this sense, converting vacant rooftops into productive spaces is a recognised strategy among researchers, city planners and developers (Carter and Keeler 2008). Rooftops have an unprecedented exploitation potential, as they cover up to 32% of cities and built-up areas (Frazer, 2005) and can improve the urban metabolism by producing resources such as energy, greening, food and water (Mahmoud et al., 2014; Specht et al., 2014; Goldstein et al., 2016, Yang and Zou, 2016; Petit-Boix et al., 2018). The transformation of these urban rooftops into productive spaces is becoming standard practice in many cities worldwide (Proksch, 2011). For instance, rooftop greenhouses (RTGs) for food production are gaining popularity in large cities such as New York, Singapore and Montreal (Ackerman et al., 2012; Deng and Quigley, 2012; Haberman et al., 2014). Similarly, as recently noted by Sanyé-Mengual et al. (2015), RTGs are finding deployment in experimental projects also in the Mediterranean context because of the favourable climate conditions. Furthermore, in order to mitigate the environmental impacts of urbanization, researchers worldwide have been recently looking at ways of turning buildings into net energy producers. Solar energy is an infinite and clean resource, and scientists have been assessing systems such as Building-Applied Photovoltaics (BAPV), which consist of generating considerable fractions of urban electricity without the need of dedicating exclusive surface areas for solar photovoltaic (PV) plant installations (Santos and Rüther, 2012). BAPV systems are typically used in retrofits, with off-the-shelf PV panels mounted on a separate metal support structure, superimposed on an existing building’s roof or façades. Among existing applications for BAPV, rooftops are considered the ideal option, since pitched roofs with a proper angle and orientation provide the highest energy harvesting (Heinstein et al., 2013). Food production and energy generation on urban rooftops are also an important source of environmental benefits. Table 1 summarizes the main environmental benefits of using BAPV and RTGs systems.

In the recent scientific literature, sustainable urban solutions addressing food supply, on the one hand, and energy supply, on the other, have been increasingly assessed. A range of studies have focused on the role played by urban agriculture (UA) in urban food self-reliance and environmental impact mitigation (Grewal and Grewal, 2012; Haberman et al., 2014; Orsini et al., 2014; Benis and Ferrão, 2016; Wielemaker et al., 2018, among others). Further studies have estimated the potential of renewable energy systems such as PV to fulfil urban energy needs (Hofierka and Kanuk, 2009; Amado and Poggi, 2014; Byrne et al., 2015) and investigated the environmental costs and benefits of this technology (Fthenakis et al., 2009; Peng et al., 2013; Corcelli et al., 2016, 2017; Eskew et al., 2018; among others). Green roofs (GR) are the main rooftop interventions considered, but comparison with food production remains unexplored. For instance, Elzeyadi et al. (2009) investigated the effectiveness of GRs and ‘cool’ roofs in mitigating the Urban Heat Island (UHI) comparing temperatures on a single building and finding that GRs are cooler in both north and south roof orientation. Nonetheless, few experimental works investigated the multi-functionality of rooftops by combining food and energy systems. Hui and Chan (2011) and Nagengast et al. (2013) found that, in places where temperature is normally higher, the benefits of an integrated PV - GR will be more visible. Perez et al. (2012) and Lamnatou and Chemisana (2014, 2015) explored the environmental performance of different roof uses (PV-GR, PV-gravel, GR, standard built-up roof). In all above-mentioned works, the results showed that the technology combining PV - GR offers multiple benefits, in particular in warmer climates and in the long term.

Moreover, a wide variety of studies have used the life cycle assessment (LCA) methodology to compare different types of rooftop uses. For example, Saiz et al. (2006) conducted a comparative LCA study between an extensive GR, a white roof and a gravel roof. A similar study was conducted by Kosareo and Ries (2007), which compared extensive and intensive GRs with a conventional roof. Carter and Keeler (2008) conducted two experimental studies in order to examine three environmental local benefits, i.e. stormwater retention, temperature mitigation and habitat creation of GRs compared to impervious surfaces. In all cases, the results verified the advantages of green roofs (e.g. for the energy savings of a building) in comparison with conventional roofs. Sanyé-Mengual et al. (2015) and Sanjuan-Delmás et al.'s (2018) studies on UA in Barcelona (Spain) compared the environmental performance of growing tomatoes in RTGs against conventional supply chains, finding that the former can have lower life-cycle GHG emissions and toxicity impacts. A recent review by Goldstein et al. (2016) found that UA is posited to have numerous advantages over conventional agriculture that will supposedly result in UA's superior environmental performance.

To date, LCA studies have yet to compare alternative uses of building rooftops for food or energy production, accounting for a variety of environmental indicators and using a systematic framework with common assumptions and boundaries for the assessment of both systems. Only Benis et al. (2018) conducted a cost-benefit analysis of the simultaneous production of food and energy in the Mediterranean context. Our study aims to fill this gap by analysing the strategic use of rooftops in urban areas in order to provide a basis to local stakeholders and policy makers for comparing the environmental advantages and disadvantages of implementing these productive uses of rooftops under Mediterranean climatic conditions, such as in the city of Barcelona (Spain). The objective was to answer the following question: "If a given surface of urban roof is available, which is the best option in terms of environmental impacts for solar energy exploitation: food or energy production?" Indeed, Barcelona is endowed with abundance of solar energy, receiving about 1,660 kWh/m^2/year of solar radiation per year (Perpiña Castillo et al., 2016). When an RTG is placed in the available surface a given amount of food is produced on-site and the conventional production is avoided. Alternatively, if a BAPV system is installed, electricity is produced, but also in this case, it is possible to account for the savings in primary energy, according to the selected electric mix. In particular, this work aims to compare the environmental performances of both pilot rooftop systems located at the Autonomous University of Barcelona Campus (Barcelona, Spain). The life cycle for each system was assessed by means of LCA, with a special focus on those steps and hotspots that present the highest environmental impacts and proposing improvement scenarios for minimizing such impacts. The novelty of this study lies in the comparison of two different rooftop systems by thoroughly assessing the environmental burdens and benefits of both production processes. Real data were used to evaluate the environmental loads of local food and energy production and to quantify the potential benefits deriving from energy and material efficiency measures in order to optimize the environmental performance of both analysed systems.

Table 1. Summary table of the main environmental benefits of using photovoltaic panels for energy generation and rooftop greenhouses for food production.

	Theme	Benefits	Sustainable Rooftop Systems	
			BAPV	RTG
Environmental Benefits	**Energy**	Produce energy[a]	✓	-
		Save direct energy consumption[a]	✓	-
		Save indirect energy consumption[b]	-	✓
		Mitigate Urban Heat Island[b]	-	●
	Food	Increase urban food security[b]	-	✓
		Reduce product losses[a,b,c]	✓	✓
	Water	Prevent aquatic pollution from urban runoff[b]	-	✓
		Mitigate storm water[b]	-	✓
		Rainwater harvesting[b]	-	✓
	Land	Prevent soil erosion[d]	-	✓
		Optimize urban space[b,c]	✓	✓
		Reduce waste through recovery[e,f]	✓	✓
	Air	Reduce GHG emissions[g]	✓	✓
		Improve air quality[g]	✓	✓
	Ecology	Enhance biodiversity[b]	-	●
	Landscape	Improve aesthetics[h,i]	●	●
	Other	Improve rooftop's performance[l]	●	✓
		Reduce noise[l]	-	✓

Legend of symbols: Yes (✓), No (-), Possibly (●)

a) Eskew et al., 2018, b) Cerón-Palma et al., 2012, c) Sanyé-Mengual et al., 2015; d) Specht et al., 2013, e) Sanyé-Mengual et al., 2013, f) Sica et al., 2018, g) Goldstein et al., 2016, Sanjuan-Delmás et al., 2018; h) Proksch, 2016, i) Prasad, 2014, l) Proksch, 2011

2. Materials and methods

LCA is the methodological framework used in this paper as defined by ISO standards (ISO 2006 a, b) and ILCD Handbook guidelines (EC 2010, 2011). LCA is one of the main techniques for quantitatively assessing environmental impacts during a product's life cycle – from raw material extraction through material processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling (from 'cradle to grave' or 'cradle to cradle', according to a very common definition of LCA). It identifies the most relevant environmental impacts and hotspots and can underpin decision-making strategies for environmental improvements from a life cycle perspective (Baumann and Tillmann, 2004). LCA consists of several interrelated steps: i) goal and scope definition; ii) inventory analysis (LCI); iii) impact assessment (LCIA) and iv) interpretation of results. The same scheme is followed in this paper.

2.1. Goal and scope definition

The goal of this work was to quantify and compare the environmental impacts related to two types of rooftop systems, namely RTG and BAPV in the Metropolitan Area of Barcelona (second largest city in Spain). It is worth clarifying that the investigated roofs are pre-existent, easily accessible and did not undergo any structural modification for implementing both systems. Furthermore, each roof was studied as a 'single' system (and not as subsystem of the building) to understand its individual impacts; thereby, the results are not presented in terms of the total building performance. In order to guide decision-making and help select the most suitable system, the functional unit was 1 m^2 of flat rooftop using either RTG or BAPV.

The system boundaries of the LCA, shown in Fig. 1, include all the life cycle phases, i.e. raw material extraction, manufacturing processes, installation, operation/maintenance and end-of-life (EoL) (dismantling, recycling and final disposal). Therefore, a ‘cradle-to-grave’ approach was adopted. Most of the past studies did not include the EoL of PV technologies, mainly because of the low number of panels that reached their end of useful life and the lack of data (Latunussa et al., 2016). Nevertheless, a comprehensive analysis should consider the contributions of each phase of the life cycle (Fthenakis et al., 2009). During the last years, the recycling processes were investigated and developed and the EoL management of PV is gaining more interest (Xu et al., 2018). Additionally, in Europe, a drive towards responsible EoL management for PV panels has taken form in the Directive on Waste Electrical and Electronic Equipment (WEEE; Directive 2012/19/UE of the European Parliament and the Council), according to which decommissioned PV panels are included as domestic and professional types of WEEE. For this reason, the EoL step of such technology was included in this study as an important step which needs to be investigated.

This study is aimed at providing decision-makers with potentially useful recommendations for local resources production planning, without however accounting for large-scale consequences on the background system (e.g., large-scale food and energy sectors, marginal changes of resource costs due to recovery, policy options etc). According to the ILCD Handbook (EC, 2010), this study is centred in the proper accounting of different environmental impacts when comparing systems, hence the attributional LCI modelling principle was chosen for this comparative LCA (so-called situation A).

