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More than the sum of the parts

System analysis of the usability of roofs in housing estates

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Abstract

Housing estates, that is, mass social housing on middle- and high-rise apartment blocks, in urban areas are found all over the world with very similar constructive patterns and a multiplicity of environmental and socio-economic problems. In this regard, such areas are optimal for the implementation of a roof mosaic which involves applying a combination of urban farming, solar energy, and harvesting rainwater systems (decentralized systems) on unoccupied roofs. To design sustainable and productive roof mosaic scenarios, we develop an integrated framework through a multi-scale (municipality, building, and household) and multi-dimensional analysis (environmental and socio-economic, structural, and functional) to optimize the supply of essential resources (food, energy, and water). The proposed workflow was applied to a housing estate to rehabilitate unused rooftops (66,433 m^2). First, using the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism methodology, we determined metabolic rates across buildings and municipality levels, which did not vary significantly (12.60–14.50 g/h for vegetables, 0.82–1.11 MJ/h for electricity, 0.80–1.11 MJ/h for heating, and 5.62–6.59 L/h for water). Second, based on a participatory process involving stakeholders to qualitatively analyze potential scenarios further in terms of preferences, five scenarios were chosen. These rooftop scenarios were found to improve the resource self-sufficiency of housing estate residents by providing 42–53% of their vegetable consumption, 9–35% of their electricity use, and 38–200% of their water needs depending on the scenario. Boosting new urban spaces of resource production involves citizens in sites which face social and economic needs. This article met the requirements for a gold-gold JIE data openness badge described at http://jie.click/badges.

KEYWORDS
industrial ecology, rainwater harvesting, renewable energy, roof mosaic, urban agriculture, urban metabolism

1 INTRODUCTION

Cities have expressed different urban forms since their inception depend not only on their physical but also on their non-physical characteristics, for example, density, distribution, size, shape, urban layout, building/housing types (Jenks & Colin, 2010). One of the most globalized urban forms are housing estates (HEs), that is, mass social housing (Kabisch & Grossmann, 2013; Monclús & Medina, 2016), which are characterized by high- and medium-rise apartment blocks built between the 1950s and 1970s (Benkő, 2012; Murie et al., 2003). These massive building programs were and still are a global phenomenon identified for their uniformity and lack of identity (Turkington et al., 2004). HEs are found across Europe (more than 41 million dwellers) and in former Communist countries (15–60% of the housing stocks) and other regions (Benkő, 2012).

Housing estates concentrate a variety of social and environmental issues. Currently, most HEs are located in low-cost areas and are characterized by deep social problems (Harloe, 1994; Rieradevall i Pons, 2014) related to poverty, conflict, ageing populations, segregation, and a lack of investment (Murie et al., 2003; Van Kempen et al., 2005). HEs are the consequence of not only housing and planning policies, but also of current social concerns such as immigration, ethnic concentration, and economic crisis (Bolt, 2018). They confront, similarly, environmental issues such as decayed buildings and surroundings, degraded local and public services and infrastructures (Van Kempen et al., 2005), and a lack of energy and water system efficiency due to obsolete constructions and a need for rehabilitation (Hess et al., 2018). Limited building insulation increases the consumption of basic resources (e.g., electricity, natural gas, and water) where many families generally struggle to make ends meet (Matilla Ayala, 2011). Food–energy–water (FEW) poverty remains entrenched among residents, and their main concerns are related to the social and urban degradation of the environment (Hess et al., 2018). As an advantage, such dwellings usually have similar construction and urban design features for a more manageable renovation and application of emerging strategies (Hess et al., 2018).

Upgrading strategies to implement in such areas should not only focus on climate change related strategies but also on providing well-being, urban equity, and economic benefits to these run-down areas (Ruth & Coelho, 2007; Solecki et al., 2011). Some examples include the general improvement of areas with high economic costs (Helleman & Wassenberg, 2004); the demolition of buildings with high environmental burdens (Arthurson, 1998); enhancing public spaces such as green spaces; or the creation of leisure and service facilities (Wassenberg, 2004; Wassenberg et al., 2010). Within the city context, Ramaswami et al. (2016) advocated an array of local infrastructure provisions for developing a sustainable and healthy city: green/public spaces, food, energy and water supplies, buildings, etc. Thus, centralized sectors such as FEW supplies—that is, conventional networks of electricity, natural gas and water, and global food distribution network—play a central role in mitigating environmental pressures and resource consumption when they are replaced with decentralized systems within urban centers (Bazán et al., 2018; Gondhalekar and Ramsauer, 2017; Peter-Varbanets et al., 2009; Toboso-Chavero et al., 2019)

