Towards Productive Cities

Environmental Assessment of the Food-Energy-Water Nexus of the Urban Roof Mosaic

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Summary

Cities are rapidly growing and need to look for ways to optimize resource consumption. Metropolises are especially vulnerable in three main systems, often referred to as the FEW (i.e., food, energy, and water) nexus. In this context, urban rooftops are underutilized areas that might be used for the production of these resources.

We developed the Roof Mosaic approach, which combines life cycle assessment with two rooftop guidelines, to analyze the technical feasibility and environmental implications of producing food and energy, and harvesting rainwater on rooftops through different combinations at different scales. To illustrate, we apply the Roof Mosaic approach to a densely populated neighborhood in a Mediterranean city. The building-scale results show that integrating rainwater harvesting and food production would avoid relatively insignificant emissions (13.9–18.6 kg CO_2 eq/inhabitant/year) in the use stage, but their construction would have low environmental impacts. In contrast, the application of energy systems (photovoltaic or solar thermal systems) combined with rainwater harvesting could potentially avoid higher CO_2 eq emissions (177–196 kg CO_2 eq/inhabitant/year) but generate higher environmental burdens in the construction phase.

When applied at the neighborhood scale, the approach can be optimized to meet between 7% and 50% of FEW demands and avoid up to 157 tons CO_2 eq/year. This approach is a useful guide to optimize the FEW nexus providing a range of options for the exploitation of rooftops at the local scale, which can aid cities in becoming self-sufficient, optimizing resources, and reducing CO_2 eq emissions.

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Introduction

Cities are frequently considered the home of prosperity and development, but they are also large resource consumers, generating pollution, unsustainable growth, and social inequality (UN-Habitat 2013). Approximately 66% of the world population is expected to live in urban areas by midcentury (United Nations 2014). In this sense, highly populated cities are especially vulnerable in three key systems: food, energy, and water. The complex interactions among these systems are referred to as the food-energy-water (FEW) nexus (Garcia and You 2016). European cities consume approximately 70% of the total EU energy (EEA 2015), 32% of the total water use (EEA 2016), and their daily per-capita food supply has increased by 10% in the past 50 years (Roser and Ritchie 2017).

Hence, urban sustainability practices are essential to reduce resource consumption and its impacts (EEA 2015). Cities might benefit from a transition towards a circular economy that uses renewable resources and energy and designs cyclical and efficient systems (Ghisellini et al. 2016). For instance, the use of underutilized areas, such as rooftops and public spaces, might help enhance urban sustainability (European Commission 2011). In this sense, rooftops are a valuable resource in areas where space is scarce and expensive, which might increase self-sufficiency in compact cities when used to produce food and clean energy or to harvest rainwater.

To understand the relevance of rooftops in cities, urban planning must be considered. After the Second World War, Europe had to meet a large housing demand (Harloe 1994). The massive construction of large buildings with similar characteristics promoted mainly by governments, that is, mass social housing (Murie et al. 2003; Harloe 1994), provided housing to the most vulnerable population (Van Kempen et al. 2005; Blos 1999). In Europe, excluding the former Union of Soviet Socialist Republics (USSR), approximately 41 million people live in this type of construction (Dekker and Van Kempen 2004). In Spain, housing demand grew during the 1950s and 1960s (Blos 1999), which simultaneously increased the surface area of unused rooftops in urban areas. Currently, many of these buildings require refurbishment of their deteriorated roofs and façades (Konstantinou and Knaack 2011; Jornet 2010; Scalon and Whitehead 2008).

A potential action plan is to increase the utility of urban rooftops. We introduce a novel framework, which we call the "Roof Mosaic" approach, to analyze the technical feasibility and environmental implications of using suitable rooftops at local scale (i.e., neighborhoods, districts, industrial and retail parks) to provide food, energy, and water; collectively contribute to environmental, social, and economic benefits; and promote self-sufficiency. The transformation of rooftops to improve the performance of buildings has been in practice for many decades (see a list of applications in figure A.1 in the supporting information available on the Journal's website). Nevertheless, the concept of multiple rooftop uses that create collective, neighborhood-scale benefits has not been yet explored. Most urban rooftops are still used solely as a protective layer that houses technical equipment (Kellett 2011). An extensive amount of literature documents the utility of single systems on rooftops, but none of the research has combined different systems at the neighborhood level. For instance, Orsini and colleagues (2014) determined the great potential of rooftop food production in a city, and Sanyé-Mengual and colleagues (2015b) environmentally and economically assessed the implementation of a rooftop greenhouse in a building. Benis and colleagues (2018) analyzed food production versus photovoltaic (PV) energy generation on rooftops in a mixed-use neighborhood. Armendariz-Lopez and colleagues (2016) and Cucchiella and Dadamo (2012) estimated the life cycle cost (LCC) and the environmental performance of PV systems in different building roofs, respectively. Carnevale and colleagues (2014) compared PV and solar thermal (ST) systems at the household scale. The environmental assessment and the LCC of implementing rainwater harvesting (RWH) were analyzed at building and neighborhood scales (Devkota et al. 2015, 2013; Tavakol-Davani et al. 2013; Petit-Boix et al. 2018).

Hence, we need to understand how the FEW nexus can become a driver towards a sustainable, urban circular economy through the application of the Roof Mosaic, albeit specific methodologies, criteria, or tools for assessing its implementation do not exist. To address this literature gap, our main goal is to design a comprehensive approach that helps to evaluate the technical feasibility and environmental implications of applying the Roof Mosaic in urban areas. We hypothesize that combinations of FEW systems on rooftops can provide more advantages at the neighborhood than at the building scale due to resource redistribution and the provision of all three resources. We test the Roof Mosaic approach on a mass social housing neighborhood in the city of Barcelona at the building and neighborhood scales.

Materials and Methods

A Guide for Assessing the Implementation of the Roof Mosaic Approach

The steps proposed for assessing the implementation of the Roof Mosaic approach are described in figure 1. Each step is explained in the following sections.

