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Susana Toboso-Chavero^{1,2} , Cristina Madrid-López¹ , Xavier Gabarrell Durany^{1,2} and Gara Villalba^{1,2,*}

¹ Sostenipra Research Group (2017 SGR 1683), Institute of Environmental Science and Technology (ICTA; «María de Maeztu» Units of Excellence (CEX2019-000940-M)), Z Building, Universitat Autònoma de Barcelona (UAB), Campus UAB, 08193 Bellaterra, Barcelona, Spain

² Department of Chemical, Biological and Environmental Engineering, Universitat Autònoma de Barcelona (UAB), Campus UAB, 08193 Bellaterra, Barcelona, Spain

* Author to whom any correspondence should be addressed.

E-mail: Susana.Toboso@uab.cat, Cristina.Madrid@uab.cat, Xavier.Gabarrell@uab.cat and Gara.Villalba@uab.cat

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Abstract

With the overall aim to design successful implementation strategies of food-energy-water production systems on urban roofs, we propose an integrated process that includes participatory processes and a multi-dimensional sustainability assessment of environmental, social and economic indicators. The proposed framework was applied to a typical housing estate in the Metropolitan Area of Barcelona made up of 201 buildings and 13,466 inhabitants and characterized by a high share of low-income families. We assess several future scenarios of joint electricity production (photovoltaic panels), vegetable production (through open-air farming and greenhouses), green roof implementation and rainwater harvesting and rank them according to non-participatory and participatory approaches. In general, there was a tendency for residents to choose strategies providing energy and water rather than the food production potential of rooftops. However, the environmental assessment indicated that the least impacting alternatives from a life cycle approach were those promoting vegetable production, meeting 42 to 56% of the residents' fresh produce demand and reducing environmental impacts by 24 to 37 kg CO₂eq m⁻² of rooftop/year. Hence, we found that residents were mainly concerned with energy expenses and not so much with food insecurity, social cohesion or the impacts of long-distance supply chains. Our assessment supports urban sustainability and helps identify and breach the gap between scientific and user preferences in urban environmental proposals by informing and educating residents through a participatory integrated assessment.

1. Introduction

Cities are implementing a range of climate action programmes to develop resilient and environmentally, socially and economically healthy communities in response to the United Nations' Sustainable Development Goal (SDG) 'sustainable cities and communities' (Rosenzweig *et al* 2010, United Nations 2020). One key to sustainable urban areas, is the sustainable supply of food, energy, and water and the optimization of this supply based on their interconnectedness, normally referred to as the food-energy-water (FEW) nexus (Garcia and You 2016). Metropolises dominate the demand for these flows, although production normally occurs elsewhere, consuming two-thirds of the primary energy demanded (IEA 2015) and up to 70% of the food supply (FAO 2017). Equally relevant is accessibility for vulnerable populations and/or marginalised sites with limited

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financial resources to guarantee equal access and prevent FEW insecurity at the urban scale (Newell and Ramaswami 2020).

An emergent strategy for procuring FEW in cities with limited land availability that covers these premises is the use of rooftops to grow vegetables, produce energy or harvest rainwater, termed the roof mosaic. The roof mosaic tries to intertwine the different flows of these resources (FEW) and seeks synergies and interactions within urban areas, proposing partial self-sufficiency of these resources. We conducted an initial study that analysed the environmental impacts of this strategy's adoption (Toboso-Chavero *et al* 2019) and a second study screened a municipality's metabolic pattern to detect hotspots in FEW resource consumption (Toboso-Chavero *et al* 2021). Nonetheless, to implement this strategy effectively in complex systems such as cities, a more comprehensive and participatory framework has to be established (Kloepfner 2008).

In the roof mosaic framework, a sustainability assessment that integrates complex environmental, social and economic values is crucial to ensure forward-looking sustainability assessment methodologies (Kloepfner 2008, Kühnen and Hahn 2019). Such assessments provide a 'triple bottom line' political background (environmental, social and economic), are proactive and not reactive, are multi-criteria and not single-issue, and are guided by a stakeholder-driven approach, characterised by being complex, multi-scalar, multi-dimensional and multi-disciplinary and focused on finding integrated solutions (Finkbeiner *et al* 2010, Zamagni 2012). As an overall trend, a large number of studies on the use of cities' roofs focus their attention on only one pillar of sustainability, i.e., on the environmental aspects, calculating the environmental impacts and benefits (Cucchiella and Dadamo 2012, Lamnatou and Chemisana 2014, Bazán *et al* 2018, Sanjuan-Delmás *et al* 2018, Salvador *et al* 2019) or on the social aspects, exploring the social perception of the implementation of these systems on roofs (Cerón-Palma *et al* 2012, Specht *et al* 2016, Sanyé-Mengual *et al* 2016, Ercilla-Montserrat *et al* 2019, Zambrano-Prado *et al* 2021). Hence, efforts should be made to expand into a more integrated vision.

In the same way, as pointed out by Newell and Ramaswami (2020), public participation is often omitted in the FEW nexus literature. Following this observation, the adoption of the roof mosaic must consider its human dimensions. Accordingly, 'citizen science', a label increasingly used to define the general public's engagement in research activities (Strasser *et al* 2019) can lead to more democratic and open research and enhance science-society-policy interactions (European Commission 2014). Thus, giving voice to residents results in more effective research for the social acceptance of novel strategies (O'Faircheallaigh 2010). The International Association for Public Participation (IAP2) proposes a spectrum of public participation, with classifications for the lowest levels of participation, i.e., informing, to the highest level, i.e., empowering citizens (International Association of Public Participation 2020). Advances have been made in the integrated sustainability assessment community in this direction but in other contexts (e.g., natural resource management sectors) and using different methodologies (Pahl-Wostl 2002, Pahl-Wostl and Hare 2004, Tábara *et al* 2008, Ripoll-Bosch *et al* 2012, Saltelli and Giampietro 2017).