To advance sustainable and equitable urban systems, we posit applying a city-focused strategy called the roof mosaic approach (Toboso-Chavero et al., 2019), which considers the usability of available rooftops within an urban area from a systemic and "Nexus thinking" perspective (Garcia and You, 2016). This implies the implementation of food and energy production and harvesting rainwater from roofs as an alternative to centralized networks of distribution. The roof mosaic increases the available surface for the local production of resources. This "urban productivity" (Swilling et al., 2018) can offer such areas decentralized systems—that is, integrated systems within urban areas, independent of conventional networks—for attaining FEW security and sovereignty, alleviating energy and water poverty, improving quality of life, and optimizing urban land using exclusively the roofs of buildings (Benis et al., 2018b; Corcelli et al., 2019; Toboso-Chavero et al., 2019).

The main value of the roof mosaic lies in its systemic nature in providing services to cities that extend beyond the sum of services provided by productive rooftops of isolated buildings. As in any mosaic (Chapouthier, 2018), the pieces (buildings here) play a dual role, as individual systems and a whole system. First, they express individual patterns of resource supply and use, that is, buildings provide food, energy, and water to the residents. Second, they are key pieces that form a larger system with unique and emergent patterns of other benefits, that is, as a whole the roof mosaic could provide resources for the community, and ecosystem services such as the increase of biodiversity, amelioration of the heat island, and the consequences of extreme weather. This dual role is difficult to study and thus manage due to several issues of scale. For example, focusing on a single scale might conceal other processes that become obvious at other scales (Lovell et al., 2002). Likewise, scale mismatches occur when "the functions of the social-ecological system are disrupted, inefficiencies occur or/and important components of the system are lost," resulting in the mismanagement of ecosystems (Cumming et al., 2006). Urban metabolism, indeed, must be evaluated at multiple scales to avoid these scale mismatches and capture key requirements (Zhang et al., 2015). Consequently, when applying novel strategies such as the roof mosaic to urban agglomerations, screening at different scales is indispensable.

To the best of our knowledge, proper characterizations of the integrated FEW metabolic profile of HEs have not been developed. To address these scale issues, we perform a Multi-scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) analysis, which is a quantitative method proven valuable for studying complex multi-scale systems such as cities (Lu et al., 2016; Pérez-Sánchez et al., 2019; Velasco-Fernández et al., 2018; Wang et al., 2017), islands (Marcos-Valls et al., 2020), regions (Ariza-Montobbio et al., 2014; Ramos-Martín et al., 2009), states (Madrid-López and Giampietro, 2015), and even continents (Velasco-Fernández et al., 2020). The multi-scale and multi-dimensional metabolic profile provided by the MuSIASEM is proposed as input to inform the implementation of roof mosaics in municipalities and other urban centers.

The objective of this work is to contribute to the advancement of urban systems strategies and effective climate action for at-risk populations of a widespread urban form, that is, the housing estate, by characterizing the FEW metabolism of HE buildings and evaluating the robustness of some roof mosaic scenarios to improve living conditions, self-sufficiency, and resource security. After Section 2 on methods, Section 3 provides a multi-scale analysis of the urban metabolism of HEs at different scales and shows how scenarios are co-defined with stakeholders and assessed in this multi-scale setting to provide information for decision-making on HEs of these new infrastructure systems. We add some concluding remarks and further research opened by this study in Sections 4 and 5.

2 | METHODS

Our methodological framework is of multiple scales (municipality, building, and household), is multi-dimensional (environmental and socio-economic, structural, and functional), and is informed by different data sources (Figure 1). First, we required a wide variety of data sources to characterize the studied system. Current and scenario metabolic patterns of the studied municipality were assessed with the MuSIASEM (Giampietro et al., 2012, 2013). To evaluate current metabolic patterns, we developed data with a consumption pattern survey and also used other statistical sources. We then calculated the metabolic patterns of different scenarios of FEW supply using a roof mosaic approach (Toboso-Chavero et al., 2019). The scenarios were designed based on the concerns of residents, which were gathered in a participatory workshop.

