# 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, modelled in the professional software SimaPro, this paper aims at comparing the environmental performance of different productive uses of rooftops under Mediterranean climatic conditions. The results showed that both systems are favourable and contribute to decreasing the environmental impacts thanks to the production of resources on-site. BAPV system shows the highest avoided burdens in comparison with RTG: for instance, the impacts generated by BAPV on climate change and fossil depletion categories, corresponding to - 430 kg $CO_2$ eq/$m^2$ and -110 kg oil eq/$m^2$ respectively (*versus* -22 kg $CO_2$ eq/$m^2$ and -4.7 kg oil eq/$m^2$ in the RTG system), are around 20 times lower than RTG. Furthermore, a sensitivity analysis was performed through different scenarios, based on reductions or substitution of the most sensitive input flows, thus providing some useful tools for improved environmental performances. Attention to additional energy and material efficiency, in favour of the more environmentally sustainable choice, should remain a main point of investigation.

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**Keywords:** 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 not self-sustaining, 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 (World Bank, 2010). 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; Elzeyadi et al., 2009, Nadal et al., 2017a). 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. (2015a), RTGs are finding deployment in experimental projects also in the Mediterranean context because of the favourable climate conditions. At the same time, 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; Benis et al., 2018). 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 (Santos and Rüther, 2012). 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; Benis et al., 2018). Food production and energy generation on urban rooftops are also an important source of environmental benefits. Table 1 summarizes the main environmental benefits relevant for the RTGs and BAPV systems under investigation in this study.

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 such as solar power systems to satisfy the high-energy demands of growing urban areas (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., 2017, 2018a; 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. The importance of maximizing spatial efficiency and the need to design spatial decision support systems that integrate all potential renewable resources in a given area were highlighted by Calvert et al. (2015). As for land use, the generation of multifold renewable resources can also be addressed by rooftops, that are suitable for the integrated application of multiple technologies in a given site. Some recent studies investigated the integration of solar energy systems into rooftop farming activities. 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) method 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 benefits of green roofs (e.g. for the energy savings of a building) in comparison with conventional roofs (Lamnatou and Chemisana, 2014). Sanyé-Mengual et al. (2015a) and Sanjuan-Delmás et al.'s (2018a) 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 environmental advantages over conventional agriculture. Benis et al. (2018) compared four different rooftop systems (three greenhouse systems and one PV system) in the Mediterranean context using a cost-benefit analysis.

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. Our study aims at filling 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 (Carnevale et al., 2014). 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 evaluated using LCA, with a special attention on those phases and hotspots that display the highest environmental impacts and proposing enhancement scenarios for decreasing such impacts. The originality of this study lies in the first comparison of two different rooftop systems by thoroughly assessing the environmental burdens and benefits of both production processes. A large set of environmental indicators and real empirical data were used to evaluate the environmental loads of local food and energy production. Additionally, the potential benefits deriving from energy and material efficiency strategies were considered 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, under investigation in this study.

| | 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., 2015a; 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., 2018a; h) Proksch, 2016, i) Prasad, 2014, l) Proksch, 2011

## 2. Materials and methods

The assessment has been performed by applying LCA methodological framework based on ISO standards (ISO 2006 a, b) and International Reference Life Cycle Data System (ILCD) Handbook guidelines (EC 2010, 2011). LCA is a common and standardised tool for quantitatively assessing the potential environmental burdens during all stages of a product system, from raw material extraction to the disposal of the product at the end of its life, including manufacturing, transportation, installation, use and disposal or recycling (i.e., cradle-to-grave). LCA identifies the most relevant environmental impacts and key processes ('hotspots') and can support decision-making strategies for environmental improvements from a life cycle perspective (Baumann and Tillmann, 2004). For the implementation of the LCA the following steps are adopted in this study: i) goal and scope definition; ii) life-cycle inventory analysis (LCI); iii) life-cycle impact assessment (LCIA) and iv) interpretation of results.