We performed a participatory integrated sustainability assessment of the implementation of FEW resources on roofs based on a novel combination of participatory processes with different methodologies, such as a Multi-scale Integrated Assessment of Societal and Ecosystem Metabolism (MuSIASEM) (Giampietro *et al* 2014) and a life cycle assessment (LCA). Our study aims to be applicable to urban mitigation strategies, defining the specific indicators to be considered and the methods for the analysis. To do this, we i) codesign with stakeholders, identify and propose a set of indicators to assess the implementation of different roof mosaic scenarios through a coherent, comprehensive and multi-scale methodology and ii) implement participatory processes in which stakeholders are allowed to value climate change adaptation and mitigation strategies that affect their daily life.

2. Materials & methods

The conception of this research is founded on an initial article dedicated to the metabolism of the area under study, the municipality of Badia del Vallès (13,466 inhabitants; density: 14,387 inhabitants km^{-2}), a typical housing estate in the Metropolitan Area of Barcelona (AMB) that faces common environmental, economic and social issues such as energy and water poverty and urban and social degradation (Toboso-Chavero *et al* 2021). The two methodological components that constitute this study are the participatory processes (steps 1, 2 and 6; section 2.1) and the sustainability assessment (steps 4 and 5; section 2.2). The framework used (figure 1) is based on a combination of quantitative and qualitative methodologies with the aim of proposing a comprehensive and participatory assessment for the deployment of a novel strategy: the roof mosaic.

2.1. Participatory processes stages

The participatory processes are split into two stages.

Stage 1: Codesign of scenarios and of assessment indicators. The first participatory process was carried out with residents of the municipality who were over 18 years of age. Participants were invited in December 2018. A

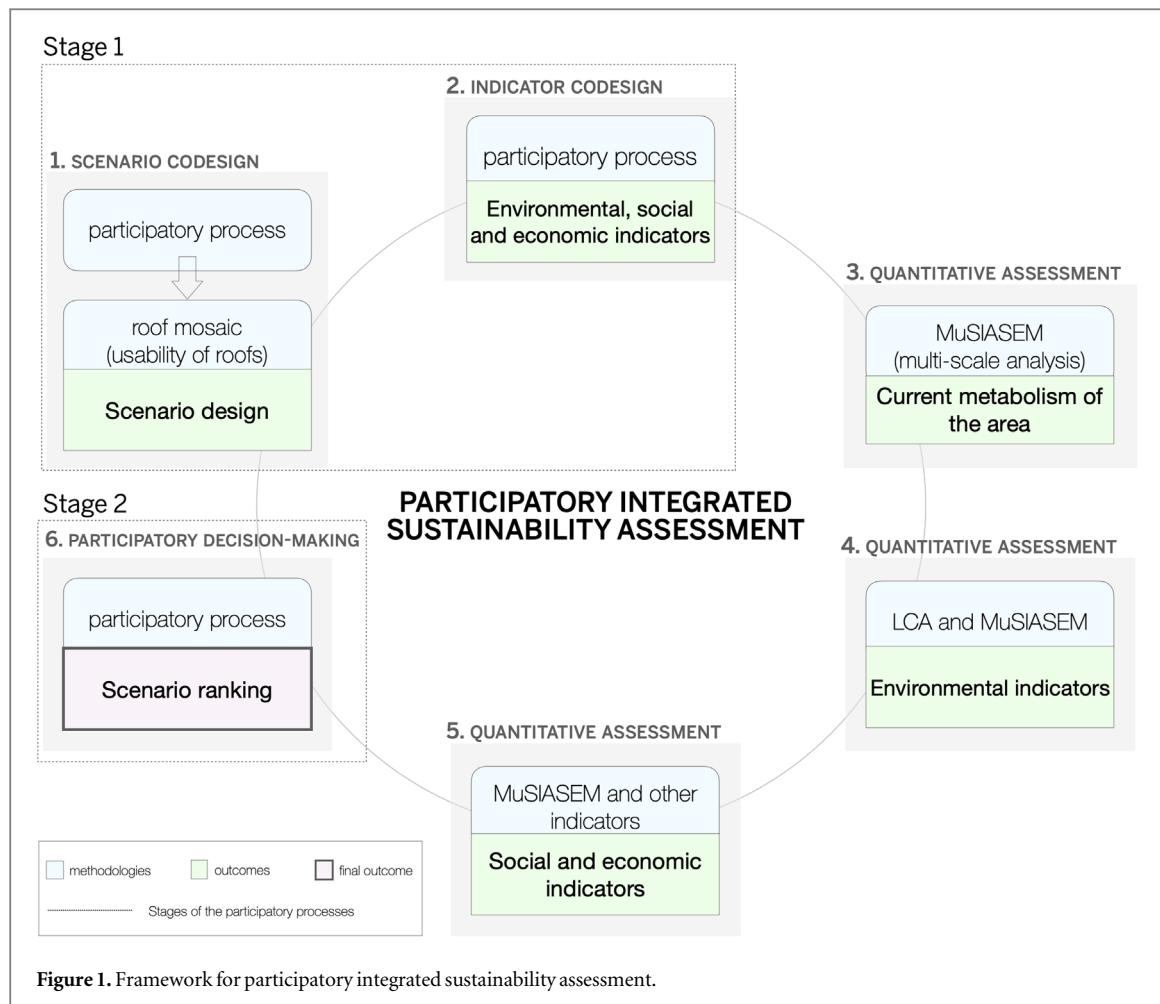


Table 1. Matrix to establish the scores of the different answers related to the concepts retrieved from the participatory process.