Step 1: Characterization of the Area under Study

A wide variety of data is required to design the Roof Mosaic configuration. The characterization of the area under study is based on:

1. Urban features, for example, type of housing, urban form, and available rooftops.
2. Climatic variables, for example, monthly rainfall for sizing the rainwater tank, temperature for choosing suitable crops, solar radiation for sizing the solar panels, and wind velocity and direction for sizing wind energy.

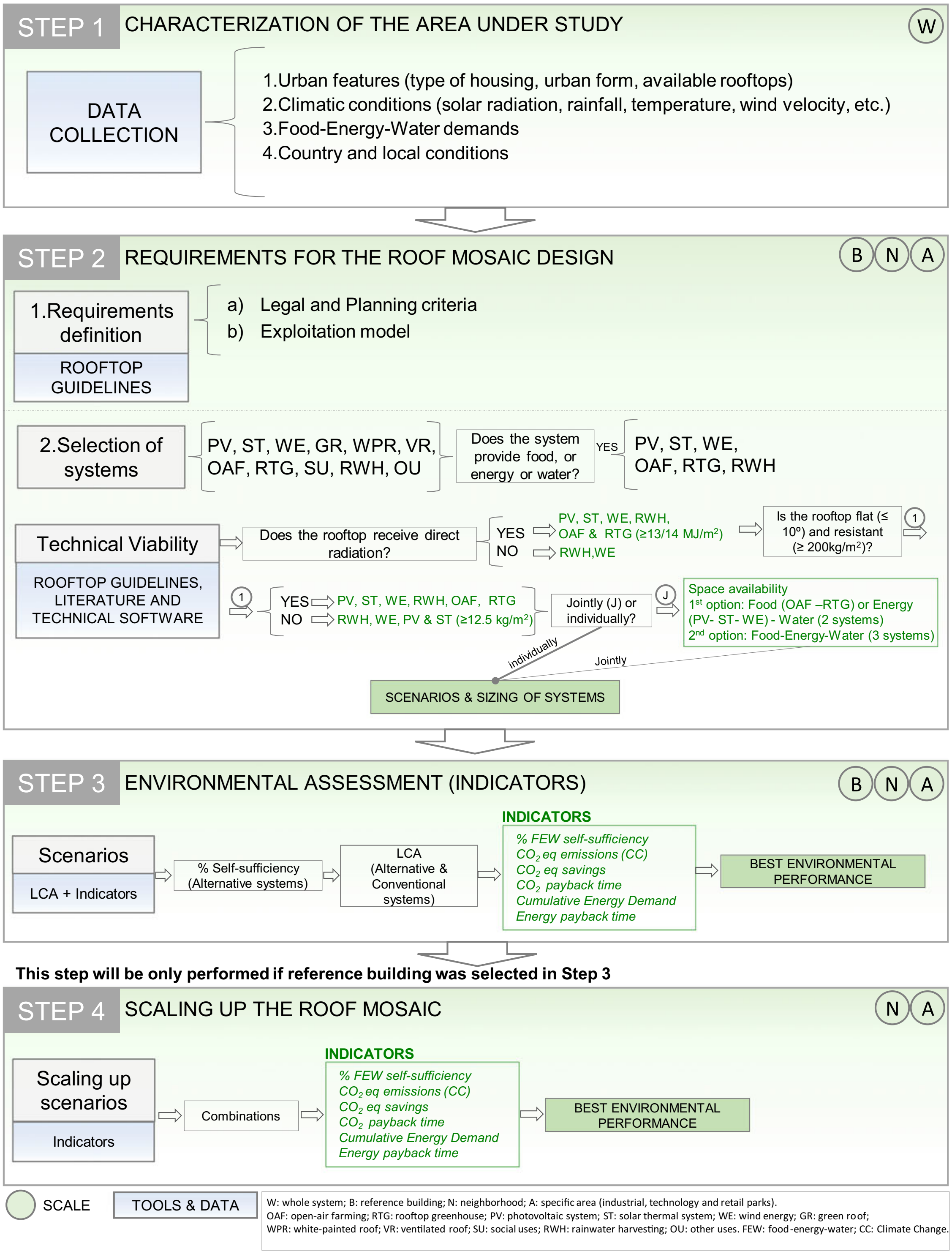

Figure 1 Steps proposed for assessing the Roof Mosaic approach.

3. Daily demand for produce (kilograms [kg]), energy (kilowatt hours [kWh] or megajoules [MJ]) and water (cubic meters [m^3]) to determine the resource quantity required.
4. Country and local social conditions, for example, income per capita, population pyramid, FEW security, and typical food diet. The typical food diet suggests appropriate vegetables/fruits to be grown on rooftops. The income per capita helps to identify target neighborhoods. The rest of the social conditions support the selection of the most suitable system combinations when results yield several possibilities on rooftops.

Step 2: Requirements for the Roof Mosaic Design

This process consists of two parts. The first aims to identify the rooftops that are adequate for implementing FEW systems. To do so, we use two geographically sensitive criteria for rooftop characterization developed by Nadal and colleagues (2017) and Sanyé-Mengual and colleagues (2015a):

1. Legal and planning criteria: Local and regional building laws and building and security codes must be considered to ensure that the new infrastructures meet legal requirements. Rooftop uses and building characteristics are usually defined in urban planning and local ordinances.
2. Exploitation model: Rooftops can be employed for commercial, social, and/or self-sufficiency purposes. The exploitation model depends on the desired activities and their particular regulations in the area.

The second part of this step aims to define and size the combinations of FEW systems based on the previous requirements and additional implementation criteria. The first criterion is to decide between potential FEW-related technologies, that is, open-air farming (OAF) and rooftop greenhouses (RTGs) for food production, wind energy (WE), PV and ST for energy, and RWH for water. The second criterion is the technical viability (see table A.1 in the supporting information on the Web). First, energy systems (except WE) require direct solar radiation, which must be higher than 13 to 14 MJ/square meters (m^2) for agriculture systems (Nadal et al. 2017). Second, if the roof is flat (surface slope $\leq 10°$) and the load capacity is higher than 200 kg/m^2, all systems can be implemented. In the case of RWH, restrictions may apply if the tank is located on the roof, but it might be more flexible if an underground storage tank is considered (Angrill et al. 2012, 2016). A floating filter and filter media for suspended solids can be provided for possible pollution issues. We assume they are enough for nonpotable water purposes (Petit-Boix et al. 2018).