*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 the following life cycle phases: 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. In line with Sanyé-Mengual et al. (2015a), the consumption phase is excluded from the assessment due to its dependence on tomato preparation methods (e.g. from raw consumption to oven-grilled). 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 (Corcelli et al., 2018a; 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 (Sica et al., 2018). 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 intended to provide policy makers with potentially useful suggestions for local resources production planning, without however accounting neither 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) nor for the effects of the investigated systems on the market (Ripa et al., 2017). According to the ILCD Handbook (EC, 2010) the analyzed context can be identified as a micro-level decision support (so called situation A in ILCD) and an attributional LCI modeling framework (e.g. the potential environmental impacts are attributed to a system or a product over its life cycle) is therefore applied. As a consequence, a system expansion based on average data (i.e. market mix) was carried out for crediting energy recovery in the case of BAPV system and tomatoes production in the case of RTG. Within the attributional LCI modelling, the average technology was selected (rather than the marginal technology), according to Finnveden et al. (2009) and to Nemecek et al. (2015), the latter highlighting that in crop production, average practice should be understood as conventional agriculture as practiced by a majority of producers.

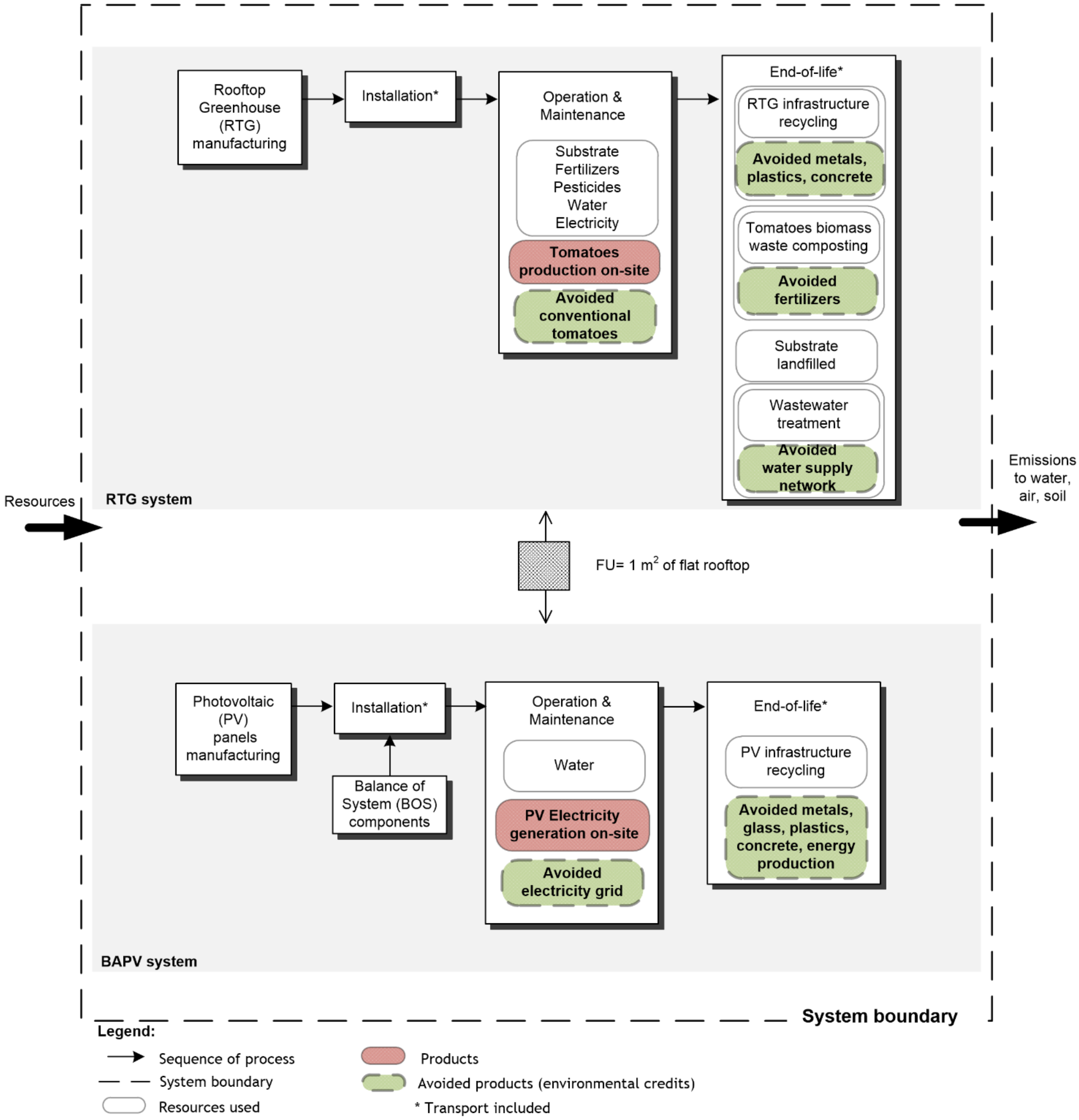


**Figure 1.** System boundaries and process chain under study.

*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) (Nadal et al., 2017b). 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; Sanjuan-Delmás et al., 2018a). Additionally, its design is based on building-integrated agriculture philosophy, multifunctionality and passive systems that promote energy efficiency (Nadal et al., 2017b; Sanjuan-Delmás et al., 2018b). The external structure of the ICTA-ICP building is composed of a metal frame with corrugated polycarbonate sheets that can be opened or closed to provide ventilation. This structure covers the walls and the roof of the building and the RTG. 