SCORE	1	2	3	4	5
Frequency of the concepts	1 to 3	4 to 6	7 to 10	11 to 13	more than 13

workshop of fourteen neighbours (29% women, 71% men) was conducted with no preselection of participants based on the World Café methodology (Brown 2005). This methodology is characterized by a relaxed environment of small groups (4/5 people maximum), with a facilitator that gives agency to the participants, and takes notes of all the conversations on the topic proposed. The workshop aimed to scrutinize the concerns and preferences of neighbours related to their municipality, the application of FEW systems on their roofs and the relevant indicators for them. According to the IAP2, this participatory process is at the ‘collaborative’ level, the second highest position within the spectrum of public participation. The design protocol for the participatory process is available in the supporting information.

We examined the data based on grounded theory methods (Corbin and Strauss 1990), coded the data, and extracted the key concepts from the answers. Subsequently, we applied content analysis by counting the concept frequencies. They were scored from 1 to 5 depending on the number of responses related to each concept (table 1).

Stage 2: Participatory decision-making. This process was carried out in September 2020 and aided in identifying neighbours’ preferences and comparing the most suitable scenarios obtained from the sustainability assessment. We designed six different posters with this information. One poster displayed the current situation in the municipality as retrieved from a consumption pattern survey carried out by the authors (Toboso-Chavero *et al* 2020), and five posters (see posters in the supporting information) with the five scenarios proposed and with all the indicators (section 2.2). An exhibit of these posters and a short questionnaire were conducted in the

municipality. This questionnaire could be answered online at <https://docs.google.com/forms/d/e/1FAIpQLSepoPptehmltBNNHRT0ShSGGCetksv31ssXcE2ub5AciqlkUQ/viewform> or in hard copy. The questionnaire asked for gender, age, and type of stakeholder and then asked for the most suitable scenario for the municipality and also a ranking from the first position to the last position of the five scenarios. The possibility of not using rooftops for anything was also included. The exhibit lasted for twelve days, and residents were able to vote for their choices within this time. After that, all the responses were gathered, analysed, and compared with those retrieved from the sustainability assessment (see the following protocol in the supporting information).

According to the IAP2, this participatory process is at the ‘involve’ level, the middle position in the spectrum of public participation. Furthermore, it was performed under COVID-19 circumstances (September 2020), where no more than ten people were allowed to meet in the same place and visits to the exhibition were restricted to those with a prior appointment.

2.2. Integrated sustainability assessment

This component includes an array of environmental, social and economic indicators selected in harmony with previous studies (Toboso-Chavero *et al* 2019, 2021) and the residents’ concerns resulting from the participatory process (section 2.1). Table 2 summarizes the different indicators, including the degree of interest that was assessed, including the same scores as in section 2.1. The indicators used for the sustainability assessment were as follows:

2.2.1. Sustainability indicators

These indicators include environmental, social and economic dimensions. Therefore, we included them under the same umbrella and with the same name: sustainability indicators.

The MuSIASEM was employed to calculate four different indicators: self-sufficiency and production of vegetables, electricity and water. The increase in green spaces ($\text{m}^2/\text{inhabitant}$) was chosen as the most commonly used indicator for measuring green infrastructures (Van Herzele and Wiedemann 2003, Taylor *et al* 2011, Kabisch and Haase 2013).

2.2.2. Environmental indicators

The LCA methodology was used for three of the environmental indicators: Global Warming (GW; $\text{kg CO}_2\text{eq m}^{-2}/\text{year}$), Global Warming of the conventional networks for CO_2 savings ($\text{kg CO}_2\text{eq m}^{-2}/\text{year}$), and Cumulative Energy Demand (CED; $\text{MJ m}^{-2}/\text{year}$) (Hischier *et al* 2010). These indicators were evaluated in compliance with ISO 14040-44 (ISO 2006) using Simapro 9.0 software with the ReCiPe method at the midpoint level (hierarchical perspective) and the Ecoinvent Database 3.5 (Swiss Centre For Life Cycle Inventories 2018). The functional unit is 1 m^2 that supplies different resources, this translates into the supply of electricity ($76 \text{ kWh m}^{-2} \text{ year}^{-1}$), vegetables—tomatoes, lettuces, green beans and peppers—($10.3 \text{ kg m}^{-2} \text{ year}^{-1}$ for open-air farming (OAF)) (Boneta *et al* 2019) and $14.16 \text{ kg m}^{-2} \text{ year}^{-1}$ for rooftop greenhouses (RTGs) (Rufí-Salís *et al* 2020)), a $1 \text{ m}^2 \text{ year}^{-1}$ green roof (GR) system and $1 \text{ m}^3 \text{ year}^{-1}$ of rainwater harvesting (RWH). The system boundaries include the extraction of raw materials, production, transport and use, and the end-of-life is excluded due to the long life span of the systems, which was assumed to be 30 years. All the inventories of photovoltaic (PV) panels, GR, OAF, RTG, RWH and conventional networks are available in open access (Toboso-Chavero *et al* 2021). They came from experimental data from the Barcelona region and were adapted to this study. Other derived indicators for the LCA were CO_2 payback time (CPBT; years) (Phylipsen and Alsema 1995) and energy payback time (EPBT; years) (Sumper *et al* 2011).

2.2.3. Social indicators

The MuSIASEM methodology was effective for providing different types of social indicators, such as the human activity budget (hours (h)/year) and maintenance investment (h/household/year). Energy and water poverty, i.e., ‘an inability to realise essential capabilities as a direct or indirect result of insufficient access to affordable, reliable and safe energy/water services’ (Day *et al* 2016) are based on the literature as the most commonly used indicators for this topic (Lawrence *et al* 2002, The Green/EFA group of the European Parliament 2016).

2.2.4. Economic indicators

Different indicators, such as investment and maintenance costs, were obtained from companies that work and currently implement these types of systems. The monetary savings were retrieved from public prices (2019) of electricity, water, and vegetables. The payback period was also selected, as it is a relevant indicator in the field (Watson 2004).

Table 2. List of indicators for assessing the different proposed scenarios.