2.1 | System characterization

The system under study is the municipality of Badia del Vallès in the Metropolitan Area of Barcelona (AMB) with 13,466 inhabitants (Institut d'Estadística de Catalunya, 2018). It is a typical and very dense HE (14,387 inhabitants/km^2) constructed in the 1970s due to a massive influx of immigrants from rural to urban areas (Blos, 1999). The municipality is representative of mass social housing found in Europe and faces issues typical of housing estates (Consell Comarcal del Vallès Occidental, 2017; Turkington et al., 2004). The municipality is composed of four different types of buildings differentiated by shape and height as shown in Figure 4a,b. There are 69 identical type A high-rise buildings that are 9 and 11 stories tall and provide 1402 households; 48 identical type B medium-rise buildings of 5 stories tall that provide 1440 households; 49 identical type C high-rise buildings that are 9 and 11 stories tall and provide 2148 households; and 35 identical type D buildings of 5 and 16 stories tall that provide 614 households with a total roof area of 66,433 m^2 (see Figures S1-2 and S1-3 in Supporting Information S1 for an extended characterization of the municipality and buildings).

The municipality's population is characterized by the contractive pyramid (Figure S1-1 in Supporting Information S1) (Saroha, 2018) typically associated with developed countries with low mortality and fertility and an ageing population. Figure 2 shows the percentages of employed, unemployed, and inactive populations in the municipality and by each typology of building where a significant portion is shown to be inactive or unemployed.

By the same token, Figure 3 displays human activity (HA) (h) related to household activities, which includes time spent in social, leisure, and education activities and the physiological overhead (time spent by each person sleeping, eating, care, and so on) for each type of building and residents' working status for the population over 15 years of age. These activities and population characteristics are retrieved from the consumption survey performed and are necessary to analyze the metabolism of the HE as will be shown later in this article.