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., 2015a). This study considers RTG crops based on hydroponic systems (i.e. soil-less crops that use mainly inert substrates), as the agro-urban system applied. Rainwater collection is included in this study, although it does not represent a standard for RTG systems, particularly in a retrofit situation. 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, decreasing the demand for drinkable water from the conventional water supply system (Sanjuan-Delmás et al., 2018a). 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 total area of RTG is 122.8 $m^2$, 84.34 $m^2$ of which are cropped (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 (Sanjuan-Delmás et al., 2018a). A hydroponic system was employed for irrigation to distribute a nutrient solution (water plus fertilisers, also called 'fertigation') to plants on an inert substrate consisting of perlite bags. The system produced 30.1 kg of tomatoes per square meter over 15.5 months, furnishing a total of 2,540 kg of food and covering the requirements for tomatoes of nearly 60% of the building (Sanjuan-Delmás et al., 2018a). Further technical information about the crop and the greenhouse structure can be found in Sanjuan-Delmás et al. (2018a).

*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 thermal screens, backup lighting, rainwater harvesting systems, and climate control systems. The installation stage accounts for energy consumption requirements of the machinery used to construct the RTG. According to earlier studies, a 50 years lifespan was considered for the rainwater harvesting system (Vargas-Parra et al., 2013; Sanjuan-Delmás et al., 2018a) and the greenhouse structure (Sanye-Mengual et al., 2015a), 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 averaged distance travelled 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 (consumed for crop irrigation) and energy needs (i.e. electricity used for opening and closing the walls and roof of the greenhouse and for lighting and irrigation pumps). 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. (2018a), 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, the investigated RTG source: Sanjuan-Delmás et al., 2018a).

*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 balance the emissions from more environmentally intensive sources of electricity and reduce electricity transmission losses (Cubi et al., 2016). 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). In accordance with Fu et al. (2015), 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. In line with Eskew et al. (2018), 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 and IEA-PVPS, 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).