Food production consists of a variety of farming techniques (i.e., soil-based, hydroponics, or aquaponics) (Santo et al. 2016). PV, ST, and WE systems can be selected based on the technologies available in the market (Paiano 2015; Kalogirou 2004; Cace et al. 2007). Wind turbines can generate rooftop turbulences and aerodynamic noise levels in residential areas (Bond et al. 2013) and can be more suitable for industrial areas. These systems can be used on rooftops individually (e.g., only RWH) or jointly. If these systems are proposed jointly, combining energy and food systems is not advisable in some cases because shadows might reduce their efficiency and productivity. Hence, the three systems combined on one rooftop are mostly recommended for large rooftops, which should be analyzed in each case study. Aerial imagery and geographic information systems can be used to retrieve useful information such as rooftop area, shape, or slope and also to manage information by creating multilayer maps (David and Haselmayr 2012; García-Pérez et al. 2016).

After that, the scenarios are created and each system is sized accordingly.

Step 3: Environmental Assessment of the Different Scenarios and Selection of Indicators

This step can be performed at reference building, neighborhood, or specific area scale. After defining the different scenarios, we need to estimate the degree of self-sufficiency. Alternative rooftop systems are expected to meet the demand for FEW to a certain extent, but the features of each configuration can be associated with a complementary input of food, energy, and water coming from conventional production systems (i.e., natural gas, electricity, and water networks and conventional agriculture). These flows of conventional production should be considered in the assessment by defining an appropriate functional unit.

The environmental performance of each scenario can be studied through life cycle assessment (LCA) in compliance with International Organization for Standardization (ISO) 14040–44 (ISO 2006). In this case, based on work by Steinmann and colleagues (2016), only eight impact categories were analyzed, that is, climate change (CC; kg CO_2 eq), ozone depletion (OD; kg trichlorofluoromethane eq), terrestrial acidification (TA; kg sulfur dioxide eq) freshwater eutrophication (FE; kg phosphorus eq), terrestrial ecotoxicity (TET; kg 1,4 dichlorobenzene eq), marine ecotoxicity (MET, kg 1,4-DB eq), agricultural land occupation (ALO; $m^2 \times$ year), urban land occupation (ULO, $m^2 \times$ year), along with the cumulative energy demand (CED; MJ) (Hischier et al. 2010). The LCA includes alternative and conventional systems or only alternative systems if the self-sufficiency is 100%.

To assess both the technical feasibility and environmental implications of the Roof Mosaic, we propose a combination of LCA and field-specific indicators (Lamnatou and Chemisana 2017; Petit-Boix et al. 2017). The Roof Mosaic scenario with the best environmental performance will be the one displaying a larger number of outperforming indicators when compared to the other scenarios, always with the same functional unit. The nine indicators considered are CC, CED, avoided kg CO_2 eq/year per inhabitant (CC_A, equation (1); Alsema [2000]), CO_2 eq payback time (CPBT, equation (1); Alsema and Phylipsen [1995]), energy payback time (EPBT, equation (2); Sumper et al. [2011]) and FEW self-sufficiency percentages. The CPBT is the time period required for a system to avoid the production of the same amount of CO_2 generated to produce the system itself, and the EPBT is defined as the period required for the energy system to produce the same amount of energy that was utilized for all these life cycle stages. All indicators are equally weighted.

$$CPBT = \frac{CC_P + CC_T + CC_I}{\frac{CC_A}{year} - \frac{CC_{UM}}{year}} \quad where$$

$$\frac{CC_A}{year} = Yield_f \times \frac{CC_f}{U_f} \tag{1}$$

$$EPBT = \frac{CED_P + CED_T + CED_I}{\frac{E_G}{year} - \frac{CED_{UM}}{year}} \tag{2}$$

where CPBT indicates CO_2 eq payback time (years); EPBT, energy payback time (years); CC, climate change (life cycle kg of CO_2 eq); CED, cumulative energy demand (MJ); E, energy (MJ); P, production; T, transport; I, installation; A, avoided emissions; UM, use and maintenance; G, energy generation; f, resource flow (i.e., food, energy, or water flows); Yield, kg of produce, kWh and MJ of energy, or m^3 of water supplied by alternative systems; and U, unit of product.

Step 4: Implementation of the Roof Mosaic Approach in Neighborhoods When a Reference Building Is Selected

This last step will be performed only if a reference building was selected in step 3. Here, we seek to upscale the reference building scenarios proposed in step 3 to create neighborhood designs through the Roof Mosaic approach. To prioritize these upscaled designs, we considered (1) the proportion of each FEW configuration in the building, looking for combinations with a balanced degree of resource self-sufficiency (equation (4)); and (2) their environmental performance based on the environmental indicators defined in step 3 (equation (3)).

$$IN = \frac{\sum_{s=1}^{n} (EI_s \times B_s)}{TB} \tag{3}$$

$$SSN_f = \frac{\sum_{s=1}^{n} (Yield_{f,s} \times B_s)}{D_{f,B} \times B_N} \tag{4}$$

where IN is the average indicator of the neighborhood per inhabitant; EI, environmental impact indicator; B, number of buildings; TB, total number of buildings; SSN, self-sufficiency indicator of the neighborhood; f, resource flow (i.e., food, energy, or water flows); N, neighborhood; and D, demand for flow f.

All the combinations are compared based on the nine indicators, and the one that displays a larger number of outperforming indicators, that is, those with the lowest environmental impact, will be the best option. Again, all indicators are equally weighted.

Application to a Case Study

Step 1: Characterization of the Area under Study

We tested the Roof Mosaic approach in Barcelona. In particular, we chose the Montbau neighborhood, which is representative of the European mass social housing built between the 1950s and 1970s (Rieradevall i Pons 2014). It comprises four building typologies. We focused on one rooftop type, defining a reference building hosting 981 residents in 396 dwelling units of 9 identical buildings (Camarero 2013). The reference rooftop layout was determined based on the features of typical building units in the neighborhood with an area of 684 m^2. In terms of resources, the neighborhood is connected to the conventional water, electricity, and gas networks. For this study, we chose tomatoes as the main crop because they are one of the most consumed vegetables in Catalonia (Generalitat de Catalunya 2015) (see further information of the neighborhood in figures A.2, A.3, and A.4 in the supporting information on the Web).