Indicator	Description	Unit	Calculation	Reference	Degree of interest
Sustainability Indicators					
Self-sufficiency	Quantifies the percentage of the self-production on rooftops of the different resources	% (percentage)	(TS/TC)*100	MuSIASEM	4
Increase in green spaces	Considers the total green area (GR, OAF, RTG) in relation to the total population	$\text{m}^2/\text{inhabitant}$	TGS/Tin	Van Herzele and Wiedemann (2003), Taylor <i>et al</i> (2011), Kabisch and Haase (2013)	1
Production of vegetables	Quantifies the quantity of vegetables produced per m^2 of rooftop and year	$\text{kg m}^{-2} \text{year}^{-1}$	TS/TR	MuSIASEM	4
Production of electricity	Quantifies the quantity of electricity produced per m^2 of rooftop and year	$\text{kWh m}^{-2} \text{year}^{-1}$	TS/TR	MuSIASEM	5
Production of water	Quantifies the quantity of water harvested per m^2 of rooftop and year	$\text{L m}^{-2}/\text{year}$	TS/TR	MuSIASEM	4
Environmental Indicators					
CO ₂ savings	Quantifies the annual avoided GHG emissions (Global Warming impact category) related to FEW conventional networks per m^2 of rooftops if the decentralised systems are implemented	$\text{kg CO}_2 \text{eq m}^{-2}/\text{year}$	$\sum_{s=1}^n \text{GWc}$	LCA- Recipe method (H), Goedkoop <i>et al</i> (2013)	4
Global Warming	Quantifies the total GHG emissions of the construction phase of FEW systems (OAF, RTG, GR, PV panels and RWH)	$\text{kg CO}_2 \text{eq m}^{-2}/\text{year}$	$\sum_{s=1}^n \text{GWp}$	LCA- Recipe method (H), Goedkoop <i>et al</i> (2013)	3
CO ₂ payback time (CPBT)	It 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	years	GWp/GWc	LCA- Phylipsen and Alsema (1995)	1
Cumulative Energy Demand (CED)	Represents the direct and indirect energy use throughout the life cycle of the FEW systems (OAF, RTG, GR, PV panels and RWH)	$\text{MJ m}^{-2} \text{year}^{-1}$	$\sum_{s=1}^n \text{CED}$	LCA- Hischier <i>et al</i> (2010)	1
Energy payback time (EPBT)	Considers the time need to compensate the energy produced by the construction of the FEW systems	years	CED/Eg	LCA- Sumper <i>et al</i> (2011)	1
Social Indicators					
Energy poverty coverage	Quantifies de number of households coverage of electricity from decentralised systems	(%; number of households)	TS/Th	The Green/EFA group of the European Parliament (2016)	3
Water poverty coverage	Quantifies de number of households coverage of water from decentralised systems	(%; number of households)	TS/Th	Lawrence <i>et al</i> (2002)	3
Human activity budget (THB)	It is the human time of a given population dedicated to each system (FEW)	total hours/year	—	MuSIASEM- Giampietro <i>et al</i> (2012) // Project data & Distribution companies	4
Maintenance investment	Hours of dedication for each system (OAF, RTG, GR, PV panels and RWH) per household and year	hour/household/year	THB/Th	MuSIASEM // Project data & Distribution companies	4
Economic Indicators					
Monetary savings (MS)	Quantifies the amount of annual money savings for using decentralised systems per household and year	€/household/year	—	Public prices	5
Investment (TI)	The money invest to implement the decentralised systems (OAF, RTG, GR, PV panels and RWH) per m^2	€ m^{-2}	—	Distribution companies	5

Table 2. (Continued.)

Indicator	Description	Unit	Calculation	Reference	Degree of interest
Maintenance cost	Considers the annual maintenance cost of the implementation of decentralised systems per m^2 and year	$\text{€ m}^{-2}/\text{year}$	—	Distribution companies	5
Payback period	It is the time, expressed in years, required to generate sufficient savings to recover the initial capital outlay of the project	years	TI/MS	Watson (2004)	1

TS = Total annual supply; TC = Total annual consumption; TR = Total m^2 of rooftops; TGS = total green spaces; Tin = Total inhabitants; GWc = Global Warming of conventional networks; GWp = Global Warming production phase; CED = Cumulative Energy Demand; Eg = Energy generated; Th = Total households; THB = Total human budget; TI = Total Investment; TMS = Total monetary savings.

Table 3. Outcomes of the first participatory process. Main social perceptions of the residents regarding their municipality and the use of roofs. Score = 1 to 5.

TOPICS	MAIN CONCERN		PREFERENCES ON ROOFS		BARRIERS OF USING ROOFS		OPPORTUNITIES OF USING ROOFS		PREFERENCES ON INDICATORS	
		score		score		score		score		score
Type of Concepts	Urban degradation	1	Social use	0	Significant investment	4	Money savings	5	Energy & water poverty	3
	Financial resources	2	Rainwater harvesting	1	Maintenance	4	Resource savings	5	Monetary savings	5
	Little involvement of the neighbours	4	Energy production	4	Little involvement of the neighbours	4	Self-sufficiency	4	Investment cost	5
	Social degradation	5	Food production	1	Difficult access	1	Sustainability	2	Maintenance cost	5
 Best score (green) Worst score (red)										

Conforming to these indicators, the results present the most viable scenarios considering the objective indicators and residents' concerns and preferences. The quantitative indicators were later compared with the results of the participatory decision-making process of the residents' choices.

3. Results

3.1. Codesign of scenarios and assessment indicators

A set of scenarios and indicators were proposed based on the preferences of participants at our workshop. The concerns of the municipality's residents (table 3) are mainly related to aging, many senior citizens living alone, lack of social cohesion and lack of economic resources. They are also worried about the lack of residents' commitment and limited political involvement in the issues of the municipality.