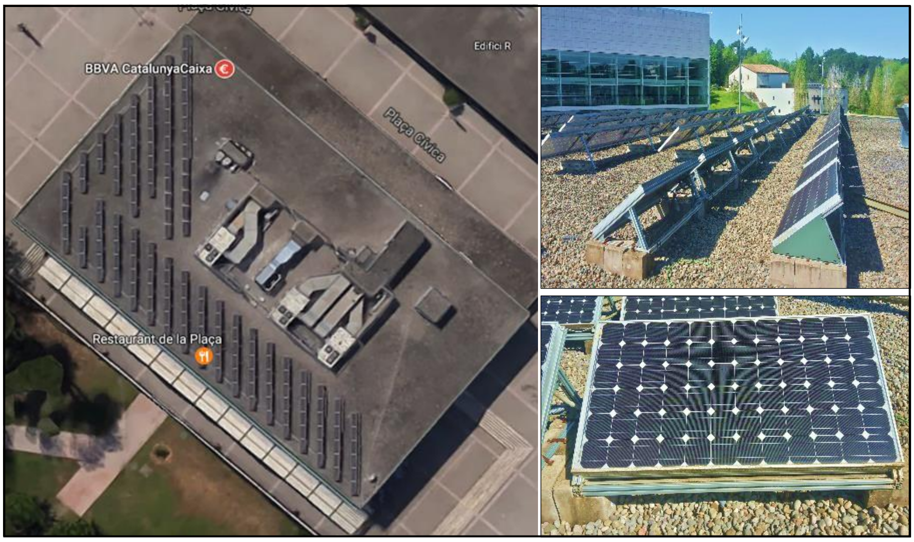


**Figure 3.** Top view of roof-mounted photovoltaic (on the left, source: 2017 © Google LLC) and the investigated PV sytems (on the right).

*2.3 Life cycle inventory and main assumptions*

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 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. (2015a) and Sanjuan-Delmás et al. (2018a). 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, Fu et al., 2015) and literature (Corcelli et al., 2018a). 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 in Spain (Almeria) by means of conventional farming in a standard greenhouse (Nemecek et al., 2015). The multi-tunnel greenhouse model was used as a representative conventional greenhouse commonly used in Spain (Torrellas et al., 2012). The recycling costs and benefits related to materials recovery were accounted for in the analysis. In this sense, the substitution ratio takes into account the quality of the products from waste in comparison with that of the corresponding avoided product. In particular, the avoided production of primary steel, aluminium, silicon, iron and copper were assumed for crediting metals recovery, with a substitution ratio of 0.9:1, due to processing losses (Ramachandra Rao, 2006). Likewise, for crediting lithoid based materials such as concrete and glass recovery, the avoided production of the corresponding primary material was assumed, with a substitution ratio of 0.9:1, due to degradation in the recycling process (Blengini and Di Carlo, 2010.). 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 (Thoden van Velzen et al., 2017). In the case of RTG system, the credits deriving from the irrigation water recovery was also considered, thus reducing the demand for potable water from the conventional distribution network. It should be highlighted that most of the water consumed in the RTG was rainwater collected from the building (80-90%), while the remaining 10-20% was tap water (Sanjuan-Delmás et al. 2018a). Moreover, for crediting tomato biomass composting, the avoided production of inorganic fertilizers was included. In this latter case, the considered substitution ratio of 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; Ripa et al., 2017).

**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. (2015a) |
| 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. (2015a) |
| 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. (2018a) |
| 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. (2018a) |
| **End-of-life** | | | |
| Steel scraps (to recycling) | kg | 8.37E-01 | Ecoinvent 3.1 database (Wernet al., 2016) |
| Plastics scraps (to recycling) | kg | 3.57E-01 | // |
| Aluminium scraps (to recycling) | kg | 7.80E-03 | // |
| Concrete scraps (to recycling) | kg | 2.12E-01 | // |
| Perlite substrate waste (to landfill) | kg | 1.87E+00 | // |
| Tomatoes biomass waste (to composting) | 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. (2018a) |
| Transport* to recycling facility, lorry (aluminium, steel, plastics, concrete scraps) | tkm | 4.24E-02 | Sanyé-Mengual et al. (2015a) |

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

**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#** | | | |
| 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 (to recycling) | kg | 1.74E+00 | Modified from Corcelli et al. (2018a); Ecoinvent 3.1 database (Wernet al., 2016) |
| Glass scraps (to recycling) | kg | 1.87E+00 | // |
| Silicon scraps (to recycling) | kg | 2.25E-01 | // |
| Copper scraps (to recycling) | kg | 9.96E-02 | // |
| Iron scraps (to recycling) | kg | 5.22E-06 | // |
| Steel scraps (to recycling) | kg | 1.21E+00 | // |
| Concrete scraps (to recycling) | kg | 1.23E+01 | // |
| Plastics scraps (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.
# The emissions during the operation phase were considered negligible according to Alsema and de Wild-Scholten (2006) and Peng et al. (2013).