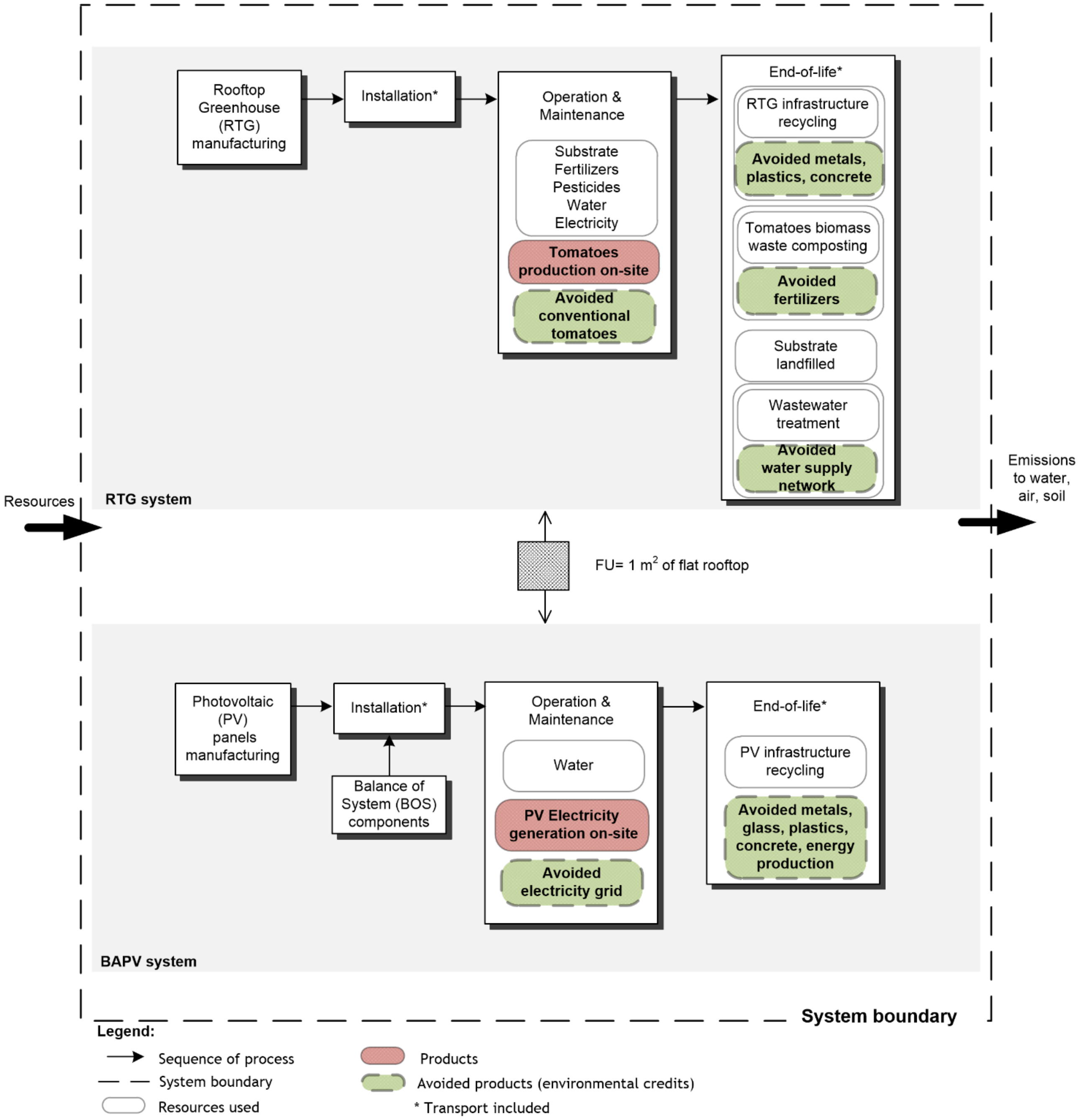

Figure 1. System boundaries and process chain under study.

2.2. System description

Main assumptions and life cycle phases accounted for in the inventory of the RTG and BAPV systems under analysis are presented below.

2.2.1. Case study: food production from rooftop greenhouse

The ICTA-ICP building houses the headquarters of the Institute of Environmental Science and Technology (ICTA) and the Catalan Institute of Paleontology (ICP). The building is situated in the Autonomous University of Barcelona (UAB) campus, 25 km away from the Barcelona city centre. It can be considered representative of office buildings in cities, because it holds four floors with offices and is similar in terms of size (7,500 m^2) and users to other standard buildings (Schloss, 1984). Additionally, its design is based on building-integrated agriculture philosophy, multifunctionality and passive systems that promote energy efficiency (Nadal et al., 2017). The pilot RTG under study, implemented by the Fertilecity project (funded by the Spanish Ministry of Economy and Competitiveness - MINECO), is placed on the building roof and utilises residual heat from the building, CO_2 concentrations in this residual air and rainwater collected from the rooftop (Sanyé-Mengual et al., 2015). More specifically, residual heat and CO_2 integration are expected to increase crop yields, whilst untreated rainwater is used in the RTG to irrigate the crops and water ornamental plants in the building, reducing the demand for potable water from the conventional distribution network. Despite the potential benefits of the RTG on the building, our study focuses on the greenhouse structure and predicts potential crop outputs but, except for the rainwater collection, does not include an assessment of flow exchanges in the building due to lack of data.

Characteristics of the crop

The RTG has a total area of 122.8 m^2 and a crop area of 84.34 m^2 (Fig. 2). The crops were beef tomato varieties (*Lycopersicon esculentum*, *Arawak* for spring crops and *Tomawak* for winter crops), grown from February 2015 to July 2016. A hydroponic system was used for irrigation to supply a nutrient solution (water plus fertilisers, also called fertigation) to plants located on an inert substrate composed of perlite bags. The system produced 30.1 kg of tomatoes per square metre over 15.5 months, providing a total of 2,540 kg of food and covering the requirements for food of nearly 60% of the building. Further technical information about the crop can be found in Sanjuan-Delmás et al. (2018).

Infrastructure & Installation. The RTG's structure mainly consists of steel, aluminium, polycarbonate covers, low-density polyethylene film curtains and concrete block anchors. In addition, the installation is equipped with backup lighting, rainwater harvesting systems, thermal screens, and climate control systems. The installation stage accounts for energy consumption requirements of the machinery used to construct the RTG. According to previous studies, a 50 years lifespan was assumed for the rainwater harvesting system (Vargas-Parra et al., 2013; Sanjuan-Delmás et al., 2015) and the greenhouse structure (Sanye-Mengual et al., 2015), and a 10 years lifespan was assumed for the auxiliary equipment (Hoffman et al., 2007). Transportation of materials from the market to the RTG was also included. The travelled distance was 35 km for fertilisers, pesticides and auxiliary equipment, 60 km for rainwater harvesting construction materials and 850 km for substrate bags imported from Almeria (South of Spain).

Operation & Maintenance. The RTG operation consisted of inputs required for hydroponic cultivation (fertilizers, pesticides, compost, etc.), water and energy needs. In particular, the assessment of fertilisers and pesticides included local emissions to air generated during their application and the treatment of leachates in a wastewater treatment plant. Furthermore, the waste biomass from the crop plants was composted in the greenhouse, thus avoiding transport and landfilling, although emissions generated during the composting process were accounted for. According to Sanjuan-Delmás et al. (2018), a lifespan of 3 and 5 years was assumed for the perlite bags and HDPE materials, respectively.

End-of-life. For the EoL assessment, the impacts of landfilled materials (substrate) were included. Infrastructure and auxiliary equipment (pumps, rainwater tanks) were assumed to be recycled. A distance of 30 km was assumed from the RTG to the landfill or the recycling facility.

Figure 2. Top view of rooftop greenhouse (on the left, source: 2017 © Google LLC) and tomatoes produced (on the right, source: Sanjuan-Delmás et al., 2018).

2.2.2. Case study: energy generation from Building-Applied Photovoltaics

Building-Applied Photovoltaics (or 'BAPV'), in Fig. 3, is a form of on-site electricity generation that can offset the emissions from more environmentally intensive sources of electricity and reduce electricity transmission losses. The BAPV examined has a total nominal power of 50.49 kWp and is placed in UAB campus, on the restaurant and library building's rooftops. The PV system was implemented within the framework of univERsol, a European project developed between 2002-2004, whose objective was the installation of PV panels in 26 universities, schools, technology centres and city councils in four European Union countries (Spain, France, England, Holland). The total roof area used is 1,600 m^2, whereas the roof area covered by PV panels is 380 m^2 (UAB's personnel. Personal communication, 2017).

Infrastructure & Installation. The BAPV installation includes 297 single crystalline silicon (c-Si) photovoltaic panels and the balance of system (BOS). Each panel has the following characteristics: 170 Wp, 72 cells, 159 x 79 cm^2 dimensions, tilt angle=35°, electrical efficiency=14%, weight=15.4 kg. In particular, the PV cells are enclosed in an aluminium frame and sealed between two plastic sheets in ethylene vinyl acetate (EVA) foil and glued between glass and polyvinyl fluoride (PVF). The system boundary of the research included upstream processes, ranging from silica extraction to the crystalline silicon bar and ingot growth, and midstream processes, which involved cell and panel fabrication as well as aluminium frame and BOS production.

Regarding the installation phase, it was modelled by considering the electricity consumption for PV infrastructure installation work. The BOS components included the mounting structure (aluminium and steel), 17 inverters (necessary for transforming the direct current to alternating current and for connecting to the normal electricity grid), copper and plastic materials for cables and contact boxes. Components excluded from the system are the surge protector, pyranometer, digital indicating controller, uninterruptible power supply device, and computer monitoring system. The life expectancy of the PV panels and metal support structures were assumed to be 30 and 60 years, respectively (Peng et al., 2013; Sherwani et al., 2010). Inverters and transformers were considered to last for 20 years, but parts must be replaced every 10 years, according to well-established data from the power industry on transformers and electronic components (Fthenakis and Kim, 2011).

The transportation distances were covered by a heavy truck. All the components, except for the PV panels, were assumed to be purchased from factories 100 km away from Barcelona, while the PV panels were purchased from Madrid (UAB's personnel, Personal communication, 2017).