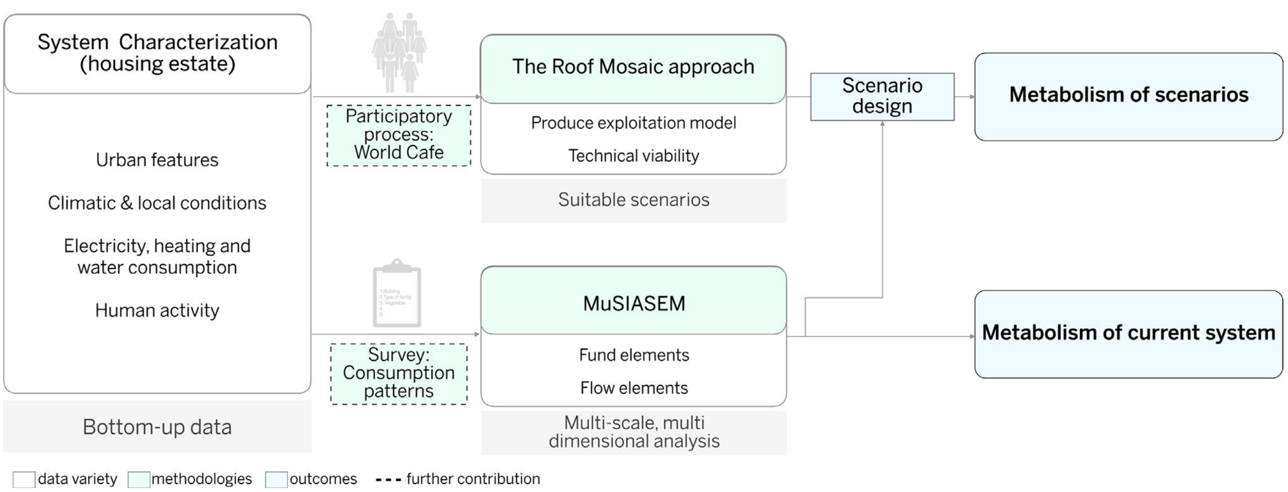


FIGURE 1 Schematic workflow designed for the proposed urban system strategy

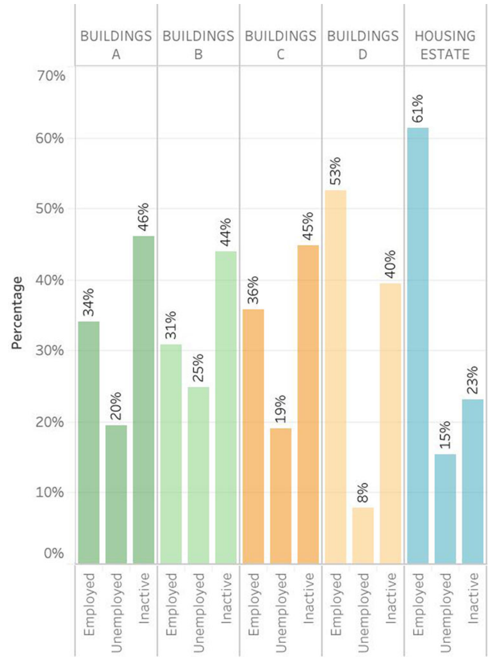


FIGURE 2 Percentages of residents' employment status among housing estate and buildings (2018). Underlying data used to create this figure can be found in Supporting Information S2

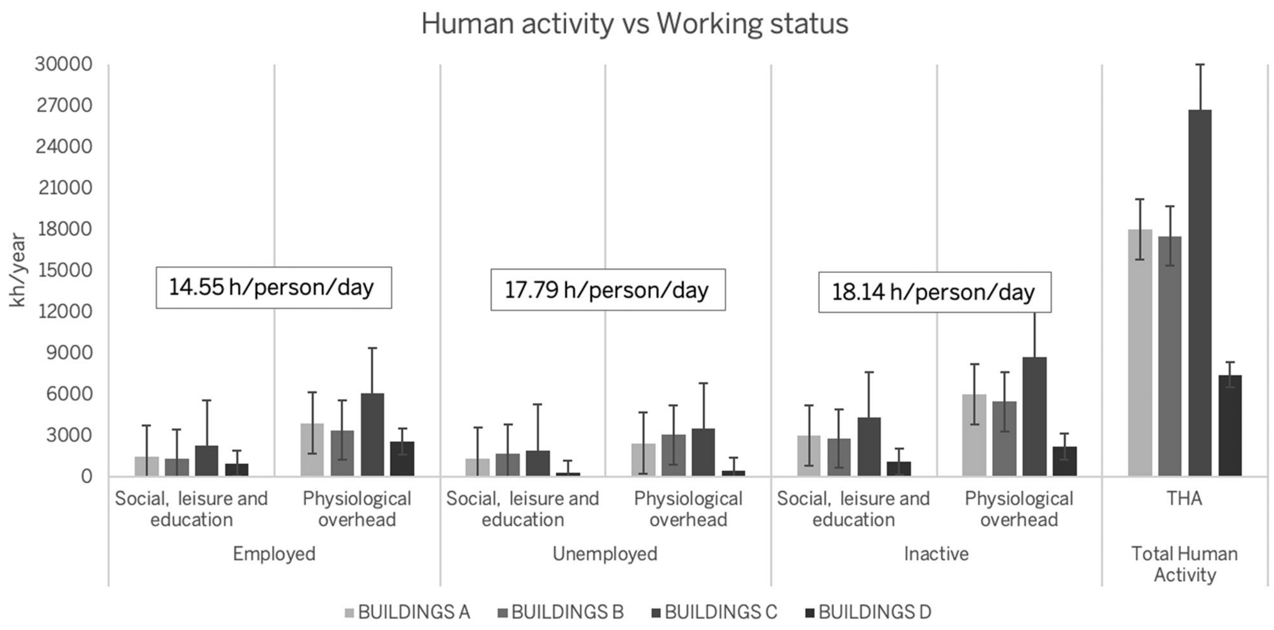


FIGURE 3 Human activity in social, leisure, and education activities and physiological overhead per working status and building type. Boxes illustrate the average human activity (h/person/day) of all household activities. h, hour; kh, kilohour. Underlying data used to create this figure can be found in supporting Information S2

We used three different types of data:

1. Physical conditions: Urban features characterizing types of buildings and roofs are necessary for the implementation of FEW systems on roofs and for identifying current dwelling conditions. These data can be obtained from city councils, government institutions, or imagery data (Table S1-1 in Supporting Information S1). We gathered these data from the city council of the studied municipality and from a validated high-density airborne LIDAR sensor executed in 2013 and 2018 (Zambrano-Prado et al., 2020) (Figure S1-4 in Supporting Information S1).