### *2.4. Life Cycle Impact Assessment (LCIA)*

The environmental impact assessment was performed using the ReCiPe Midpoint method (hierarchist perspective), one of the most recent and up-to-date LCA methods (Goedkoop et al., 2009; Vezzoli, 2018). The LCA software SimaPro version 8.0.5 (Pre-Consultants, 2014), integrated with ecoinvent v3.1 database (Wernet et al., 2016), was used to construct the LCA model and implement the impact assessment calculations. In this study, the following impact categories were explored: 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 conducted to find out how sensitive the model was to changes in the input parameters. To this end, alternative scenarios were proposed, based on progressive reductions or substitution of the most sensitive input flows.

## 3. Results and Discussion

As a first approach to the evaluation of the systems performance, the "avoided impacts" were not included in the assessment, neglecting the potential credits or benefits for secondary materials production (recycling) or recovered energy (incineration and sometimes landfilling). In such a way the crucial phases still needing improvement are not hidden (Section 3.1). However, additional information about potential benefits may also be needed. Therefore, a second assessment was carried out including a system expansion in order to consider the environmental burdens that are avoided due to the recovery of goods and energy (Section 3.2). The observed negative values mean that the credits associated to the recovery of goods (i.e. metals, biomass) and energy (i.e. electricity, heat) are greater than the environmental burdens generated during the whole life cycle (Gala et., 2015; Corcelli et al., 2018b). Finally, a comparison between RTG and BAPV systems was 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<br>kg $CO_2$ eq | OD<br>kg CFC 11 eq | TA<br>kg $SO_2$ eq | FE<br>kg P eq | POF<br>kg NMVOC | TE<br>kg 1,4 - DB eq | WD<br>$m^3$ | MD<br>kg Fe eq | FD<br>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 |