Operation & Maintenance. Usually, PV systems do not show any emission to air or water during operation (Alsema and de Wild-Scholten, 2006; Raugei and Fthenakis, 2010; Tao and Yu, 2014, Eskew et al., 2018). Some panels might be washed by the user on an annual basis. In this study, the use of 20 litres of water per year and square meter for washing the panels was assumed (Frischknecht et al. 1996). Moreover, the inverters were assumed to have a 10-years lifetime, thus requiring to be replaced during the 30-years lifetime of the system. The electricity produced by the BAPV system amounts to 62.089 MWh/yr (UAB's personnel, Personal communication, 2017).

End-of-life. Most materials in PV systems are reusable, including aluminium, glass, silicon or copper (IRENA, 2016; Xu et al., 2018). Therefore, a recycling scenario of all recyclable materials was supposed for the EoL phase, assuming a distance of 590 km for the transportation of BAPV system components to the recycling facility (located near Madrid).

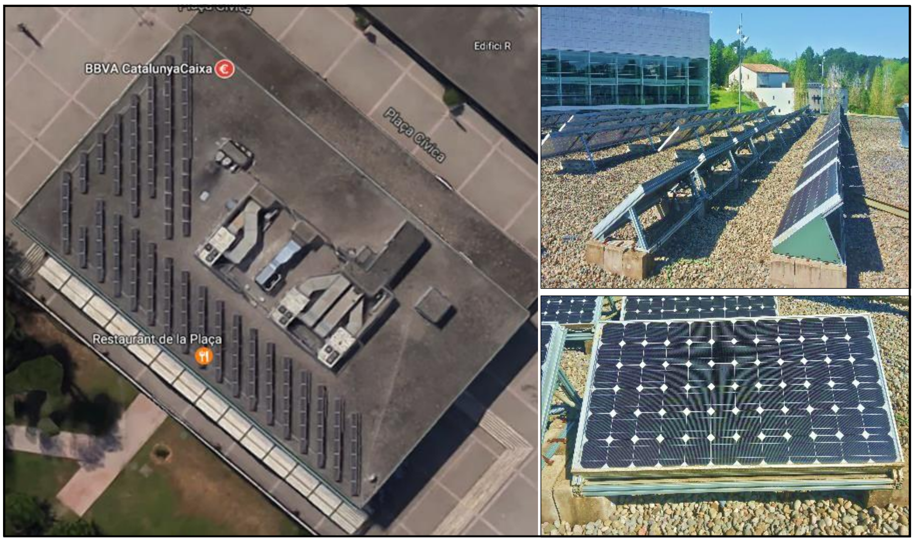

Figure 3. Top view of roof-mounted photovoltaic (on the left, source: 2017 © Google LLC) and PV panels (on the right).

2.3 Data sources and life cycle inventory

Inventory data for RTG and BAPV case studies are given in Tables 2 and 3, referred to the selected functional unit (1 m^2 of flat rooftop). In order to make possible a comparison between tomatoes production and PV energy production, inventory data for tomato production, which referred to 15.5 months, were averaged over 12 months, taking into account the variability of climate conditions along the whole year for both systems. For the inventory analysis both systems were structured in several stages in order to facilitate the study and interpretation of the results obtained. Regarding the RTG system, specific literature was used as data sources for the LCA. In particular, the inventory for the infrastructure manufacturing, installation, operation/maintenance and transport of waste to the treatment site was deduced from Sanyé-Mengual et al. (2015) and Sanjuan-Delmás et al. (2018). The inventory data about BAPV systems, including the material consumption and environmental emissions involved in the production of solar-grade silicon, wafers, cells, and panels and their EoL were mainly obtained from ecoinvent 3.1 database (Jungbluth et al., 2012) and literature (Corcelli et al., 2016). Additionally, for the installation and operation/maintenance phases foreground data were provided by expert personnel in UAB. Other background data, related to energy use, auxiliary materials and impacts of the waste management (e.g. wastewater treatment, composting, EoL treatments of infrastructure materials) have been derived from the ecoinvent 3.1 database (Wernet et al., 2016). It should be pinpointed that the present study is representative of technologies installed in the Spanish territory. As a consequence, this analysis assumes that all the production, installation, operation processes and also the recycling treatments for both roofing systems are developed in Spain, thus the Spanish power mix (2015) was used as a reference. The energy outputs from the BAPV system were considered to be used as alternative to energy produced by means of traditional fossil fuels combustion, in particular, to the electricity from the Spanish grid, where over 60% of electricity come from nuclear and fossil fuels (coal) (Red eléctrica de España, 2015), thus drawing a potential evaluation of environmental benefits. Additionally, the tomatoes production from the RTG system was considered as substitute for tomatoes produced by means of conventional farming in a standard multi-tunnel greenhouse. The avoided cost deriving from the production of tap water for crop irrigation was also considered. Moreover, in both case studies, for crediting recycled materials (metals, glass, plastics, concrete) and tomato biomass composting, the avoided production of primary materials and inorganic fertilizers, respectively, was included.

Table 2. Life cycle inventory data for tomatoes production in RTG, referred to 1 m^2 of flat rooftop (FU) (timeframe 1 year).

Materials/Energy	Unit/ FU	Amount	Data Sources
Infrastructure manufacturing			
RTG structure:			
Steel	kg	8.36E-01	Sanyé-Mengual et al. (2015)
Concrete	kg	2.12E-01	//
Low Density Polyethylene (LDPE)	kg	7.80E-02	//
Polycarbonate	kg	1.60E-01	//
Polyester	kg	7.80E-03	//
Aluminium	kg	7.80E-03	//
Auxiliary equipment:			
Low Density Polyethylene (LDPE)	kg	2.30E-02	//
Polystyrene	kg	2.60E-02	//
High Density Polyethylene (HDPE)	kg	9.40E-03	//
Polyvinylchloride (PVC)	kg	4.40E-03	//
Steel	kg	5.00E-04	//
Installation*			
Electricity	kWh	4.00E-04	Sanyé-Mengual et al. (2015)
Transport, lorry	tkm	3.24E-01	//
Transport, transoceanic freight ship	tkm	1.61E-01	//
Transport, van	tkm	2.00E-04	//
Operation and Maintenance			
Substrate:			
Expanded perlite	kg	1.87E+00	Modified from Sanjuan-Delmás et al. (2018)
High Density Polyethylene (HDPE)	kg	4.88E-02	//
Fertilizers:			
KNO_3	kg	3.95E-01	//
KPO_4H_2	kg	2.00E-01	//
K_2SO_4	kg	4.41E-01	//
$Ca(NO_3)_2$	kg	5.57E-01	//
$CaCl_2$	kg	1.82E-01	//
$Mg(NO_3)_2$	kg	3.72E-01	//
Hortrilon/Tradecorp	kg	1.49E-02	//
Sequestrene	kg	1.49E-02	//
Pesticides	kg	6.89E-02	//

Water (rainwater)	m^3	1.30E+00	//
Tap water	m^3	2.26E-01	//
Electricity	kWh	4.73E-01	//
Local emissions to water:			
Cl^-	kg	8.11E-02	//
NO_3^-	kg	3.29E-01	//
PO_4^{3-}	kg	3.64E-02	//
SO_4^{2-}	kg	1.70E-01	//
K^+	kg	2.06E-01	//
Mg^{2+}	kg	2.32E-02	//
Ca^{2+}	kg	1.05E-01	//
Local emissions to air:			
NH_3	kg	6.40E-03	Estimated from Montero et al. (2009)
N_20	kg	2.67E-03	//
NO_x	kg	2.13E-02	//
Produced tomatoes on-site[#]	kg	2.33E+01	Modified from Sanjuan-Delmás et al. (2018)
End-of-life			
Steel scraps (to recycling)[a]	kg	8.37E-01	Ecoinvent 3.1 database (Wernet al., 2016)
Plastics scraps (to recycling)[b]	kg	3.57E-01	//
Aluminium scraps (to recycling)[a]	kg	7.80E-03	//
Concrete scraps (to recycling)[a]	kg	2.12E-01	//
Perlite substrate waste (to landfill)	kg	1.87E+00	//
Tomatoes biomass waste (to composting)[c]	kg	9.45E+00	//
Wastewater treatment	m^3	1.53E+00	//
Transport* to landfill, lorry (perlite substrate)	tkm	5.62E-02	Modified from Sanjuan-Delmás et al. (2018)
Transport* to recycling facility, lorry (aluminium, steel, plastics, concrete scraps)	tkm	4.24E-02	Sanyé-Mengual et al. (2015)

[*] Process of transport included vehicle, road manufacture and maintenance, as well as diesel consumption and relative emissions.

[#] For crediting tomatoes production on-site, the avoided environmental burden from conventional production in a standard multi-tunnel greenhouse was assumed.

[a] A substitution ratio of 0.9:1 was assumed for steel, aluminium and concrete scraps, meaning that 1 unit of secondary material replaces 0.9 unit of the corresponding primary material.

[b] A substitution ratio of 1:1 was assumed for plastics scraps, meaning that 1 unit of secondary material replaces 1 unit of the corresponding primary material.

[c] The substitution ratio takes into account the quality of the products from waste in comparison with that of the corresponding avoided product. 0.4:1 means that 1 ton of biomass waste corresponds to 0.4 ton of compost/dry waste (as average value). In the case of composting, 1 ton of compost was assumed to substitute:23 kg of N-fertilizer, 9.5 kg of P fertilizer and 9 kg of K-fertilizer (Blengini et al., 2008).

Table 3. Life cycle inventory data for energy generation from BAPV, referred to 1 m^2 of flat rooftop (FU) (timeframe 1 year).