Step 2: The Roof Mosaic Design

The legal and planning criteria vary depending on the system. Food production is not restricted, as long as the harvests are used for self-sufficiency, which is the goal of the Roof Mosaic in this study. Agriculture for commercial purposes is not permitted in Barcelona because the territory is classified as urban land (Metropolitan area of Barcelona 2018). RTGs cannot be built on some rooftops of Barcelona because of height/volume restrictions, so allowances are determined on a case-by-case basis by local technicians (Ajuntament de Barcelona 2018a). No constraints are associated with housing ST, PV, and RWH systems on rooftops. In fact, the Spanish Technical Building Code sets mandatory minimums for electricity and sanitary hot water self-sufficiency in new buildings that exceed a built area of 5,000 m^2 (Spanish Government 2007) and requires also a separate RWH system (Spanish Government 2017).

The roof is a typical vented flat roof ($\leq 10°$ surface slope) with live loads greater than 200 kg/m^2. The solar radiation is suitable for all systems because it is higher than 13 to 14 MJ/m^2/day (Nadal et al. 2017). The features of the rooftop enable the application of any FEW systems. Our design assigned 550 m^2 to energy or food production and the rest of the surface to house the water tank due to the L-shape of the building (see the layout in figures 3 and A.4 and A.5 in the supporting information on the Web). Furthermore, the total surface of the rooftop was used to harvest water. Food production included OAF and RTGs. In the case of energy, PV and ST were assessed separately to evaluate the supply of electricity and hot water, respectively. WE systems were not assessed because wind turbines can cause rooftop disturbances and additional problems for the residents. As a result, we proposed four pairwise scenarios in the same rooftop complemented with conventional supply to meet the resource demand within the same functional unit. The multifunctional rooftops are:

- Scenario 1 (S.F1): RWH + OAF (+ conventional systems)
- Scenario 2 (S.F2): RWH + RTG (+ conventional systems)
- Scenario 3 (S.E1): RWH + PV (+ conventional systems)
- Scenario 4 (S.E2): RWH + ST (+ conventional systems)

For food systems, we considered only one tomato production cycle per year in spring-summer. We applied hydroponics to limit rooftop loads (80–100 kg/m^2) (Nadal et al. 2017). We considered a yield of 10 and 15.3 kg/m^2 in OAF and RTG, respectively (Sanjuan-Delmás et al. 2018; Martínez-Blanco et al. 2009). The technologies used for PV and ST systems were the most commonly applied, that is, multicrystalline silicon (multi-Si) modules (Paiano 2015) and thermosyphon ST systems (Kalogirou 2009). The PV and ST outputs were 42,150 kWh/year and 384,102 MJ/year over 10 years, respectively. After this period, an efficiency reduction of 0.7% per year is assumed for PV systems (Fthenakis et al. 2011). To size the tank, we used the rainfall series from 1996 to 2015 from the nearest weather station to Montbau. Water demand was calculated using the average demand for laundry in a European household

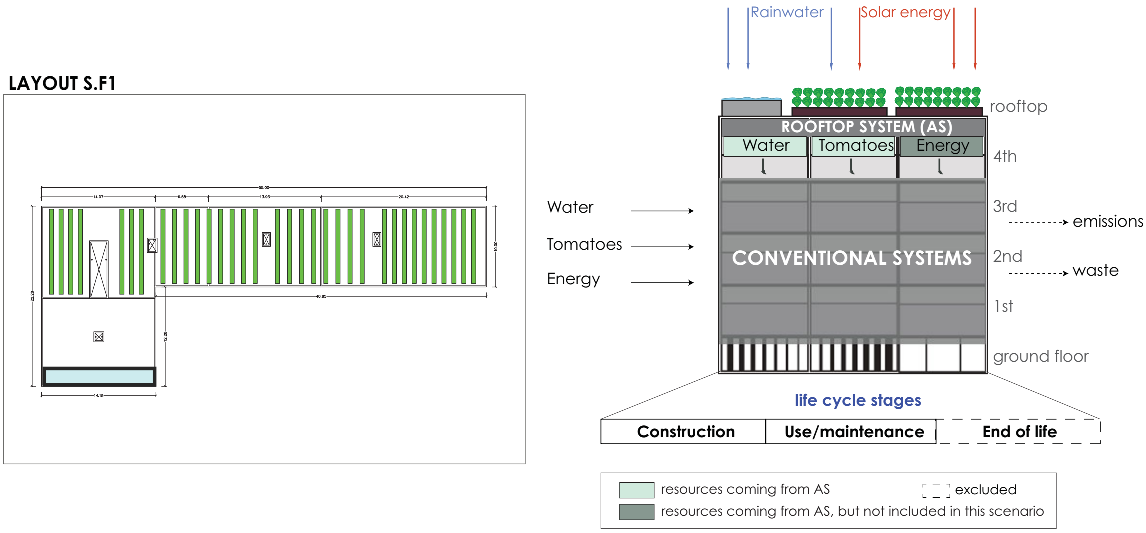

Figure 2 Layout (left-hand side) and diagram (right-hand side) of the system represented by S.F1 where water and tomatoes come from rooftop system (AS = alternative systems). Energy (electricity and hot water) comes from conventional systems in this scenario. The rest of the scenarios are available in figure A.5 and A.6 in the supporting information on the Web.

Table 1 The eight different combinations proposed in the neighborhood

Neighborhood scale	*C.1*	*C.2*	*C.3*	*C.4*	*C.5*	*C.6*	*C.7*	*C.8*
Scenarios (reference building)	*Number of buildings*							
S.F1 (RWH + OAF)	3	0	2	2	1	2	3	2
S.F2 (RWH + RTG)	0	3	2	2	2	1	2	3
S.E1 (RWH + PV)	3	3	3	2	3	3	2	2
S.E2 (RWH + ST)	3	3	2	3	3	3	2	2

Note: Combinations (C) of systems (food, energy, water); S: Scenario. Every column shows the number of rooftops using every scenario. RWH = rainwater harvesting; OAF = open-air farming; RTG = rooftop greenhouse; PV = photovoltaic; ST = solar thermal.