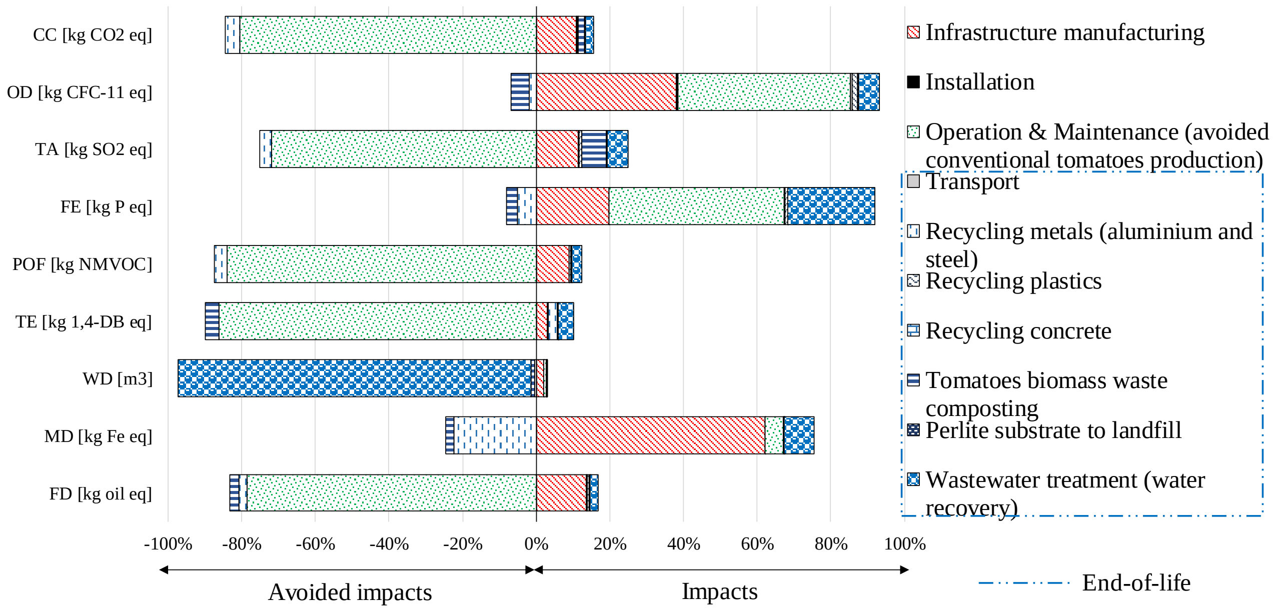


**Figure 4.** Percentage contribution of each phase to the overall environmental impacts of RTG system, referred to a functional unit of 1 $m^2$ of flat rooftop. Results include avoided impacts (negative values) due to recovery of energy and material flows.

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. It should be noted that the energy outputs from the BAPV system were considered to be used as alternative to the Spanish electricity grid, mainly based on nuclear (21.8%), coal (20.3%) and oil (10.1%) (Red eléctrica de España, 2015), thus entailing large environmental benefits. 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** 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 | 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** |

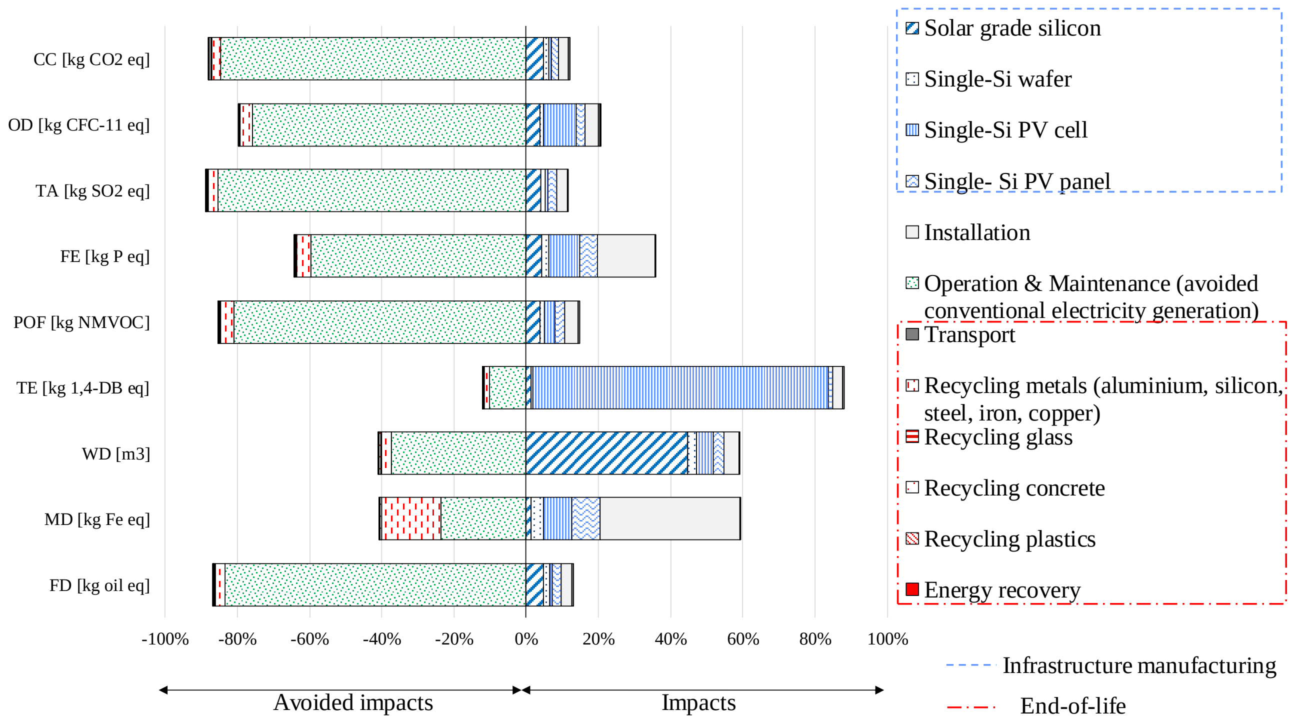


**Figure 5.** Percentage contribution of each phase to the overall environmental impacts of BAPV system, referred to a functional unit of 1 $m^2$ of flat rooftop. Results include avoided impacts (negative values) due to recovery of energy and material flows.