Materials/Energy	Unit/ FU	Amount	Data Sources
Infrastructure manufacturing			
PV panel components:	m^2	2.30E-01	Ecoinvent 3.1 database (Jungbluth et al., 2012)
Solar cell (c-Si)	m^2	2.14E-01	//
Aluminium alloy	kg	6.05E-01	//
Polyvinyl fluoride	kg	2.54E-02	//
Polyethylene terephthalate	kg	8.58E-02	//
Glass sheet, tempered	kg	2.32E+00	//
Ethylene vinyl acetate	kg	2.30E-01	//
Copper	kg	2.59E-02	//
Nickel	kg	3.74E-05	//
Soldering flux	kg	2.02E-03	//
Methanol	kg	4.96E-04	//
Silicone	kg	2.80E-02	//
Corrugated board box	kg	2.52E-01	//
Tap water	kg	4.90E+00	//
Electricity	kWh	1.39E+00	//
Installation			
Balance of System:			
Steel	kg	1.21E+00	Field data supplied by UAB's engineers
Aluminium	kg	8.76E-01	//
Concrete	kg	1.23E+01	//
Copper	kg	1.14E-01	//
Polyvinylchloride (PVC)	kg	6.50E-02	//

Inverters	p	1.06E-02	//
Electricity	kWh	4.76E-02	//
Transport*, van	tkm	1.41E+00	//
Transport*, lorry	tkm	3.37E+00	//
Operation and Maintenance[a]			
Tap water	kg	1.00E+00	Field data supplied by UAB's engineers
Produced electricity on-site from PV[#]	kWh	3.54E+01	//
End-of-life			
Aluminium scraps[b] (to recycling)	kg	1.74E+00	Modified from Corcelli et al. (2016); Ecoinvent 3.1 database (Wernet al., 2016)
Glass scraps[b] (to recycling)	kg	1.87E+00	//
Silicon scraps[c] (to recycling)	kg	2.25E-01	//
Copper scraps[b] (to recycling)	kg	9.96E-02	//
Iron scraps[b] (to recycling)	kg	5.22E-06	//
Steel scraps[b] (to recycling)	kg	1.21E+00	//
Concrete scraps[b] (to recycling)	kg	1.23E+01	//
Plastics scraps[d] (to recycling)	kg	6.53E-02	//
Wastewater treatment	kg	1.00E+00	//
Transport*, lorry	tkm	1.01E+01	Field data supplied by UAB's engineers

[*] Process of transport included vehicle, road manufacture and maintenance, as well as diesel consumption and relative emissions.

[#] For crediting electricity production on-site, the avoided environmental burden from the conventional production of Spanish electricity mix was assumed.

[a] The emissions during the operation phase were considered negligible according to Alsema and de Wild-Scholten (2006) and Peng et al. (2013).

[b] A substitution ratio of 0.9:1 was assumed for aluminium, glass, steel, iron, copper and concrete scraps, meaning that 1 unit of secondary material replaces 0.9 unit of the corresponding primary material.

[c] A substitution ratio of 0.95:1 was assumed for silicon scraps, meaning that 1 unit of secondary material replaces 0.95 unit of the corresponding primary material.

[d] A substitution ratio of 1:1 was assumed for plastics scraps, meaning that 1 unit of secondary material replaces 1 unit of the corresponding primary material.

2.4. Life Cycle Impact Assessment (LCIA)

The environmental assessment of the process was modelled by means of LCA software SimaPro v.8.0.5 (Pre-Consultants, 2014), integrated with ecoinvent v3.1 database (Wernet et al., 2016). The impact assessment was performed by means of one of the most recent and up-to-date LCA methods, the ReCiPe method (Goedkoop et al., 2009; Vezzoli, 2018). The ReCiPe Midpoint (H) v.1.10 (http://www.lcia-recipe.net/) was chosen, considering that it includes both upstream categories (i.e. referred to depletion of natural resources, such as fossil, metal and water depletion categories) and downstream categories (i.e. referred to impacts generated on natural matrices, such as terrestrial, marine or freshwater acidification) (Frischknecht et al., 2007). In this study, in order to support decision makers by means of a simplified overall assessment across areas of environmental concern, the following impact categories were analyzed: Climate Change (CC, in kg CO_2 eq), Ozone Depletion (OD, in kg CFC-11 eq), Terrestrial Acidification (TA, in kg 1,4-DB eq), Freshwater Eutrophication (FE, in kg P eq), Photochemical Oxidation Formation (POF, in kg NMVOC), Terrestrial Ecotoxicity (TE, in kg 1,4-DB eq), Water Depletion (WD, in m^3), Metal Depletion (MD, in kg Fe eq) and Fossil Depletion (FD, in kg oil eq).

Furthermore, a sensitivity analysis was performed to test the robustness of the results. To this end, alternative scenarios were proposed, based on progressive reductions or substitution of the most sensitive input flows (both energy and material flows) and the effects of these changes on final results were examined.

3. Results and Discussion

As a preliminary approach to the evaluation of the systems performance, the "avoided burdens", i.e. the credits or benefits resulting from the production of secondary raw materials (recycling), energy, water and biomass recovery, were not included in the assessment, so as not to hide crucial steps still needing improvement (Section 3.1). However, policy makers may also need additional information about potential benefits linked to avoided burdens. As a consequence, a second assessment was performed including a system expansion based on average data (i.e. market mix) for crediting energy and material recovery (Section 3.2). Concerning the avoided costs (observed as the negative values), environmental savings of goods and energy (i.e. metals, glass, biomass, etc) were subtracted from the accounting of the system's impacts, considering that their production by means of conventional routes for later use in other processes is avoided. Finally, a comparison between RTG and BAPV systems is performed in order to see which system shows the best environmental performance (Section 3.3).

3.1. Environmental costs

3.1.1. RTG system

Table 4 shows the characterized impacts of the RTG system, with reference to the functional unit of 1 m^2 of flat rooftop, broken down into the different life cycle steps with the percentage contribution to the total environmental impacts. The results show that most of the environmental impacts are generated during the Operation & Maintenance phase in almost all analysed impact categories, especially in ozone depletion (OD), freshwater and terrestrial eutrophication (FE, TE), where the contribution from Operation & Maintenance phase ranges from 73% to 80%. In the remaining impact categories, the impacts linked to Operation & Maintenance overcome 58%, except for water depletion (WD) and metal depletion (MD) where the main impacts are generated by EoL (91%) and infrastructure (63%), respectively.

Within the Operation & Maintenance of the RTG, the use of fertilizers generates the highest impacts in five out of nine impact categories (from 21% in POF to 62% in TE), whereas the use of pesticides contributes to 47% of the impacts to ozone depletion (OD). Among fertilizers, calcium nitrate resulted the most impactful (data not shown) due to the large amounts of chemicals (such as nitric acid) and energy (heat and electricity) required for its production. Local emissions (namely, emissions from the foreground system) affect only terrestrial acidification (23%), freshwater eutrophication (65%) and photochemical oxidant formation (31%) categories. To a lesser extent, the substrate bags also generate substantial impacts, accounting for 12-19% of climate change (CC), ozone depletion (OD), terrestrial acidification (TA), photochemical oxidant formation (POF) and fossil depletion (FD) and <3% of the other four remaining impact categories. Most of these environmental impacts are generated during the production of the substrate.

Infrastructure manufacturing is another environmental hotspot of RTG. The RTG structure generates between 16-63% of the impacts on photochemical oxidant formation (POF), ozone depletion (OD), climate change (CC), fossil depletion (FD) and metal depletion (MD) and 2-10% of the impacts on the remaining categories. In particular, steel is the material that generates the largest environmental load (from 48% in CC to 100% in MD), followed by polycarbonate (2-39%) especially in those categories where thermoplastics tend to have the most significant impact (OD, FD). Concrete only marginally affects the different indicators (<2 %).

Concerning the EoL phase, wastewater treatment entails the highest contribution to water depletion (corresponding to 90%), while the transport, metals recycling, composting and substrate landfilling steps display minor impacts (always less < 11%) in all analyzed impact categories.

Table 4. Characterized impacts calculated for RTG system, broken down into different process steps, referred to a functional unit of 1 m^2 of flat rooftop.

	CC kg CO_2 eq	**OD** kg CFC 11 eq	**TA** kg SO_2 eq	**FE** kg P eq	**POF** kg NMVOC	**TE** kg 1,4 -DB eq	**WD** m^3	**MD** kg Fe eq	**FD** kg oil eq
Infrastructure manufacturing									
RTG structure	3.2E+00	5.1E-07	1.3E-02	1.3E-03	1.1E-02	2.9E-04	3.2E-02	2.5E+00	8.6E-01
[%]	19.5	18.4	10.5	7.2	15.9	6.3	2.1	63.0	25.4
Auxiliary equipment	1.7E-01	2.6E-09	5.4E-04	5.9E-06	6.9E-04	4.1E-06	3.3E-03	2.1E-03	1.1E-01
[%]	1.0	0.1	0.4	0.03	1.0	0.1	0.2	0.1	3.2
Installation									
Transport	2.9E-02	5.6E-09	1.3E-04	2.2E-06	1.5E-04	1.5E-05	1.0E-04	1.1E-03	1.1E-02
[%]	0.2	0.2	0.1	0.01	0.2	0.3	0.01	0.03	0.3
Electricity	1.6E-04	1.9E-11	9.9E-07	4.1E-08	5.3E-07	5.1E-09	5.5E-07	4.3E-06	3.9E-05
[%]	<<1	<<1	<<1	<<1	<<1	<<1	<<1	<<1	<<1
Operation & Maintenance (tomatoes production on-site)									
Substrate	2.5E+00	3.6E-07	1.5E-02	5.9E-04	8.5E-03	1.4E-04	1.5E-02	5.2E-02	6.5E-01
[%]	14.9	12.8	12.5	3.2	11.8	3.0	1.0	1.3	19.4
Water	9.2E-05	1.0E-11	4.1E-07	5.2E-08	2.8E-07	1.0E-08	2.3E-04	1.4E-05	2.4E-05
[%]	<<1	<<1	<<1	<<1	<<1	<<1	0.02	<<1	<<1
Fertilizer	5.6E+00	3.6E-07	3.1E-02	1.6E-03	1.5E-02	2.8E-03	7.5E-02	6.2E-01	9.8E-01
[%]	34.0	13.1	25.6	8.5	21.2	61.7	4.9	15.9	29.1
Pesticides	7.6E-01	1.3E-06	6.9E-03	3.7E-04	3.1E-03	4.8E-04	5.7E-03	8.1E-02	2.8E-01
[%]	4.6	46.7	5.6	2.0	4.4	10.6	0.4	2.1	8.2
Electricity	1.8E-01	2.3E-08	1.2E-03	4.9E-05	6.3E-04	6.0E-06	6.5E-04	5.1E-03	4.7E-02
[%]	1.1	0.8	1.0	0.3	0.9	0.1	0.04	0.1	1.4
Local emissions	8.1E-01	<< 1	2.8E-02	1.2E-02	2.2E-02	<< 1	<< 1	<< 1	<< 1
[%]	4.9	<< 1	23.1	65.5	30.6	<< 1	<< 1	<< 1	<< 1
End-of-life									
Transport	3.7E-02	6.4E-09	1.2E-04	3.3E-06	1.4E-04	1.3E-05	1.1E-04	1.9E-03	1.3E-02
[%]	0.2	0.2	0.1	0.02	0.2	0.3	0.01	0.05	0.4
Recycling metals	6.1E-01	1.0E-07	4.1E-03	7.1E-04	2.4E-03	3.7E-04	1.9E-02	3.3E-01	1.9E-01
[%]	3.7	3.7	3.3	3.9	3.3	8.2	1.3	8.6	5.7
Recycling plastic	1.47E-01	1.98E-08	8.36E-04	5.06E-05	5.08E-04	1.56E-05	1.13E-03	2.24E-03	4.56E-02
[%]	0.9	0.7	0.6	0.3	0.7	0.3	0.1	0.1	0.4
Recycling concrete	1.2E-03	2.2E-10	9.7E-06	4.7E-08	1.7E-05	4.3E-08	2.7E-06	4.5E-05	4.2E-04
[%]	0.01	0.01	0.01	<<1	0.02	<<1	<<1	<<1	0.01
Tomatoes biomass waste composting	1.6E+00	2.1E-10	1.4E-02	4.5E-06	2.9E-03	6.7E-07	3.8E-03	5.7E-04	3.2E-04
[%]	9.8	0.01	11.1	0.02	4.0	0.01	0.3	0.01	0.01
Perlite substrate to landfill	2.0E-02	5.2E-09	1.4E-04	5.7E-06	1.9E-04	1.9E-06	5.2E-04	1.5E-03	1.1E-02
[%]	0.1	0.2	0.1	0.03	0.3	0.04	0.03	0.04	0.3
Wastewater treatment	8.3E-01	8.4E-08	7.1E-03	1.7E-03	4.1E-03	4.1E-04	1.4E+00	3.4E-01	1.8E-01
[%]	5.0	3.0	5.8	9.0	5.7	9.0	89.7	8.7	5.3
TOTAL	1.7E+01	2.8E-06	1.2E-01	1.8E-02	7.2E-02	4.6E-03	1.5E+00	3.9E+00	3.4E+00
[%]	100	100	100	100	100	100	100	100	100