(40 L/household/day) (Comission Regulation [EU] 2010) and the average dwelling occupation in Montbau (2.4 inhabitants/household) (Ajuntament de Barcelona 2017). RWH also supplied rainwater to the crops, accounting for 2.59 and 2.18 L/m^2/day in OAF and RTGs (Sanyé-Mengual 2015; Sanyé-Mengual et al. 2015b). Using Plugrisost software (Morales-Pinzón et al. 2015), we obtained a 7-m^3 tank (see technical data in the supporting information on the Web).

Step 3: Environmental Assessment of Implementing the Roof Mosaic Approach in the Reference Building

Goal and Scope

The functional unit was to meet the annual FEW demands of an average resident of Montbau. This translates into the supply of tomatoes (17.4 kg/year), electricity (1334 kWh/year), sanitary hot water (2398 MJ/year), and water for laundry and irrigation (6.1–6.5 m^3/year) through alternative systems complemented with the supply of conventional systems (i.e., imported food, and energy and water networks). We assumed a life span of 30 years. The system boundaries (figure 2) include construction (i.e., production of materials, transport to site, and installation) and use/maintenance, whereas the end of life was excluded due to the long life span considered and the corresponding uncertainty in relation to the realistic end-of-life scenarios.

Moreover, other parts of the building structure or distribution systems used to connect the buildings were not considered in the calculation of the environmental impacts.

Life Cycle Inventory

To create the inventories for alternative production systems, we used data from the literature based on modeling and experimental case studies located in similar contexts for RWH (Angrill et al. 2012), OAF (Sanyé-Mengual 2015), RTGs (Sanyé-Mengual et al. 2015b), and ST and PV systems (Frischknecht et al. 2015; Carnevale et al. 2014). Data were completed with the ecoinvent 3 database (Weidema et al. 2013) and real case studies on PV in the Autonomous University of Barcelona. All data for conventional systems were retrieved from ecoinvent (see inventories in tables A.5 to A.9 in the supporting information on the Web).

Life Cycle Impact Assessment and Indicators

The life cycle impact assessmet (LCIA) was performed using Simapro 8.1.4 (PRé Consultants 2017) and the ReCiPe (H) method (Goedkoop et al. 2013). The nine indicators described in step 3 were selected and the remaining LCA indicators are provided in the supporting information.

Step 4: Implementation of the Roof Mosaic Approach in Montbau

We assessed eight different combinations (C.1–C.8) of the reference building scenarios S.F1 to S.E2 within the neighborhood following the purpose of the Roof Mosaic, which is to seek a balance in providing FEW to the neighborhood at the minimum environmental cost. Following these premises, the most accurate options were chosen (table 1). Potential additional combinations were rejected due to unbalanced proportions among the three FEW systems.

The same nine indicators of step 3 were proposed and compared among these combinations.

Results

Environmental Burdens of the FEW at the Reference Building Scale

Environmental Impacts and Self-Sufficiency of the Four Proposed Scenarios

Figures 3 and A.7 in the supporting information on the Web compile the environmental impacts of the building-scale scenarios, including all analyzed life cycle stages of alternative systems complemented with conventional systems. In general, combining food systems with RWH (S.F1 and S.F2) was the most environmentally sound option when compared to energy systems with RWH (S.E1 and S.E2). This trend is true for all midpoints except for ionizing radiation, where S.E1 had the lowest impact. Food systems scored between 10% and 90% better than energy systems. Among farming techniques, OAF seemed to be the best alternative for all impact categories, except for agricultural land occupation, as RTGs had a larger yield.

Nevertheless, these results depend on the degree of self-sufficiency of each scenario (table 2) or, in other words, on the contribution of conventional supply systems to the environmental scores of each configuration. Food production reached high self-sufficiency (S.F1 = 52% and S.F2 = 69%), and the impacts of food production were much lower in alternative than in conventional systems in all categories; this is because fewer and more environmentally friendly materials were used. The alternative energy systems in S.E1 had greater impacts (55%–93%) than conventional systems did in six of the nine categories. S.E2 had similar results, except for OD (ozone depletion) and ALO (agricultural land occupation), where the percentage was higher than and equal to that of conventional systems, respectively. However, the difference in self-sufficiency between energy systems was remarkable (S.E1 = 30% and S.E2 = 100%), mainly because of the higher efficiency of ST collectors compared to PV panels. In addition to this difference, alternative energy supply systems require large amounts of impactful materials for their construction (S.E1 = 34.8 kg/m^2 and S.E2 = 29.4 kg/m^2), such as metals, chemical products, and energy, which generate negative effects in these categories.

Likewise, when disaggregating the life cycle impact of alternative systems, the largest contribution to all of the impact categories came from the production of materials, which ranged from 55% to 100% among categories (see figure A.8 in the supporting information on the Web).

Avoided Carbon Dioxide Equivalent Emissions and Carbon Dioxide and Energy Payback Times

Table 3 illustrates the avoided kg CO_2 eq/year per inhabitant and CPBT and EPBT of alternative systems. Food systems were environmentally better and had slightly higher self-sufficiency than S.E1 but lower than S.E2 (100%), whereas the avoided kg CO_2 eq were much higher in energy systems, which would avoid approximately 10 times more CO_2 eq emissions than food systems. This results from the high quantities of CO_2 eq generated in the conventional electricity and natural gas networks. PV systems save the greatest amount of CO_2 eq emissions (0.49 kg/kWh). However, they are penalized by their lower self-sufficiency (30%) in comparison with ST systems (0.26 kg/kWh).

On the other hand, the CPBT results (table 3) were the lowest for food systems in S.F1. On the contrary, S.F2 had the highest payback time, 3.39 years, because of the higher emissions caused by the greenhouse infrastructure. Regarding energy systems, S.E2 obtained the highest CPBT (2.94 years), while S.E1 was slightly lower.