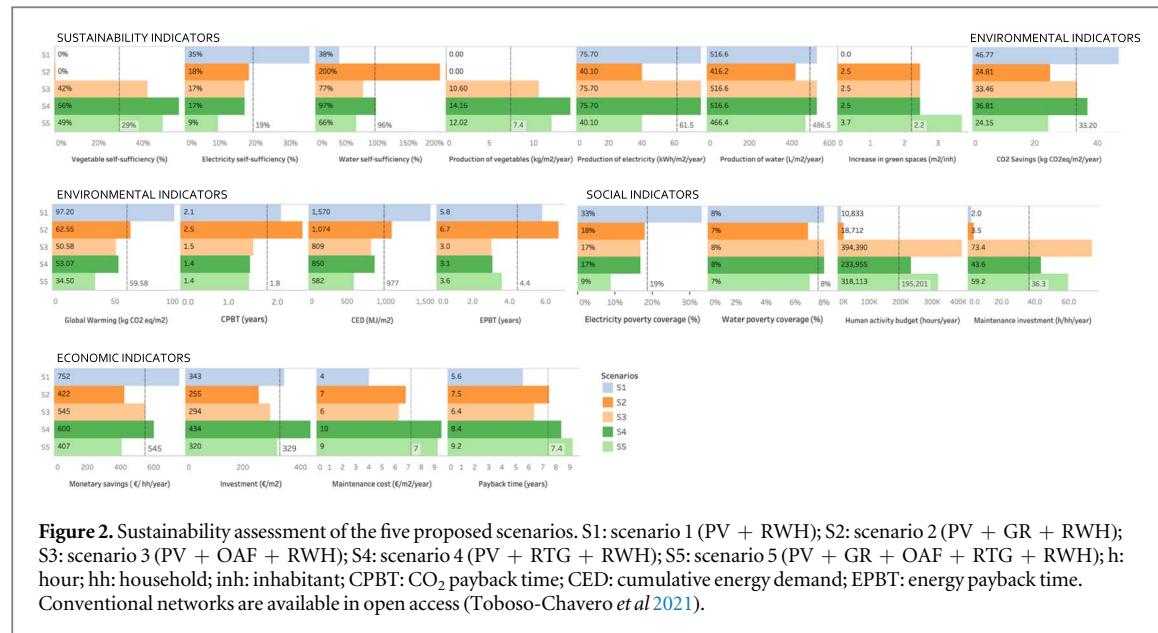
Related to the implementation of these new systems on their roofs, i.e., food and energy production and rainwater harvesting, the neighbours predominantly selected energy production, particularly electricity, due to the high price of this resource, which ranges between 50–80 €/family/month, and then water and vegetables, despite spending an average of 60–80 €/family/month (Toboso-Chavero *et al* 2020). On the one hand, the residents perceive a significant investment as difficult to afford, and on the other hand, they are concerned about the lack of involvement among their neighbours and want to know who will take care of these new systems placed in shared spaces. The participants also see many opportunities in the deployment of these systems, such as money and resource savings and self-sufficiency, empowering them to organise and assure these resources on their own.

The participatory process was fundamental for the proposal of scenarios because many scenarios could be implemented, yet only a limited number are in line with the residents' priorities. Accordingly, five different scenarios were presented (scenario 1 (S1; 100% photovoltaic (PV) panels and rainwater harvesting (RWH), i.e., all the rooftops become equipped with PV panels and set up for RWH), scenario 2 (S2; 50% PV + 50% green roofs (GR), half of the rooftops become equipped with PV and the other half with GR, and RWH is conducted on all the rooftops), scenario 3 (S3; 50% PV + 50% open-air farming (OAF) and RWH), scenario 4 (S4; 50% PV + 50% rooftop greenhouses (RTG) and RWH) and scenario 5 (S5; 25% PV + 25% GR + 25% OAF + 25% RTG + RWH)).

Regarding the indicators, the residents were mainly concerned about the initial costs and maintenance costs, as well as monetary savings. They were also interested in the environmental aspects of the options but in a more generic way and in the production of resources, in principle as a way to save money but also as a means to improve the environment in their municipality.

3.2. Characterising environmental, social and economic dimensions to support decision-making processes regarding scenario sustainability

We evaluated the different scenarios through environmental, social and economic dimensions (figure 2). According to these analyses, scenario 1 obtained the most favourable indicators, attaining the majority of its highest values in the social indicators and the others in electricity self-sufficiency (35%), monetary savings (742



€/household/year) and CO₂ savings (47 kg CO₂eq m⁻²/year). Nevertheless, it also has the most unfavourable indicators because its performance is mainly based on one resource, i.e., electricity. Scenario 4 is the scenario with the second-most positive indicators, particularly in vegetable self-sufficiency (56%; 14.16 kg m⁻² year⁻¹) and having enough rainwater to irrigate all crops. However, its performance is worse in the social and economic categories than that of scenario 1. Scenarios 2, 3 and 5 have fewer beneficial indicators, especially scenario 2, which obtained a substantial number of indicators with poor performance, such as the EPBT (6.7 years) and CPBT (2.5 years).

If we compare the different scenarios according to each indicator's average, we can assert that scenarios 3 and 4 perform considerably better than the other scenarios. These two scenarios provide vegetables—through open-air farming and greenhouses—on half of the roofs, electricity on the other half and enough water to irrigate almost all crops. However, in principle, in the first participatory process, residents indicated that they mainly preferred electricity (section 3.1), and scenario 1 offered more electricity than either of these two scenarios (S3 & S4). Nevertheless, scenario 1 has the second highest investment cost and does not provide vegetables.

Conversely, scenario 2 has the fewest indicators that are above each indicator's average. It is only the best in water self-sufficiency because less irrigation is required for extensive green roofs of sedum and in the initial investment of the systems because fewer materials are necessary. Likewise, scenario 5 has the second fewest favourable indicators. This is because in this scenario, all the systems (PV, GR, OAF, RTG and RWH) are deployed on the municipality's roofs, resulting in lower values for most of the indicators. However, in the environmental categories, this scenario performs excellently, particularly in the increase in green spaces (3.7 m²/inhabitant), decrease in Global Warming (35 kg CO₂eq m⁻²), short CPBT (1.4 years) and low Cumulative Energy Demand (582 MJ m⁻²), which implies that this option is the least environmentally demanding.