### *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 fulfill 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 (Sanyé-Mengual et al., 2013). 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 (Grewal and Grewal, 2012). 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). Moreover, the use of rooftops farming can minimize the cost of land use (in contrast to rental contracts for agricultural soil) (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, different environmental, social, economic and technical 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). The wide spread of PV technology market shows that PV is attractive as a long-term sustainable economic option (EPIA and Greenpeace, 2011; Girard et al., 2016; IRENA and IEA-PVPS, 2016) whereas as for the RTG technology, Cerón-Palma et al. (2012) and Sanyé-Mengual et al. (2015a,b) highlighted that the costs of RTG (especially for the greenhouse structure and operation) are greater than conventional or open-field agriculture. However, the investigated RTG is a pilot system at a small scale whose main purpose is to conduct research. According to Sanjuan-Delmás et al. (2018b), the application of the RTG technology at an industrial scale would contribute to reduce the economic costs of production and make this technology economically attractive. On the other hand, it should be noted that the implementation of RTGs is not always feasible due to the technical characteristics of the selected rooftop (Sanyé-Mengual et al., 2015b). Concerning the slope, the flat roofs are definitely the most indicated for greenhouses development and, at the same time, the material and structural resistance must be appropriate to match the load requirements of the greenhouse. For instance, RTGs can be implemented on reinforced concrete rooftops. In contrast, roofs made of metal (which can be both steel and aluminium structures) would have to be reinforced in a rehabilitation process. In addition, a further barrier for RTG systems can depend on local regulations concerning the maximum building height, surface area, and volume that can be built in a certain place (Cerón-Palma et al., 2012).

It is worth noting that the outcomes of both analysed systems are very 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 produced environmental costs and benefits can be affected by several uncertainty sources, such as the quality of inventory data, system boundaries definition, impact assessment methods and the modelled sources of electricity and heat (Cellura et al., 2011).Great care and attention should be devoted when comparing the results of different LCA studies: even if the FU selected is most often 1 $m^2$ of rooftop (Benis et al., 2018), food and PV energy production technologies can widely vary (PV in combination with GR or gravel, GR, building applied or building integrated PV, etc), as well as the operation and EoL phases assessed. As a consequence, 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., 2015a; Sanjuan-Delmás et al., 2018a), 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). A sensitivity analysis was performed in order to test the robustness of results when changing (by reducing or substituting) the input flows responsible for the highest environmental impacts (i.e. electricity and chemicals). Hence, 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 (Fiorentino et al., 2014).