EPBT was calculated only for scenarios with alternative energy supply (table 3). For the production of energy, both the electrical and thermal outputs were converted into primary energy values based on the efficiency of energy conversion at the demand side in Spain (Dones et al. 2007). ST systems had an EPBT of 0.66 years, while PV systems triplicated the payback time. Thus, the high energy consumption of Si-based modules was confirmed (Carnevale et al. 2014), which was the most relevant aspect of their life cycle along with the material consumption. These results could be compared with existing literature. However, this indicator depends on different factors, such as module type, primary energy conversion, or location (solar radiation) (Peng et al. 2013). Hence, different results can be found, from less than 0.5 to 1.2 years for ST systems and from 1.5 to 4.9 years for PV systems (Ardente et al. 2005; Hang et al. 2012; Alsema 2000); our results are within these ranges.

The results will be different depending on the FEW networks existing in each country. For example, in Mediterranean areas for the reference year 2014, the avoided CO_2 eq emissions from electricity fluctuate between 46 and 435 kg CO_2 eq/inhabitant/year, based on the country's electricity mix. Similarly, if we assume that all the tomatoes consumed in Barcelona come from Almeria (Spain) (Sanyé-Mengual et al. 2013), which is commonly the case, the avoided CO_2 eq emissions would be reduced to 4.4 and 6.1 kg CO_2 eq/inhabitant/year for S.F1 and S.F2, respectively. Hence, the amount of the emissions avoided will depend on where the produce originated.

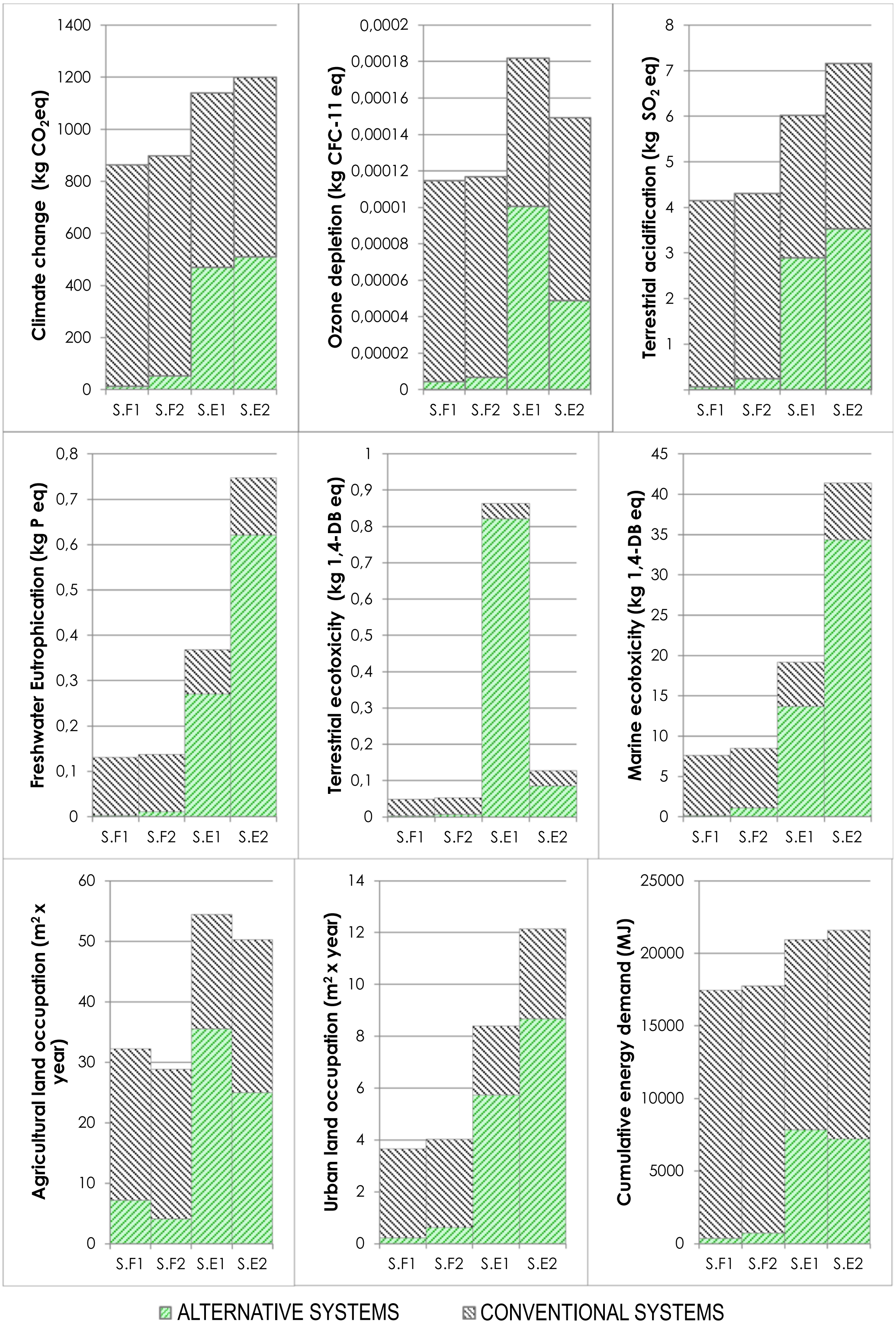

Figure 3 Environmental impacts of the four scenarios of alternative production on the rooftop and the required conventional systems to meet the total demand.

Implementation of the Roof Mosaic Approach at the Neighborhood Scale

This section focuses on the different options proposed at the neighborhood scale, using the same functional unit that was used for the reference building scale. Figure 4 displays the different combinations and an array of indicators that were obtained using this approach (step 4, table 1). At this scale, any hot water surplus (51%) could be distributed among buildings.