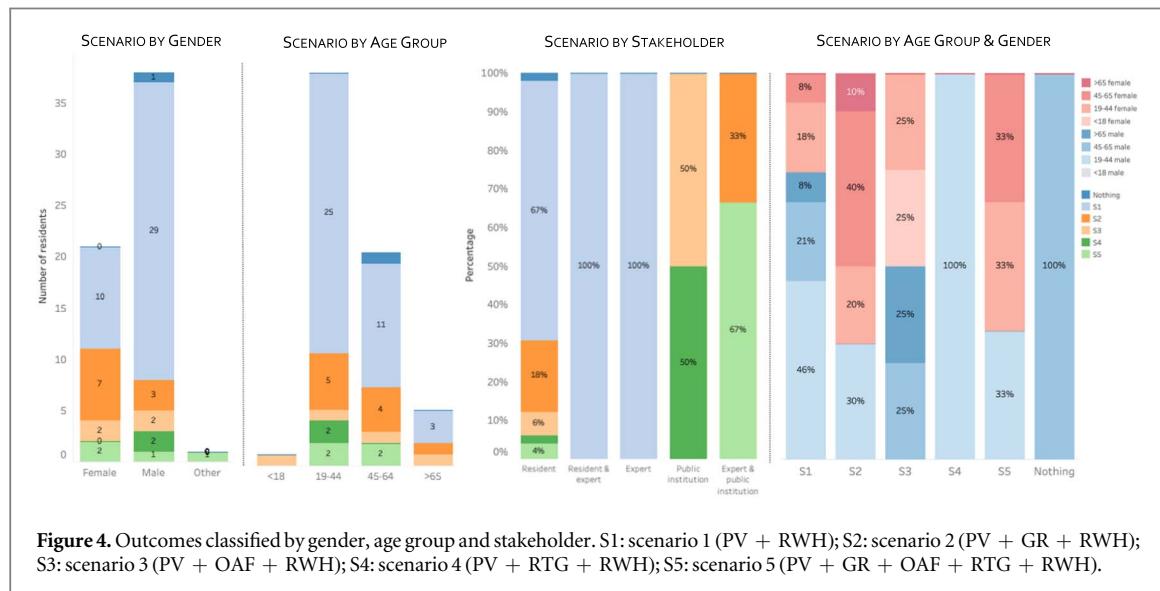
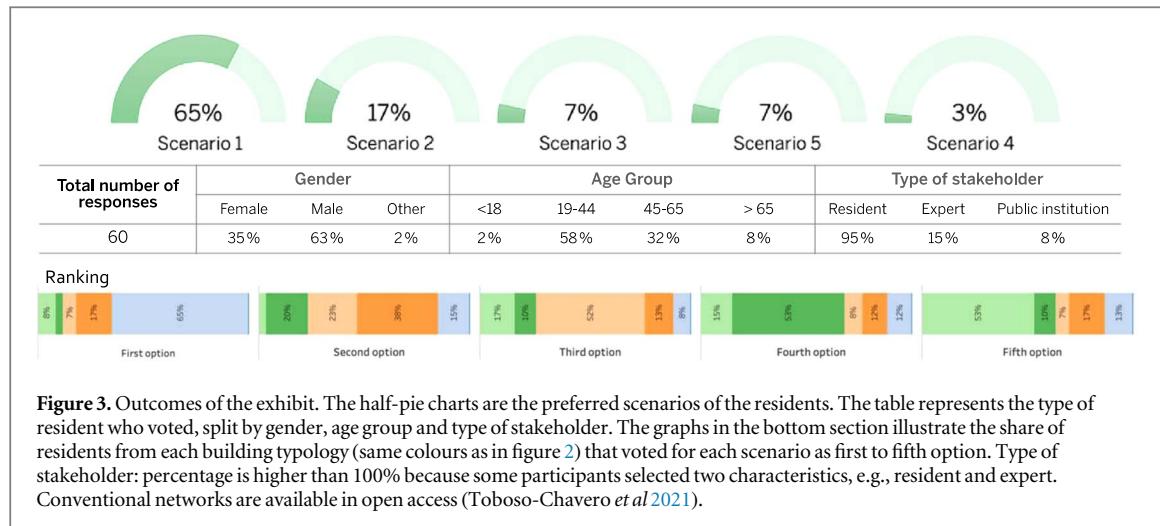
These indicators support the decision-making process used to select future scenarios for this municipality. The three pillars of sustainability are represented here: environmental, social and economic dimensions. Depending on the needs of each area, the importance of each indicator will vary. This is the reason why a participatory process is vital to the acceptance of this strategy and the selection of the most suitable option.

3.3. Characterisation of residents' preferences

Given the sustainability assessment of the scenarios, the different stakeholders had the opportunity to participate in the selection of the most practicable options. They received information on the different indicators via a poster for each scenario and voted on the most suitable alternative for their municipality *in situ* or online.

The exhibit was opened under COVID-19 restrictions. Therefore, it was complicated to gather the opinions of the residents over 65 years old since these residents are not familiar with online questionnaires. Consequently, only 8% of the total respondents were older than 65 years. The most representative age groups were 19 to 44 (58%) and 45 to 65 (32%). Similarly, women are under-represented relative to men, with only 35% of the total participants being female (See the table in figure 3).

The outcomes display a clear preference for scenario 1; 6 out of 10 residents chose to use their rooftops for producing electricity and collecting rainwater for flushing toilets. This ratio coincides with the first participatory process, where residents agreed as a first option to implement PV panels on their roofs. The second most



supported option was scenario 2, but only by 17% of the residents. Furthermore, when a ranking was requested, this scenario also appeared in the second position; nevertheless, only 38% preferred this option, followed by scenarios 3 (23%) and 4 (20%). The third most-preferred alternative was a tie between scenarios 3 and 5. However, in the ranking, the third most-preferred scenario was scenario 3. The least preferred option was scenario 4, with barely 3% of the respondents selecting this option; however, in the ranking, the least-preferred option was scenario 5 (53%). Either way, scenarios 4 and 5 are the alternatives with the least support among residents.