3.1.2. BAPV system

Table 5 shows the characterized impacts of the BAPV system, with reference to the functional unit of 1 m^2 of flat rooftop, split over the different life cycle phases with the percentage contribution to the total environmental impacts. The results display that the Manufacturing phase is dominant in almost all impact categories. The portion of total potential environmental impact associated with the Manufacturing phase ranges from 52% in freshwater eutrophication (FE) to 93% in terrestrial ecotoxicity (TE), except for a share of 30% in metal depletion (MD). The cell production process especially impacts on ozone depletion (OD) and terrestrial eutrophication (TE) categories, with loads corresponding to 41% and 89%, respectively, whilst processes of wafer and panel production contribute to a minor extent (<18%).

In contrast, the Installation phase only displays a significant impact on metal depletion (MD), with a share of 56%. In deeper detail, each element of the balance of system (BOS) contributes differently to the Installation stage. Aluminium is the material that shows the largest environmental impacts (33–57%, data not shown) in almost all investigated categories, whilst freshwater eutrophication (FE) and metal depletion (MD) are mostly affected by the inverter (since it contains silver, gold, and zinc). To a lesser extent, the Operation & Maintenance and EoL phases generate impacts lower than 11%.

Table 5. Characterized impacts calculated for BAPV system, broken down into different process steps, referred to a functional unit of 1 m^2 of flat rooftop.

	CC kg CO_2 eq	**OD** kg CFC 11 eq	**TA** kg SO_2 eq	**FE** kg P eq	**POF** kg NMVOC	**TE** kg 1,4 -DB eq	**WD** m^3	**MD** kg Fe eq	**FD** kg oil eq
Infrastructure manufacturing									
Solar grade silicon	2.7E+01	2.9E-06	1.5E-01	9.1E-03	7.9E-02	1.6E-03	1.9E+00	5.5E-01	6.9E+00
[%]	35.6	17.2	32.3	21.4	24.3	1.4	71.2	2.0	33.5
Single-Si wafer	7.9E+00	6.5E-07	4.1E-02	2.9E-03	2.4E-02	6.9E-04	1.1E-01	1.3E+00	2.4E+00
[%]	10.6	3.9	9.1	6.7	7.5	0.6	4.1	4.9	11.7
Single-Si PV cell	5.3E+00	6.8E-06	3.1E-02	4.5E-03	6.1E-02	1.1E-01	2.1E-01	3.1E+00	1.1E+00
[%]	7.2	40.6	6.9	10.6	18.8	89.2	7.4	11.3	5.4
Single-Si PV panel	1.1E+01	1.8E-06	8.2E-02	5.6E-03	5.2E-02	1.7E-03	1.3E-01	3.1E+00	3.5E+00
[%]	14.5	10.8	18.2	13.3	15.9	1.4	4.5	11.5	16.7
Installation									
Steel	2.6E+00	1.5E-07	1.2E-02	1.9E-03	1.1E-02	3.5E-04	4.1E-02	3.6E+00	5.7E-01
[%]	3.5	0.9	2.6	4.4	3.4	0.3	1.5	13.2	2.7
Aluminium	5.7E+00	1.6E-06	3.9E-02	3.2E-03	3.1E-02	1.2E-03	6.5E-02	1.8E+00	1.9E+00
[%]	7.7	9.5	8.8	7.4	9.6	1.0	2.4	6.5	9.1
Concrete	2.2E+00	1.2E-07	6.5E-03	3.0E-04	6.5E-03	1.6E-04	2.1E-02	1.8E-01	3.1E-01
[%]	3.0	0.7	1.5	0.7	2.0	0.1	0.8	0.6	1.5
Copper	2.2E-01	2.6E-08	6.6E-03	2.7E-03	2.8E-03	2.3E-04	1.1E-02	5.0E+00	6.2E-02
[%]	0.3	0.2	1.5	6.3	0.9	0.2	0.4	18.3	0.3
PVC	1.3E-01	9.8E-10	3.6E-04	4.5E-06	6.7E-04	5.9E-06	1.2E-02	4.9E-04	7.1E-02
[%]	0.2	0.01	0.1	0.01	0.2	0.01	0.4	<<1	0.3
Transport	2.4E+00	4.2E-07	9.1E-03	1.9E-04	1.2E-02	5.5E-04	7.1E-03	1.2E-01	8.3E-01
[%]	3.2	2.5	2.0	0.5	3.6	0.5	0.3	0.4	4.0
Electricity	1.9E-01	2.3E-09	1.2E-04	4.9E-06	6.4E-05	6.1E-07	6.6E-05	5.1E-04	4.7E-03
[%]	0.3	0.01	0.03	0.01	0.02	<<1	<<1	<<1	0.23

Inverter	2.2E+00	4.5E-07	2.9E-02	7.5E-03	1.4E-02	1.2E-03	3.6E-02	4.7E+00	5.9E-01
[%]	3.0	2.7	6.6	17.6	4.1	1.0	1.3	17.2	2.8
Operation & Maintenance (electricity generation on-site)									
Tap water	2.4E+00	4.5E-07	1.7E-02	1.8E-03	1.0E-02	3.7E-03	8.6E-02	8.6E-01	6.5E-01
[%]	3.2	2.7	3.7	4.3	3.0	3.1	3.1	3.1	3.0
End-of-life									
Transport	2.2E+00	3.9E-07	7.1E-03	1.7E-04	8.5E-03	4.7E-04	6.5E-03	9.9E-02	7.8E-01
[%]	3.0	2.4	1.6	0.4	2.6	0.4	0.2	0.4	3.7
Recycling metals	3.01E+00	8.63E-07	1.77E-02	2.60E-03	1.02E-02	9.28E-04	6.71E-02	2.91E+00	8.19E-01
[%]	4.0	5.2	4.0	6.1	3.1	0.8	2.4	10.6	3.9
Recycling glass	6.4E-01	1.1E-07	4.0E-03	7.8E-05	1.8E-03	5.8E-05	1.5E-03	9.9E-03	2.2E-01
[%]	0.9	0.7	0.9	0.2	0.6	0.1	0.2	0.04	1.0
Recycling concrete	7.1E-02	1.3E-08	5.6E-04	2.7E-06	9.6E-04	2.5E-06	1.6E-04	2.6E-03	2.4E-02
[%]	0.1	0.1	0.1	0.01	0.3	<<1	<<1	0.01	0.1
Recycling plastics	4.7E-02	6.3E-09	2.7E-04	1.6E-05	1.6E-04	4.9E-06	3.6E-04	7.2E-04	1.5E-02
[%]	0.1	0.04	0.7	0.04	0.1	<<1	0.01	<<1	0.1
Energy recovery	3.4E-02	4.9E-09	2.1E-04	9.4E-06	1.2E-04	1.2E-06	1.4E-04	1.0E-03	8.6E-03
[%]	0.1	0.03	0.1	0.02	0.04	<<1	<<1	<<1	0.04
TOTAL	7.4E+01	1.7E-05	4.5E-01	4.2E-02	3.3E-01	1.2E-01	2.8E+00	2.7E+01	2.1E+01
[%]	100	100	100	100	100	100	100	100	100

3.2. Environmental benefits of circular use of resources

From a circular economy standpoint, the implementation of measures for energy and material efficiency in the assessed systems leads to environmental benefits that can be quantified by accounting for the avoided impacts of conventional production of electricity, tomatoes, tap water, fertilizers and virgin metals. The characterized results of the assessment for the RTG and BAPV systems, referred to the selected functional unit (1 m^2 of flat rooftop in a timeframe of 1 year), are shown in Table 6 and 7, respectively.

In the case of RTG systems (Table 6), the environmental benefits – i.e. negative values (in bold)– deriving from material efficiency are much higher than the environmental loads attributable to the structure, local emissions during operation and wastewater treatment in six out of nine impact categories. In particular, the most relevant benefits are achieved thanks to the tomato production on-site (e.g., 25 kg CO_2 eq/m^2 are saved in climate change category), whilst a smaller benefit is provided by the avoided production of fertilizers (N, P, K) thanks to biomass waste composting. The use of rainwater to supply water requirements of the crop provides constrained benefits apart from the water depletion (WD) category, amounting to –1.59 m^3 of water/m^2 of rooftop. Metal recycling (aluminium and steel) shows a valuable contribution only in the metal depletion (MD) category, with a saving of 0.89 kg Fe eq/m^2 of rooftop.