Table 2 Self-sufficiency of each scenario at reference building scale

		Supply							
		Rooftop systems				*Conventional systems*			
Flow	*Demand*	*S.F1*	*S.F2*	*S.E1*	*S.E2*	*S.F1*	*S.F2*	*S.E1*	*S.E2*
Water (laundry + irrigation) (m^3/inhabitant/year)	6.1–6.5*	21%	22%	24%	24%	79%	78%	76%	76%
Food (tomatoes) (kg/inhabitant/year)	17.4	52%	69%	0%	0%	48%	31%	100%	100%
Electricity (kWh/inhabitant/year)	1334	0%	0%	30%	0%	100%	100%	70%	100%
Natural gas (sanitary hot water) (MJ/inhabitant/year)	2398	0%	0%	0%	100%	100%	100%	100%	0%

*Range.
kg = kilograms; kWh = kilowatt hours; m^3 = cubic meters; MJ = megajoules.

Table 3 Avoided kg CO_2 eq/inhabitant/year, the CPBT and the EPBT using alternative systems

	Avoided kg CO_2 eq/inh/year (CC_A)				*CPBT (years)*				*EPBT (years)*			
Flow	*S.F1*	*S.F2*	*S.E1*	*S.E2*	*S.F1*	*S.F2*	*S.E1*	*S.E2*	*S.F1*	*S.F2*	*S.E1*	*S.E2*
Water (laundry + irrigation)	0.44	0.45	0.46	0.46	1.77	1.77	1.77	1.77	NA	NA	NA	NA
Food (tomatoes)	13.5	18.1	0	0	0.91	3.39	–	–	NA	NA	NA	NA
Electricity	0	0	195.5	0	–	–	2.40	–	–	–	1.80	–
Natural gas (sanitary hot water)	0	0	0	176.1	–	–	–	2.94	–	–	–	0.66

CC_A = avoided kg CO_2 eq/year per inhabitant; CPBT = CO_2 eq payback time; CO_2 eq = carbon dioxide equivalent; EPBT = energy payback time; inh = inhabitant; kg = kilograms; NA = not available; - = the flow (food or/and energy) is not in this scenario.

		Indicators								
		Self-sufficiency								
COMBINATIONS		W (L+I)	F(T)	E	HW	kg CO_2 eq/inh/y (CC)	Avoided kg CO_2 eq/inh/y tons/neighborhood/y (CC_A)	CPBT (years)	CED (MJ/inh)	EPBT (years)
3 systems[a]	C.1	**23%**	17%	**10%**	**50%**	331	159 (156)	**1.76**	5134	1.23
	C.2	**23%**	23%	**10%**	**50%**	345	**160 (157)**	2.17	5256	1.23
	C.3	**23%**	27%	**10%**	34%	285	132 (129)	1.98	4452	1.34
	C.4	**23%**	27%	7%	**50%**	289	139 (136)	1.95	4383	**1.11**
	C.5	**23%**	21%	**10%**	**50%**	340	**160 (157)**	2.03	5216	1.23
	C.6	**23%**	19%	**10%**	**50%**	336	159 (156)	1.90	5175	1.23
	C.7	**23%**	33%	7%	34%	**234**	111 (109)	1.90	**3169**	1.23
	C.8	**23%**	**35%**	7%	34%	238	112 (110)	2.03	3660	1.23

[a] *3 SYSTEMS*: (C.1: RWH+ 3 OAF+ 3 PV + 3 ST) / (C.2: RWH + 3 RTG+ 3 PV+ 3 ST) / (C.3: RWH + 2 OAF + 2 RTG+ 3 PV + 2 ST) / (C.4: RWH + 2 OAF+ 2 RTG+ 2 PV + 3 ST) / (C.5: RWH + 1 OAF + 2 RTG+ 3 PV + 3 ST)/ (C.6: RWH + 2 OAF + 1 RTG+ 3 PV + 3 ST) / (C.7: RWH + 3 OAF + 2 RTG+ 2 PV + 2 ST) / (C.8: RWH + 2 OAF + 3 RTG+ 2 PV + 2 ST)

C: combination; W (L+I) water (laundry + irrigation); F (T): food (tomatoes); E: electricity; HW: hot water; CC: climate change; CPBT: CO_2 payback time; CED: cumulative energy demand; EPBT: energy payback time; Neighborhood: 981 inhabitants; inh: inhabitant; y: year; RWH: rainwater harvesting; OAF: open-air farming; RTG: rooftop greenhouse; PV: photovoltaics; ST: solar thermal systems.

Figure 4 Analysis of the indicators of eight different combinations proposed at the neighborhood scale. The best environmental performance indicator is in bold, and the darker the green color, the larger the number of outperforming indicators.

The results show that three combinations had equally high numbers of outperforming indicators, scoring four positive indicators out of nine (C.1, C.2, and C.5). They obtained the highest avoided CO_2 eq emissions (159–160 kg CO_2 eq/inhabitant/year) but also had high values of CO_2 eq emissions (CC) in their construction stage (331–345 kg CO_2 eq/inhabitant) because of the high environmental burden of the energy systems. These combinations showed nearly identical levels of self-sufficiency in all the systems, which is especially relevant to hot water.

C.4, C.6, and C.7 each achieved three out of nine positive indicators. C.4 obtained the lowest EPBT because more ST systems than PV systems were assigned to the rooftops. C.6 was similar to C.5 but obtained slightly lower CO_2 eq savings than C.5 did because it had one additional OAF system. C.7 emitted the least CO_2 eq emissions and displayed the least CED in its construction stage, as it had more rooftops with OAF systems and fewer rooftops with energy systems. C.3 and C.8 were the combinations with the fewest favorable environmental indicators, primarily because of the moderate values achieved for most of the indicators.

The combinations with a greater number of food systems on their rooftops had a larger number of positive indicators for food self-sufficiency, CO_2 eq emissions, and CED but were less favorable in terms of energy self-sufficiency and CO_2 eq savings. Conversely, the combinations with a larger share of energy systems showed greater annual CO_2 eq savings in their use phase and higher energy self-sufficiency, while they emitted approximately 40% more CO_2 eq in their construction phase than the combinations with more food systems did.

Discussion

Demonstrating the Roof Mosaic Approach

Based on the findings, combining different scenarios in a neighborhood results in lower self-sufficiency for each system than when assessing each scenario individually at the building scale. Nonetheless, FEW resources can be supplied to a certain extent at the neighborhood scale, partially fulfilling all needs, whereas only two types of resources can simultaneously be provided at the building scale (water and food or water and one type of energy). At the neighborhood scale, the FEW systems can be shared among all the buildings, by redistributing surpluses from one building to the others. In our case study, ST systems have a surplus of hot water (51%) that is lost at the building scale but is redistributed at the neighborhood scale when the ST systems and buildings are connected with adequate infrastructure.