Considering the scenarios preferred by those with different characteristics, differences by gender can be seen, where women had a more diverse opinion, voting primarily for scenarios 1 and 2 with no votes for scenario 4 (see figure 4, left-hand bar chart). For men, the best option was certainly scenario 1 (76%). In regard to age groups, the residents aged 19–44 years, the best represented group, mainly preferred scenario 1; 7 out of 10 would like to implement the production of electricity on their roofs, which is in accordance with the general results. On the other hand, the 45–65 and over 65 years old groups preferred the same option, scenario 1, but to a lesser extent. Furthermore, combining age group and gender indicates that scenario 1 was mainly selected by men, in particular men aged 19–44; in contrast, scenario 2 was mainly chosen by women (70%) and especially women aged 45–65 and more than 65 years old, accounting for 50% of the votes for this scenario.

The stakeholders participating in this process were mostly residents, and accordingly, they preferred scenario 1. Experts and experts + residents (6 respondents) selected only scenario 1 and public institutions and experts + public institutions (5 respondents) opted for scenarios 3, 4 and 5, which each included the production of vegetables.

Table 4. Ranking from the sustainability assessment compared to that from the participatory voting.

Position	1	2	3	4	5
Sustainability Assessment	Scenario 1	Scenario 4	Scenario 3	Scenario 5	Scenario 2
Participatory Voting	Scenario 1	Scenario 2	Scenario 3	Scenario 5	Scenario 4

4. Discussion

4.1. Comparison between residents' preferences and the sustainability assessment outcomes

We identified some discrepancies between the residents' preferences and the outcomes of the sustainability assessment. Such discrepancies are mostly present for scenarios 2 and 4. Scenario 1 was selected as the first choice of the residents and was also the alternative with the most favourable indicators in the sustainability assessment. Scenario 4 was the second option in the sustainability assessment, but it was ranked last by the residents because the construction of a greenhouse on their buildings was still difficult for them to envision. The fact that the upfront investment is high together with the lack of examples of rooftop greenhouses in Spain were some of the reasons presented. In contrast, scenario 2 received the second most votes from residents but performed the worst in the sustainability assessment. The rest of the rankings are listed in table 4 below.

Considering the outcomes from the first and second participatory processes, the residents showed more interest in reducing their electricity expenses by selecting scenarios 1 and 2 than in reducing their food expenses. They did not opt for the scenarios providing vegetables (scenarios 3, 4 and 5), although they spend an average of 77 €/family on vegetables versus 63 €/family per month on their average energy bill (Toboso-Chavero *et al* 2021). This can be explained by two factors. First, the food bill is split into different purchases throughout the month as opposed to a single bill in electricity. Second, residents did not perceive food production as an activity impacting global networks, and the possible lack of food supply, i.e., food insecurity, has not been identified as an issue in the municipality. Hence, if the municipality aimed to foster urban rooftop agriculture, it would need to apply policies targeting the awareness of family food expenses and the related impacts of the conventional food supply. These policies would have to mostly target men because men showed more reluctance to implement any option that is not PV panels.

The application of participatory processes with the sustainability assessment was crucial to identify the concerns of the residents regarding energy expenses in this housing estate, i.e., energy insecurity, and the lack of concern about food expenses or the environmental impacts of global food supply chains, and to identify how residents have a false sense of food security, which is also taken for granted in other Western countries (Borch and Kjærnes 2016). Residents undervalued the possibility of access to fresh vegetables or the necessity to provide for themselves. Neighbours also did not consider roofs as a new place for vegetable gardens to promote social cohesion, which they complained about in the first participatory process. In contrast, they envisioned their municipality mainly as being suitable to host a myriad of photovoltaic panels for alleviating their electricity needs and with minimum dedication to management in their buildings.

In concordance with the findings of previous works on housing estates (Baldwin Hess *et al* 2018), the main concerns of the residents in this municipality are related to social and economic limitations, to the neglect of environmental issues, which are secondary due to the basic needs residents must satisfy.

4.2. Applicability, limitations and policy suggestions

In this study, we propose a method to bring science, policy and society closer together to enhance decision-making related to urban planning strategies. To that end, we added a participatory component to the integration of LCA and social metabolism assessments. Our results show how decision-informing analyses are better suited to their goal if, for the ranking of options, they consider (i) the integration of environmental, social and economic indicators and (ii) the values of stakeholders.

Many studies strive to quantify environmental impacts and the relations among water, food and energy flows without a proper consideration of the role that their associated social and economic dimensions play in the acceptance of and in confidence in new urban strategies (Newell *et al* 2019). By integrating environmental, social and economic parameters, the method presented captures the local context of the area under study, providing relevant indicators to best customise rooftop development to meet the municipality's needs. In the case of housing estates that share similar environmental, social and economic issues, the similarity in the urban design, the repetition of the same type of buildings, flat roofs, etc, are advantages in replicating the rooftop mosaic.

Nevertheless, the complexity of the trade-offs among the environmental, social and economic parameters challenges one-sided decision-making processes. By incorporating the stakeholder's values in the decision process, complexity is embraced and managed. To provide proper guidance, this participation should go beyond

mere consultation and reach at least the level of collaboration³ as described by the IAP2 Federation (International Association of Public Participation 2020). Collaboration ensures selection of the scenarios that are better suited to the goal of the study, increasing the probability of a successful implementation. A number of examples of urban development projects that failed due to the opposition of citizens can be found in the literature; see the case of the superblock programme's pilot project in Barcelona, a large-scale intervention to address climate change challenges (Zografos *et al* 2020), or the failed wind farm projects in some communities (Bell *et al* 2005, Hindmarsh 2010).