The percentage contribution to the total environmental impacts of each step in the RTG is shown in Fig. 4.

Table 6. Characterized impacts calculated for the RTG system (broken down into different process steps), referred to a functional unit of 1 m^2 of flat rooftop. Negative values (in bold) correspond to avoided impacts thanks to energy and material recovery.

	CC kg CO_2 eq	**OD** kg CFC 11 eq	**TA** kg SO_2 eq	**FE** kg P eq	**POF** kg NMVOC	**TE** kg 1,4 - DB eq	**WD** m^3	**MD** kg Fe eq	**FD** kg oil eq
Infrastructure manufacturing	3.4E+00	5.2E-07	1.3E-02	1.3E-03	1.2E-02	2.9E-04	3.5E-02	2.5E+00	9.6E-01
Installation	2.9E-02	5.6E-09	1.3E-04	2.2E-06	1.5E-04	1.5E-05	1.0E-04	1.1E-03	1.1E-02
Operation & Maintenance	**-2.5E+01**	6.4E-07	**-8.5E-02**	3.2E-03	**-1.2E-01**	**-8.4E-03**	1.1E-02	1.9E-01	**-5.6E+00**
End-of-life									
Transport	3.7E-02	6.4E-09	1.2E-04	3.3E-06	1.4E-04	1.3E-05	1.1E-04	1.9E-03	1.3E-02
Recycling metals	**-1.2E+00**	**-2.7E-08**	**-3.8E-03**	**-3.4E-04**	**-4.9E-03**	2.5E-04	**-5.4E-03**	**-8.9E-01**	**-1.6E-01**
Recycling plastic	1.5E-01	1.9E-08	8.4E-04	5.1E-05	5.1E-04	1.6E-05	1.1E-03	2.2E-03	4.6E-02
Recycling concrete	1.2E-03	2.2E-10	9.7E-06	4.7E-08	1.7E-05	4.3E-08	2.7E-06	4.5E-05	4.2E-04
Tomatoes biomass waste composting	5.3E-01	**-6.7E-08**	8.1E-03	**-2.1E-04**	2.3E-04	**-3.7E-04**	**-1.8E-02**	**-8.4E-02**	**-1.7E-01**
Perlite substrate to landfill	2.0E-02	5.2E-09	1.4E-04	5.7E-06	1.9E-04	1.9E-06	5.2E-04	1.5E-03	1.1E-02
Wastewater treatment	7.3E-01	7.4E-08	6.7E-03	1.6E-03	3.8E-03	4.0E-04	**-1.6E+00**	3.3E-01	1.5E-01

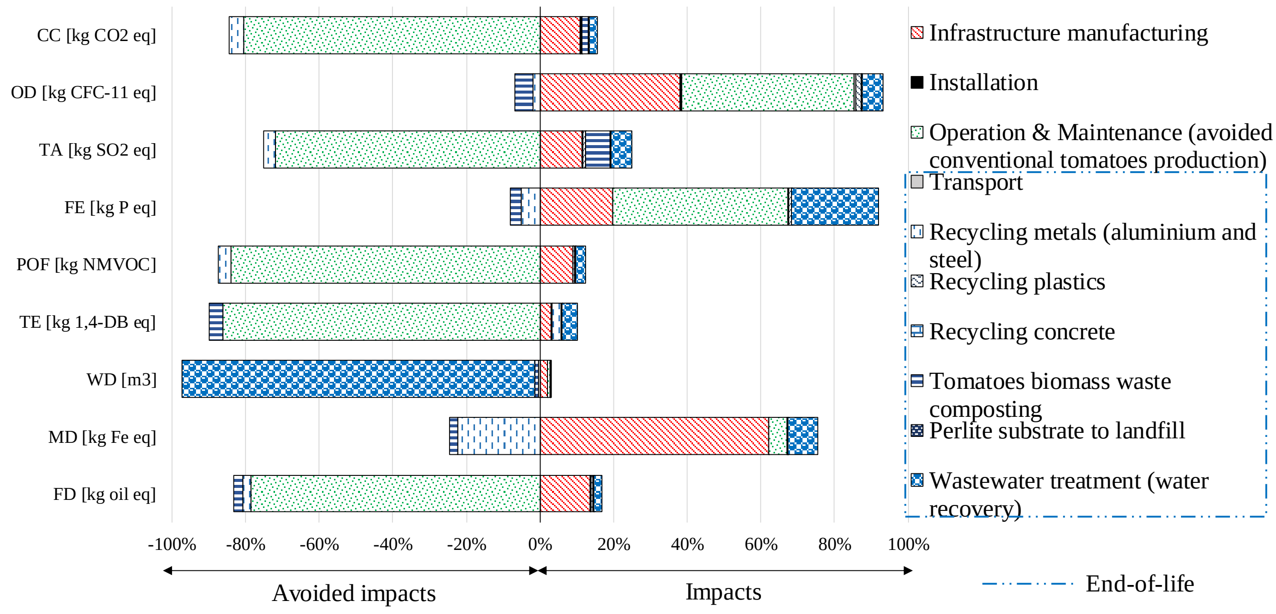

Figure 4. Percentage contribution of each phase to the overall environmental impacts of RTG system, referred to a functional unit of 1 m^2 of flat rooftop. Results include avoided impacts (negative values) due to recovery of energy and material flows.

In the case of the BAPV system (Table 7), overall negative scores (in bold) can be observed for almost all the environmental impact categories. This means that, except for TE, WD and MD categories, the environmental benefits from electricity production on-site from renewable source (Operation & Maintenance phase) (e.g., 475 kg CO_2 eq/m^2 are saved in climate change category) prevail on the environmental loads produced during the Manufacturing, Installation and EoL phases. Metal recycling (aluminium, silicon, steel, copper) plays a minor role in lowering the environmental loads as well, with a relevant share on metal depletion (MD) category only.

The percentage contribution to the total environmental impacts of each step in the BAPV is shown in Fig. 5.

Table 7. Characterized impacts calculated for the BAPV system (broken down into different process steps), referred to a functional unit of 1 m^2 of flat rooftop. Negative values correspond to avoided impacts thanks to energy and material recovery.

	CC	**OD**	**TA**	**FE**	**POF**	**TE**	**WD**	**MD**	**FD**
	kg CO_2 eq	kg CFC 11 eq	kg SO_2 eq	kg P eq	kg NMVOC	kg 1,4 -DB eq	m^3	kg Fe eq	kg oil eq
Infrastructure manufacturing	5.1E+01	1.2E-05	2.9E-01	3.5E+01	2.2E-01	1.1E-01	2.4E+00	8.1E+00	1.4E+01
Installation	1.5E+01	2.7E-06	1.0E-01	2.8E+01	7.7E-02	3.7E-03	1.9E-01	1.5E+01	4.3E+00
Operation & Maintenance	**-4.8E+02**	**-5.7E-05**	**-3.0E+00**	**-1.0E+02**	**-1.7E+00**	**-1.3E-02**	**-1.7E+00**	**-9.4E+00**	**-1.2E+02**
End-of-life									
Transport	2.2E+00	3.9E-07	7.1E-03	4.3E-01	8.5E-03	4.7E-04	6.5E-03	9.9E-02	7.8E-01
Recycling metals	**-1.4E+01**	**-2.5E-06**	**-9.2E-02**	**-6.7E+00**	**-7.5E-02**	**-1.9E-03**	**-1.2E-01**	**-6.5E+00**	**-4.0E+00**
Recycling glass	**-9.7E-01**	**-1.1E-07**	**-8.2E-03**	**-3.7E-01**	**-4.9E-03**	**-3.6E-04**	**-9.9E-03**	**-3.9E-02**	**-2.9E-01**
Recycling concrete	**-2.2E+00**	**-1.0E-07**	**-5.9E-03**	**-4.5E-01**	**-5.5E-03**	**-1.6E-04**	**-2.1E-02**	**-1.7E-01**	**-2.8E-01**
Recycling plastics	**-2.1E-01**	2.5E-09	**-5.7E-04**	**-5.2E-03**	**-8.3E-04**	**-6.2E-07**	**-3.6E-03**	**-4.1E-03**	**-1.7E-01**
Energy recovery	**-6.1E-01**	**-3.3E-08**	**-1.7E-03**	**-4.6E-02**	**-6.7E-04**	**-3.3E-05**	**-1.3E-04**	**-6.8E-03**	**-2.1E-01**

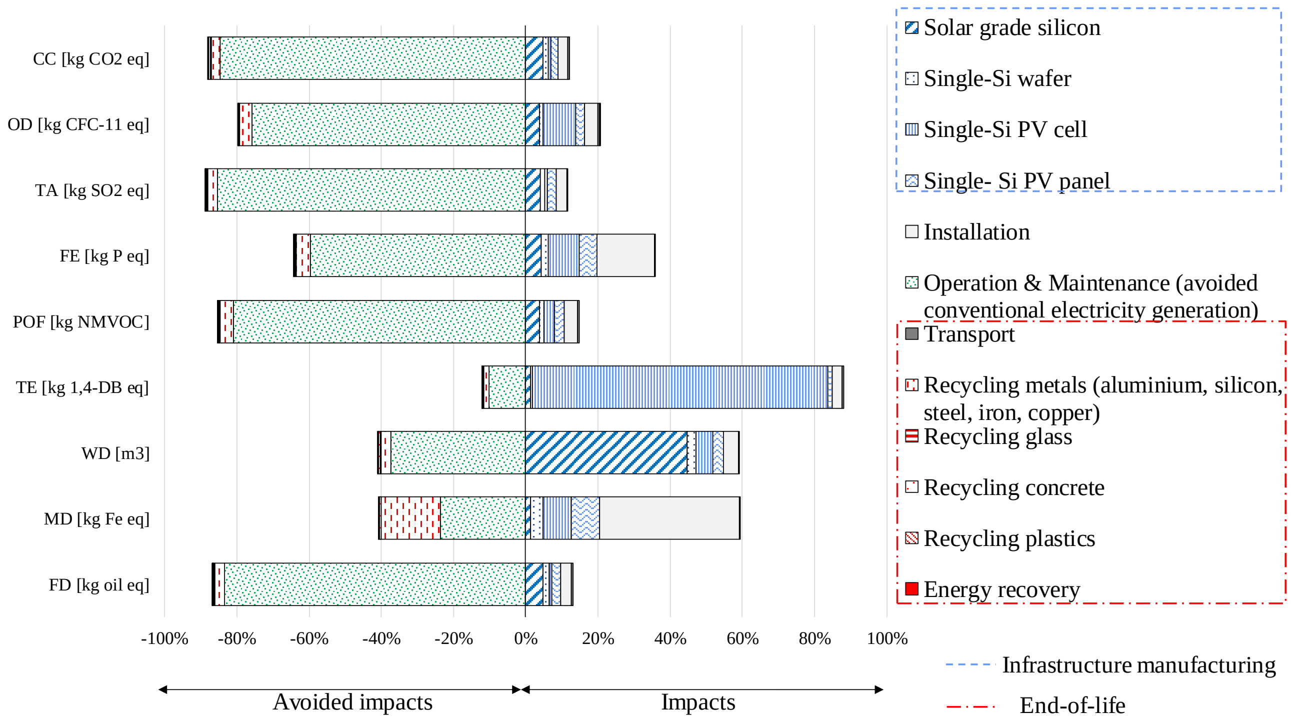

Figure 5. Percentage contribution of each phase to the overall environmental impacts of BAPV system, referred to a functional unit of 1 m^2 of flat rooftop. Results include avoided impacts (negative values) due to recovery of energy and material flows.