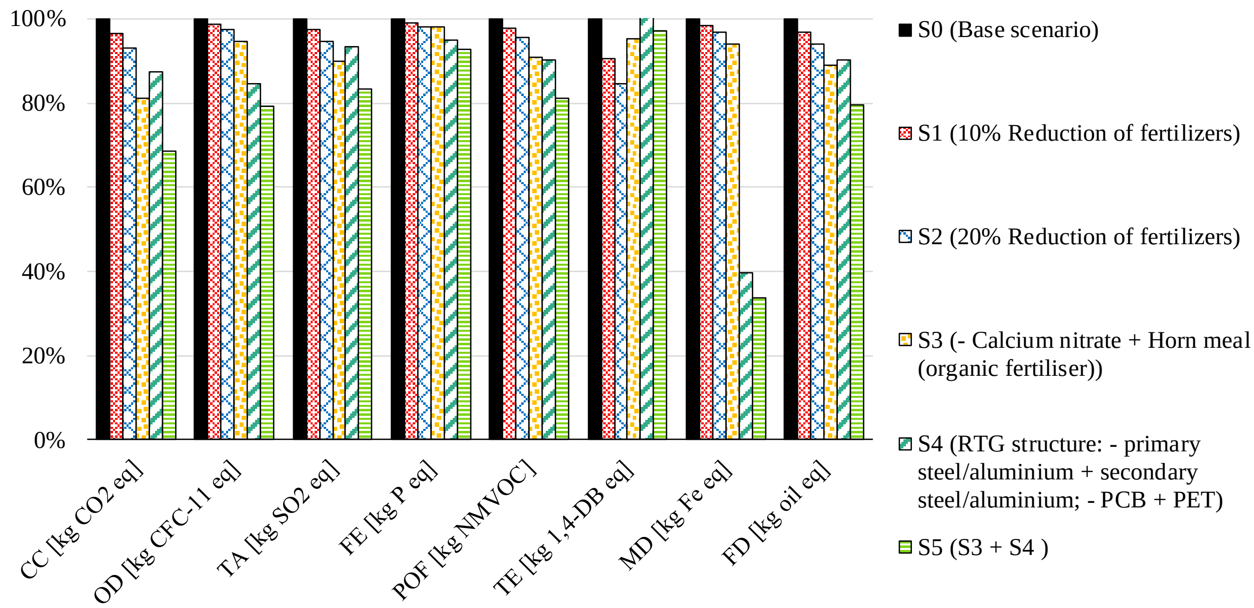


**Figure 6.** Sensitivity analysis for changes to fertilizers and infrastructure materials input flows, referred to RTG system (PCB= polycarbonate, PET= polyethylene terephthalate).

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. Accordingly, 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.

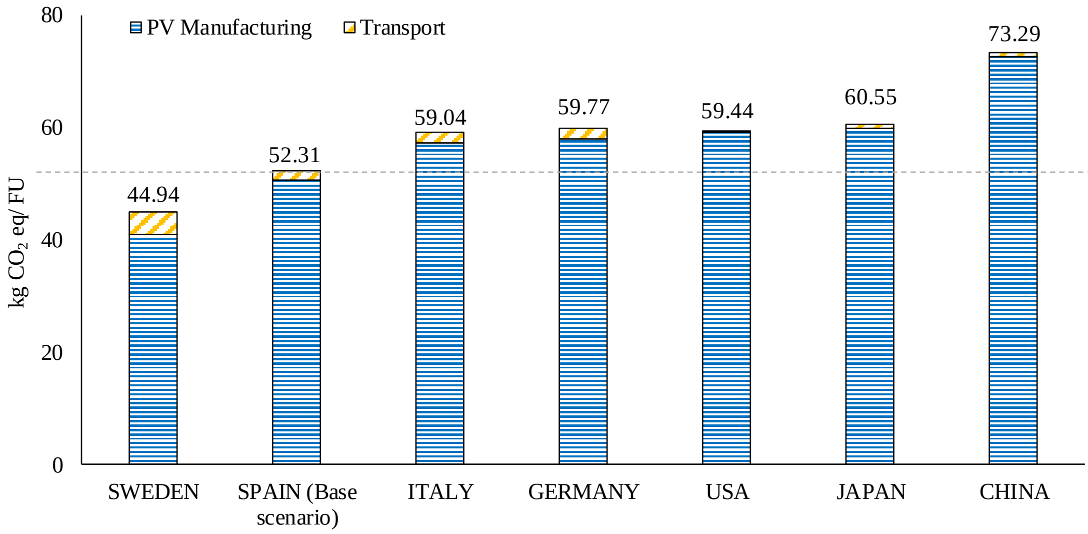


**Figure 7.** Sensitivity analysis for changes to electricity-mix and transport input flows, referred to BAPV system (only manufacturing phase is included).

**4. Conclusion**

Sustainable urban planning is essential to effectively address the needs of a growing population by changing the consumption patterns towards a better management of 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 430 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, a leading point of investigation should always be a careful focus on additional energy and material efficiency and more environmentally sustainable choice of materials. 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.

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