This case study was based on a housing estate owned by the local government and built in 1976, where few renovations have been made to the building stock. The façades and roofs of this housing estate need to be refurbished. Furthermore, this situation is similar to that in many housing estates in Europe (Blos 1999, Scalón and Whitehead 2008) and in the Barcelona region, namely, the Montbau and Ciutat Meridiana neighbourhoods and the Bellvitge municipality (Blos 1999, Monclús *et al* 2017). Consequently, the most plausible path for their renovation would be a public investment to upgrade these areas due to the economic and social issues faced by the residents, who are not able to bear these costs. This is an opportunity for public institutions to manage not only the rehabilitation of these areas but also to provide basic resources (FEW) produced on rooftops in order to ameliorate the energy and water poverty and food insecurity that some households have to cope with. Examples of new public initiatives in Barcelona for boosting rooftop use are the green roof competition⁴ or the installation of PV or solar thermal panels on roofs⁵, for which the city council subsidizes 75% and 50% of the initial cost. Another type of initiative is the proliferation of energy companies that commercialize only renewable energies, which guide citizens and help them install PV panels on their roofs through shared investments (energy cooperatives).

Nevertheless, there are still some limitations to overcome in the use of roofs as productive urban spaces, as pointed out by Zambrano-Prado *et al* (2021) and as shown in the participatory processes we carried out. The main barriers are related to social aspects such as a lack of agreement or social cohesion among residents and maintenance responsibility, and to economic aspects such as the initial and maintenance costs.

By applying the proposed framework, policymakers can foster agreements and social cohesion among stakeholders by working together to find the best future scenario for the municipality. Having environmental, social and economic indicators for these rooftop mosaic scenarios provides a framework for selecting the best alternative from all plausible perspectives and readapting the current urban regulations and policies for easy implementation of FEW production on roofs. Some examples of these policies can be found in the city of Paris with the reform of the local urban plan (PLU) (Mairie de Paris 2016), which among other things, obliges the vegetalisation of roofs larger than 200 m² in new construction, does not consider rooftop greenhouses to be a new story to the building and promotes new green spaces, of which 30 hectares must be for urban agriculture. Another example is Barcelona, which has an urban agriculture strategy for the city that promotes roofs as key spaces for increasing green spaces and vegetable production in the city in order to attain 1 m² more per person of green infrastructure by 2030 (Ajuntament de Barcelona 2019). The city council also established a strategy for promoting solar energy generation that aims to increase self-consumption, self-production and renewable and local generation and is focused on public and private roofs with public or private investments (Ajuntament de Barcelona 2017).

5. Conclusions

The participatory integrated sustainability assessment presented here aims to help decision-makers build an integrated assessment that includes an array of environmental, social and economic indicators and methodologies that engage stakeholders in every stage of the project.

The first participatory process proposed five future roof mosaic scenarios and provided a guide for the selection of assessment indicators, such as the production of resources and investment and maintenance costs. The sustainability assessment appraised the roof mosaic scenarios environmentally, socially and economically, indicating that scenarios 1 (the implementation of PV panels and rainwater harvesting) and 4 (deploying greenhouses, PV panels and rainwater harvesting) were the best options and scenario 2 (PV panels, green roofs and rainwater harvesting) was the least advisable. Subsequently, carrying out a second participatory process with the residents in which the five scenarios with all the indicators' outcomes were presented, we identified some discrepancies between the sustainability assessment and the residents' preferences, which agreed with scenario 1 (65%), voted for mainly by men (75%), as the best option, but which did not agree with the rankings of the rest of

³ ‘To collaborate’ is defined as ‘to partner with the public in each aspect of a decision.’

⁴ <https://ajuntament.barcelona.cat/ecologiaurbana/en/green-roof-competition>

⁵ <https://energia.barcelona/ca/ajuts-i-subvencions-convocatoria>

the options. Scenario 2 was the second-most preferred option among the residents (17%) and was mainly selected by women (70%) but was in the last position in the sustainability assessment. Conversely, scenario 4 was the second-best option in the sustainability assessment but the last choice among the residents (3%).

The outcomes and methods used serve as a basis for prioritising and optimising future sustainable scenarios for cities in the production of their own resources. These methods were specifically applied in a housing estate in the Barcelona region but could be useful in housing estates in other European countries or in other types of urban settings. Future research could study the implementation and follow-up of a pilot project on housing estates' rooftops to evaluate the technical and operational limitations as well as the benefits. Currently, different productive farming and productive energy rooftops have been implemented in the city of Barcelona (Ajuntament de Barcelona 2018, Ajuntament de Barcelona 2020), but none in this type of urban area, i.e., in housing estates. Therefore, we recommend that researchers, institutions and the general public continue working together to (a) foster urban strategies, such as the roof mosaic, where it is most needed, (b) design the most feasible sustainability scenarios through comprehensive assessments, (c) propose policies to address the lack of knowledge of the environmental impacts of conventional supply networks and readapt current urban planning regulations and (d) inform and educate citizens by implementing policies meant to promote local resource production in municipalities.

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Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: <http://doi.org/10.5565/ddd.uab.cat/237969>.

Conflict of interest statement

The authors declare no conflict of interest.

Ethical statement

The protocol for the participatory processes was approved by the Ethics Committee on Animal and Human Experimentation of the Autonomous University of Barcelona (<https://www.uab.cat/web/human-research/presentation-1345735629170.html>); Reference number: CEEAH 4520.

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ORCID iDs

Susana Toboso-Chavero  <https://orcid.org/0000-0001-8475-5184>
Cristina Madrid-López  <https://orcid.org/0000-0002-4969-028X>
Xavier Gabarrell Durany  <https://orcid.org/0000-0003-1730-4337>
Gara Villalba  <https://orcid.org/0000-0001-6392-0902>

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