3.3. Comparison RTG – BAPV systems

Table 8 compares the total characterized results of RTG and BAPV systems, with reference to the selected functional unit. Almost all values are negative, meaning that both systems turn out to be favourable (i.e. they contribute to decreasing the impacts) thanks to the production of resources on-site. Material and water recycling provide a relevant environmental benefit for both roofing systems, thus confirming the efficiency of circular economy patterns. Such advantages are negligible if compared with the avoided emissions produced by the substitution of fossil energy in the case of BAPV and the traditional tomato supply chain in the case of RTG.

Except for TE, WD and MD, BAPV system shows the highest avoided impacts in comparison with RTG: for instance, the impacts generated by BAPV on climate change (CC) and fossil depletion (FD) categories, corresponding to -4.3E+02 kg CO_2 eq/m^2 and -1.1+02 kg oil eq/m^2, respectively (*versus* -2.2E+01 and -4.7E+00 in the RTG system), are around 20 times lower. Conversely, in the case of TE and WD, BAPV delivers environmental loads while RTG generates benefits (i.e. negative impacts). Moreover, in MD, the impacts due to BAPV are higher than RTG.

Table 8. Characterized impacts calculated for RTG and BAPV systems, referred to a functional unit of 1 m^2 flat rooftop. Negative values correspond to avoided impacts thanks to energy and materials efficiency.

Impact category	Unit/FU	RTG	BAPV
CC	kg CO_2 eq	**-2.2E+01**	**-4.3E+02**
OD	kg CFC-11 eq	1.2E-06	**-4.4E-05**
TA	kg SO_2 eq	**-5.9E-02**	**-2.7E+00**
FE	kg P eq	5.7E-03	**-4.9E+01**

POF	kg NMVOC	**-1.0E-01**	**-1.4E+00**
TE	kg 1,4-DB eq	**-7.8E-03**	9.9E-02
WD	m^3	**-1.6E+00**	8.1E-01
MD	kg Fe eq	2.0E+00	7.6E+00
FD	kg oil eq	**-4.7E+00**	**-1.1E+02**

When seeking to identify the most environmentally friendly way of using 1 m^2 of flat rooftop, the competition between rooftop greenhouse farming and electricity production by means of PV technology seems to be an unsolved question.

Modern urban systems often import food, energy, water and other resources to fulfil essential needs, which results in the emission of harmful greenhouse gases (Grewal and Grewal, 2012). In this study, throughout the production of local resources, RTG and PV systems enhance the practical realization of the circular economy in cities, which might increase the efficiency of the system. The choice of the Mediterranean context is very appropriate, since it is considered one of the world's best locations for solar energy use with a large exploitation potential (Girard et al., 2016). Both agri-urban and PV energy systems positively affect the current metabolism of Mediterranean cities and increase their multifunctionality, implementing a new symbiotic model between urban and natural systems from a circular perspective. In particular, RTG systems can be easily realized in Mediterranean cities without additional heating because of their warm climate and their high level of solar radiation, in contrast to northern Europe where additional heat is required thus resulting in an increased energy demand. The implementation of RTG systems may also represent a means to reduce the food losses during the transport and retail stages and to eliminate transport requirements, namely the main contributor to GHG emissions (Smith et al., 2005). Additionally, organic waste from RTGs can be reused as fertilizer, resulting in less waste collection costs for the city and reduced expenditures on synthetic fertilizers. Likewise, recirculating rainwater for food production (here, tomatoes) reduces the demand for water and the costs of stormwater management. According to existing literature, among the benefits coming from local food production, the satisfaction of basic food needs can be promoted only in cities located in developing countries or neighbourhoods with limited food retail. In developed countries, additional social benefits prevail, such as learning and education facilities for children and adult city-dwellers or bridging the gap between consumers and producers (Specht et al., 2014).

In the case of PV installations, flat rooftops are generally acknowledged to be good spots for a solar energy system, given that solar panels can be adjusted to the correct angle and the most appropriate orientation (Specht et al., 2014). Many advantages of PV applications on rooftop can be obtained: they reduce dependence on fossil fuel use for electricity generation, reduce the energy losses associated with transmission and distribution and do not require land for installation. Nevertheless, several environmental constraints have been highlighted in association with both retrofitting uses of rooftops. In the case of RTG, some concerns were expressed within the social dimension, since consumers may be reluctant to use soil-less growing techniques. Furthermore, health risks might possibly derive from air pollution or irrigation with improperly treated wastewater (Specht et al., 2014), although Ercilla-Montserrat et al. (2018) concluded that the heavy metal content in the air of Barcelona is not a source of contamination for urban crops including high traffic areas. On the other hand, the environmental impacts of PV electricity are mainly determined by the upstream emissions associated with the mining and purification of raw materials and by the emissions associated with the electricity needed for the manufacturing of panels (Meijer et al., 2003; Fthenakis and Kim, 2011; Chatzisideris et al., 2016). In particular, within Si-based panels life cycle, the energy requirement for the purification step from the metallurgical-grade silicon that is extracted from quartz to solar-grade silicon by either a silane (SiH_4) or trichlorosilane ($SiHCl_3$)-based process resulted to be the main criticality (Fthenakis et al., 2008).

For the sake of clarity, it should be noted that the outcomes of both analysed systems are highly site-specific, depending on yields which vary according to local conditions, such as solar radiation that determines the efficiency of the system. Moreover, the magnitude of generated environmental loads and of attained benefits is susceptible to other factors, such as the uncertainties in inventory data, the definition of system boundaries, impact assessment methods and the modelled sources of electricity and heat. Although desirable, a direct comparison of the results achieved in this study with previous LCA literature is hardly possible: even if the FU selected in these studies is most often 1 m^2 of rooftop, food and PV energy production technologies can widely vary (PV in combination with GR or gravel, GR, building applied or building integrated PV, etc). For instance, a comparison with Benis et al. (2018) would seem thinkable. However, the type and lifespan of PV roofing technology, as well as the assessment of operation and EoL phases are different if compared to systems analysed in this study. Therefore, generalizations are hardly possible.

3.4. Sensitivity

The assessment carried out in this study elucidated both pros and cons of RTGs and BAPV systems separately. In particular, in accordance with previous studies, the use of fertilizers resulted to be a very impacting input flow for RTGs (Sanyé-Mengual et al., 2015; Sanjuan-Delmás et al., 2018), whereas the electricity used in the production of solar panels was the main hotspot in the BAPV systems (Pacca et al., 2006; Bekkelund, 2013; Eskew et al., 2018). In order to check the robustness of LCA results and their sensitivity to changes in the input flows included in the study, a sensitivity analysis was performed by assuming a reduction or substitution of the inputs correlated with the highest environmental loads (i.e. electricity and chemicals). Therefore, two independent sensitivity analyses have been performed for the investigated RTG and BAPV systems.

Regarding the RTG system, the first step of the sensitivity analysis consisted in a careful sensitivity check related to the variability of major chemical inputs in the Operation & Maintenance phase. Indeed, as described in section 3.1.1, fertilizers were the most important flow (from 5% to 62%) for all the considered impact categories, especially due to the use of nitrogen fertilizers. Taking this hotspot into consideration, a sensitivity analysis was carried out on the basis of three alternative scenarios for tomatoes grown in greenhouses, compared with the original tomato cultivation analysed in this study (S0, base scenario):

1) S1– reduction (−10%) of the amounts of each fertilizer input (Torrellas et al., 2012);
2) S2– reduction (–20%) of the amounts of each fertilizer input (Torrellas et al., 2012);
3) S3 – horn meal (an organic fertilizer) was assumed to substitute calcium nitrate at a ratio 1:1, due to the relatively high content of N.

These scenarios were developed assuming that the reduction or change of used fertilizers does not affect the crop yield, thanks to more efficient technological application per area (e.g. amount of fertiliser per area of crop) rather than marginal consumption per amount of production.

As shown in Figure 6, the decreased use of fertilizers generates a negligible decrease in the impacts on the investigated categories of the Operation & Maintenance phase (WD category is not shown since it is not affected by this hotspot at all). When the use of fertilizers is reduced by 20% of the original amount (S2 versus S0), impacts decrease in a range of 2-15% approximately, while a smaller decrease of impacts in the range 1-9% is achieved when fertilizer use decreases by 10% (S1 versus S0). Additional reductions of impacts could be reached by means of further optimized fertilization techniques, such as drip irrigation and fertigation, that are commonly recognized to increase fertilizing efficiency (Worrell et al., 1995; Kennedy et al., 2013; Solis et al., 2013) or by improving the efficiency of the background processes for industrial fertilizer production.