On the other hand, combining different FEW systems on the same rooftop generates synergy. In our case study, for instance, rainwater could be used for irrigating crops, and electricity could be used by any device needed for rainwater distribution. If only a single system is accommodated, no synergy is possible. Furthermore, the economic impact could be lower if more than one resource is obtained from the same rooftop area. Urban challenges are often addressed in an isolated way, while an integrated assessment (e.g., FEW nexus) is recommended for managing global resource systems (FAO 2014). A similar approach is desired in LCA studies, as urban issues often tend to be addressed separately, even though, in reality, they affect one another (Petit-Boix et al. 2017). In this context, Barcelona, Rotterdam, Oslo, and other cities propose multifunctional rooftops to tackle climate change and socioenvironmental issues (Ajuntament de Barcelona 2018b; Gemeente Rotterdam 2015; Oslo Kommune 2011). In parallel, research has been proposed for urban energy systems at neighborhood and district scales (Werner 2017; Letellier-Duchesne et al. 2018). Therefore, connectivity at the neighborhood scale has strong potential to contribute to the urban circular economy. In fact, environmental studies dealing with the circular economy in cities need to analyze in more detail the implementation of new strategies that involve urban planning (Petit-Boix and Leipold 2018). Given that cities are increasingly promoting these types of local initiatives, our study is a first step towards understanding their environmental effects in more detail and providing evidence-based recommendations for their implementation.

The Potentiality of the Roof Mosaic Approach

The Roof Mosaic approach delivers an environmentally focused method of systems analysis that can be used at multiple scales. This guide can be used to analyze the Roof Mosaic in a wide variety of cities. Currently, approximately 10% of residents of Western European cities and 40% of residents in cities in post-socialist countries live in mass social housing (Van Kempen et al. 2005). Currently, this approach is best scaled to a delimited space in a dense city with a limited number of buildings (e.g., neighborhoods, small towns, and industrial/technology parks). In this case study, only one typology of rooftop was proposed, but rooftops are often very diverse; thus, some will be more appropriate for food systems and others for energy and/or water. Similarly, this approach can be equally useful for a heterogeneous neighborhood with different types of rooftops. For example, flat roofs can be used for food production, tower blocks for wind turbines, and pitched roofs for solar panels.

The indicators we analyzed are a representative number of parameters that are at the core of the Roof Mosaic; these include CO_2 eq emissions and savings, energy consumption and payback times, and resource self-sufficiency. We can also incorporate demographic and social conditions (e.g., population pyramid and income) or include a multicriteria decision-making method to select the most suitable combination when several options are plausible. Other indicators can be added such as land use (Benis et al. 2018), ecosystem services (e.g., biodiversity and stormwater runoff), economic investment, and social benefits (e.g., social inclusion and employment creation) that have to be weighed along with their environmental implications to obtain a more holistic picture of sustainability.

On the other hand, we can encounter different logistical hurdles if these systems are implemented at the neighborhood scale, such as the construction of new infrastructure to connect the systems between buildings, or organizational issues among neighbors, building managers, and so on. Urban planning constraints can also be found in some cities. Zoning codes can impose some activity restrictions, such as prohibition of commercial uses or height limitations on buildings. However, the Roof Mosaic could help to overcome these constraints by identifying the most suitable scenarios from the wide range of possibilities that this approach has to offer.

Conclusion

The proposed approach aimed to evaluate the implementation of FEW resources on rooftops and to develop an analytical guide to examine the technical feasibility and environmental implications of the Roof Mosaic approach in cities. This new approach offers a basic guideline to address the complexity of the FEW nexus and determine options that house different FEW resources on rooftops at the lowest environmental cost. The analysis can be applied at different scales (i.e., building, neighborhood) and in different contexts and types of buildings. Furthermore, the approach could also assist in decision-making processes; for instance, it could be combined with other tools focused on inclusivity and urban poverty to increase equity in planning efforts, which are part of the key objectives of the European Union's urban agenda (PBL Netherlands Environmental Assessment Agency 2016).

The Roof Mosaic approach includes different legal, planning, exploitation, technical, and environmental criteria. Possible constraints can be found in legal and planning criteria depending on the FEW system and their exploitation purpose, such as nonallowed agricultural activities. Technical restrictions can also be found in the technical features of rooftops due to low load capacities or steep slopes, but energy production and RWH could still be applied. In this sense, the Roof Mosaic approach provides different system combinations where the possibilities are multiple and adaptable to almost any kind of rooftop and building.

Testing this approach on mass social housing in a compact Mediterranean area has paved the way for its application in cities. If the purpose is to fulfill the demand for three resources (FEW nexus) by seeking balance among them, the proposed combinations at the neighborhood scale would be the most suitable options, ranging from 7% to 50% resource self-sufficiency. The combinations with larger CO_2 eq savings (156–157 tons/neighborhood/year) showed higher self-sufficiency in electricity and hot water, whereas the combinations with lower environmental impacts (230–233 tons CO_2 eq/neighborhood/year) displayed higher self-sufficiency in food systems.

This first approach should be further developed from the Roof Mosaic perspective, considering not only environmental indicators but also economic and social indicators to carry out a complete life cycle sustainability assessment. In addition, the FEW networks needed for the system connectivity at neighborhood scale must also be addressed to have a global picture of this new urban planning proposal.

Studying the Roof Mosaic approach in different geographic areas and urban models would be advisable to demonstrate its viability in other contexts. Other systems can be tested to this approach such as green roofs and wind energy. This and further adaptations of the Roof Mosaic approach have a large potential to guide cities towards a sustainable circular economy.

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Supporting Information

Supporting information is linked to this article on the *JIE* website:

Supporting Information S1: This supporting information provides details of data referred to in the article, divided into the sections of Introduction, Materials & Methods, and Results. It also provides the life cycle inventory of all the systems, the environmental impacts of all impact categories and the environmental burdens of the life cycle stages of each scenario.