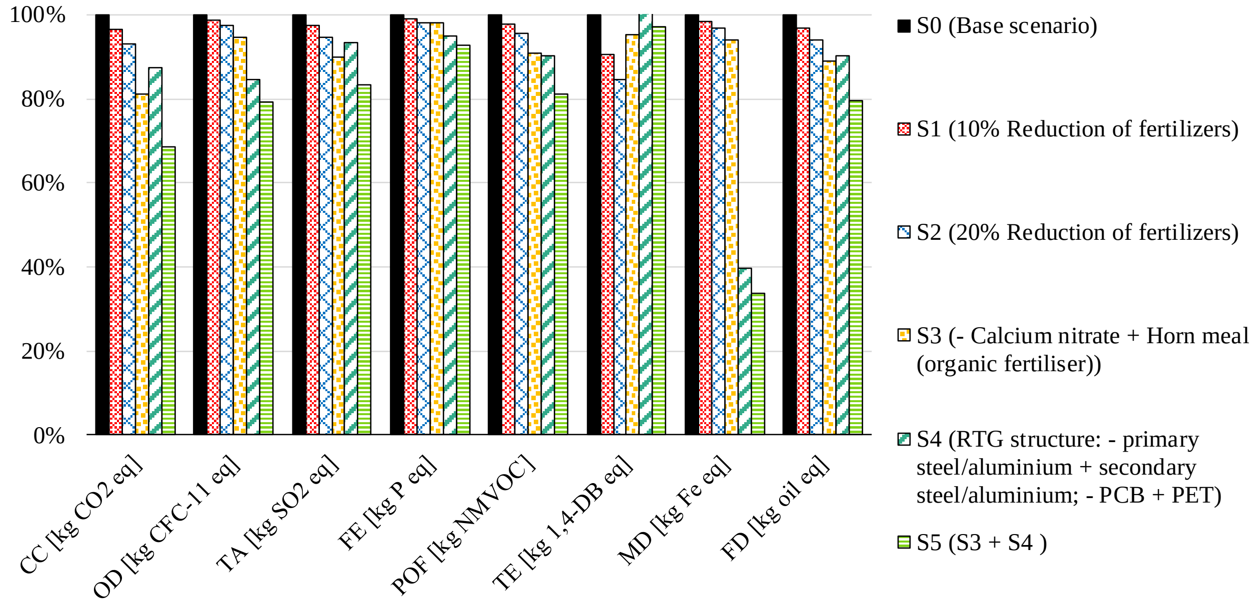

Figure 6. Sensitivity analysis for changes to fertilizers and infrastructure materials input flows, referred to RTG system (PCB= polycarbonate, PET= polyethylene terephthalate).

Since the RTG structure manufacturing was noted as a potential limitation to the implementation of RTGs due to the high environmental impact (see Section 3.1.1.), the second step of the sensitivity analysis was focused on the infrastructure materials. Thus, scenario S4 was designed considering both the substitution of virgin metals (aluminium and steel) with secondary (i.e. recycled) metals and the substitution of polycarbonate (PC) with polyethylene terephthalate (PET) (with a better environmental profile according to Franklin Associates, 2010).

The S4 scenario analysis showed that almost all impacts categories were sensitive to the material substitutions. A reduction of impacts can be observed with respect to the reference system (S0), ranging from 5% in freshwater eutrophication (FE) to 60% in metal depletion (MD). The terrestrial eutrophication (TE) is the only category that remained unchanged.

Finally, scenarios S3 and S4 were combined in the scenario S5. The results indicate that using organic fertilizer for cultivation and recycled materials for RTG infrastructure may improve the sustainability of supplying locally produced food. Indeed, the adoption of both strategies at the same time significantly reduces the impacts in all investigated categories, especially in climate change (CC) (32% reduction) and metal depletion (MD) (66%).

Concerning the BAPV system, one of the main aims of renewables is to contain the greenhouse effect. Therefore, a sensitivity analysis was carried out only for the key impact category, i.e. climate change (CC). As observed in Section 3.1.2., during the life cycle of PV, emissions to the environment mainly occur from using electricity when producing materials for solar panels (manufacturing phase). These emissions are strongly linked to the electricity mix used. Since the world's PV market is mainly dominated by China, USA, Germany and Italy (Solar Power Europe, 2018), a production chain of crystalline silicon-based panels in these countries was modelled and compared with the base scenario (Table 4). In addition, a comparison with the PV production chain in Sweden – leader country on renewable energy among the EU Member States (Eurostat, 2018) – was included, in order to see how the use of an electricity mix with a high rate of renewable sources affects the results. The life cycle inventory data of silicon production and crystalline silicon ingots, wafers, cells and panels were extrapolated from ecoinvent database and modelled by changing the Spanish electricity mix (base scenario) with the electricity mixes of the other six countries (referred to 2015) and by taking into account the transport of the manufactured panels to Barcelona, by transoceanic freight ships in the case of China, USA and Japan, and by truck in the case of European countries (Germany, Italy and Sweden).

Figure 7 shows the results of the comparison between the different electricity mixes applied during the manufacturing phase and variation of transport distances (the Operation & Maintenance and EoL phases of the base scenario are not shown in the figure since they remain unchanged). As shown in Figure 7, the c-Si panels produced in China cause about 40% higher GHG emissions compared with Spanish panels. The highest emissions result from the electricity mix used in the Chinese industry with a high share of fossil fuel power (72%). If the panel production in Japan, USA, Germany and Italy is considered, it is possible to observe GHG emissions about 15.8%, 13.6%, 14.3% and 12.9%, respectively, higher compared to panels produced in Spain. In contrast, the use of electricity from renewable energy sources (e.g. in the case of Sweden the share of renewable power is 63%) in the production chain reduces the GHG emissions by about 14% (- 7 kg CO_2-eq per m^2 of rooftop). The contribution from the transport step does not exceed 3.4%, except for the case of Sweden (9%) due to the longer distance travelled by truck.

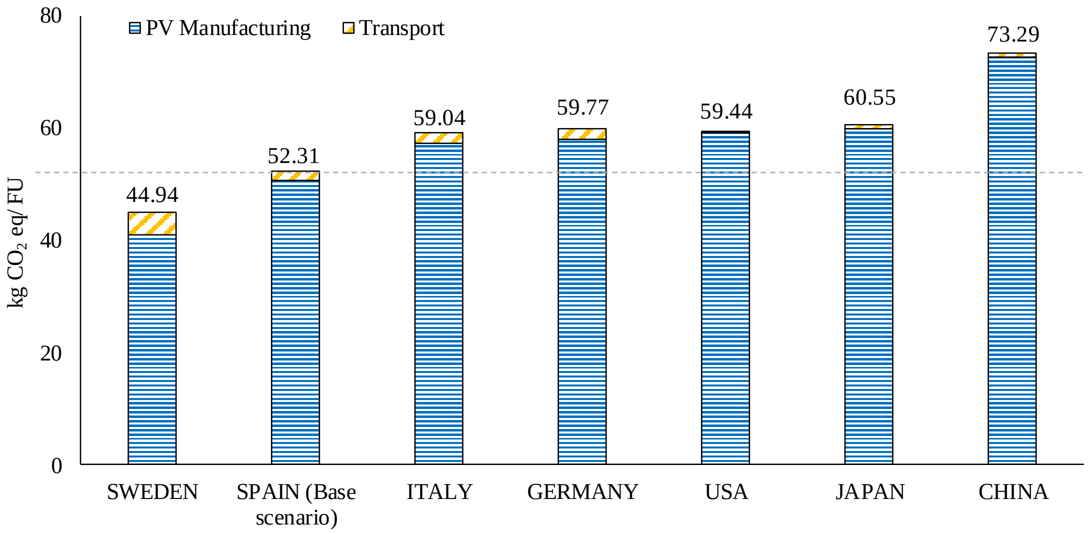

Figure 7. Sensitivity analysis for changes to electricity-mix and transport input flows, referred to BAPV system (only manufacturing phase is included).

4. Conclusion

Sustainable urban planning is essential to effectively meet the needs of a growing population and respond to changes in consumption patterns without exhausting our planet's finite resources. In this sense, the transformation of urban underused rooftops into productive spaces can improve the urban metabolism by producing or collecting locally resources such as energy, greening, food or water. The innovative contribution provided by this study is the comparison of two different rooftop systems for resources production (i.e. food and energy) with the aim of supplying additional helpful elements for promoting the circular economy at the urban scale. The adoption of the avoided burden approach allows to highlight the environmental benefits deriving from the implementation of energy and material efficiency measures, especially in warm Mediterranean climates, and from the concomitant avoided costs of conventional production of tomatoes and electricity (with savings of 22 kg CO_2 eq and 425 kg CO_2 eq for RTG and BAPV respectively). The BAPV system is more environmentally sound in all impact categories, except for TE, WD and MD, the latter being the only category that is not advantaged by neither RTGs nor BAPVs. Even if the solar PV technology impacts produced during the material manufacturing phase are high (from 52% to 93%), they are copiously balanced by the avoided impacts associated to energy output during the operation phase. Nevertheless, similar advantages are achieved by means of rooftop farming. The options suggested in the sensitivity analysis may provide some useful tools for improved environmental performances, but cannot definitely overcome the limits of each system.

In the future, potentially improved performances may be gained by means of synergy effects achieved when combining both food and energy production (Marucci and Cappuccini, 2016; Trypanagnostopoulos et al., 2017; Loik et al., 2017). Preliminary tests have shown that PV panels work more efficiently over a green roof that cools down the cells through evapotranspiration (Köhler et al., 2007). Meanwhile, the panels shade the plants, thus reducing sun exposure and favouring heat-sensitive crops. Therefore, sustainable rooftop planning for urban buildings might lead to multifunctional uses of the same roof throughout the integration or the coexistence of both investigated systems.

In conclusion, in a future prospect, attention to additional energy and material efficiency and material selection, in favour of the more environmentally sustainable choice, should also remain a main point of investigation. For instance, in the case of RTGs, both the greenhouse structure and the rainwater harvesting system can be reduced in size, and in the design phase the amount as well as the quality of materials used for their manufacture can be optimised. Likewise, a decrease in the electricity demand for manufacturing BAPV systems together with a well-designed recovery treatment would contribute to a more sustainable supply chain. Additionally, economic and social assessments should be performed in further research in order to provide a more nuanced contextualisation (either at country or city level) of RTG and BAPV systems within these sectors.

Conflicts of interest

The authors declare no conflict of interests.

Acknowledgements

The authors Corcelli and Fiorentino gratefully acknowledge the financial support received from the European Union’s Horizon 2020 research and innovation program under grant agreement No. 649342 (EUFORIE). G. Fiorentino also acknowledges the research grant received from Parthenope University, project DSTE332 - Material and Energy Efficiency in Chemical Processes for Industry and Environment. A. Petit-Boix thanks the Spanish Ministry of Education, Culture and Sports for the grant awarded (FPU13/01273) while employed at UAB, and the German Federal Ministry of Education and Research for funding the research group “Circulus - Opportunities and challenges of transition to a sustainable circular bio-economy”, grant agreement No. 031B0018.

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