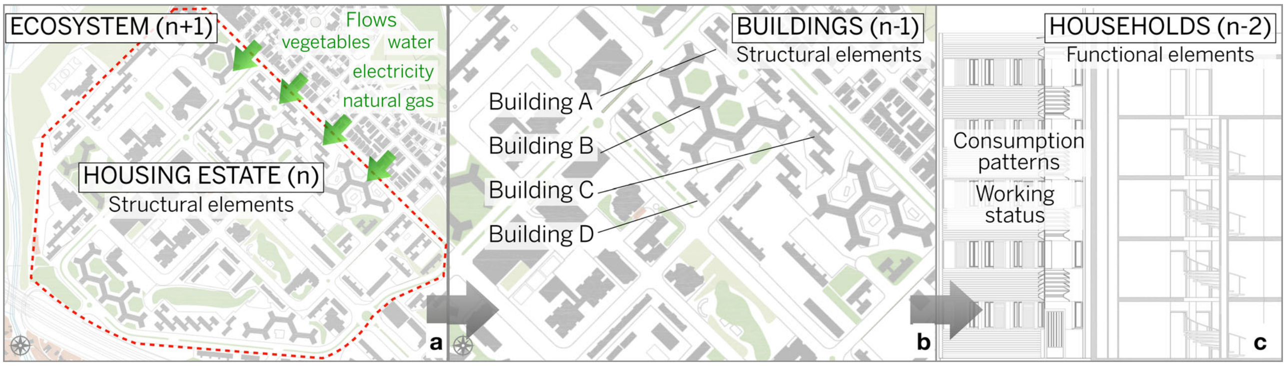


FIGURE 4 Graphical dendrogram (profile of distribution) showing structural and functional elements across the four hierarchical levels ($n + 1$, n, $n - 1$, and $n - 2$) of the case study. Panel a illustrates the housing estate and ecosystem levels, panel b shows the building level, and panel c shows the household level

2. Climatic conditions such as solar radiation, monthly rainfall, and temperatures stem from average values of the official statistics of the municipality. They are required for the implementation and the sizing of different systems (photovoltaic [PV] panels, agriculture, rainwater tanks, etc.) on roofs (Table S1-1 and Figure S1-4 in Supporting Information S1).
3. A variety of data such as FEW consumption (Table S1-1 in Supporting Information S1), the population pyramid (Institut d'Estadística de Catalunya, 2018) and human activity (hours [h]) (Figure 3) (Generalitat de Catalunya, 2011), which denotes the amount of time (h) by a given population. This depends on a demographic variable (the dependency ratio, i.e., the percentage of dependent people [0–14 and over the age of 65] relative to the number of people of working age) and on socio-economic variables (workload, length of education, retirement age, and unemployment). While these data are frequently aggregated at the municipality scale, they must also be obtained for buildings and households. We gathered these data from the city council of the studied municipality and from water and energy companies (Sorea company (Sorea, 2016) and Endesa company (Endesa, 2019)). The energy inputs come from modeling the energy demands by type of building and sun orientation with the building energy simulation program EnergyPlus©; the outcomes were validated through a survey conducted by the city council to households in 2018. The water demand is the current demand of the year 2017 provided for the Sorea distribution company split by addresses and months. It is also difficult to gather food consumption rates by building or household. We recommend carrying out a questionnaire to obtain accurate results of this flow for households. We administered a consumption pattern questionnaire with residents to collect this information. The survey used a stratified random sample from type A, B, C, and D buildings and was completed by 433 residents (see online survey at https://docs.google.com/forms/d/e/1FAIpQLSdcyaL5a8VjWBz_Ss43qnXuIS1doInxuqOhgetKZ-JubNNpgw/viewform). This survey was employed to obtain the residents' characterization such as gender, age group, working status, family unit, type of building where they live (A, B, C, and D), household incomes, monthly energy, water, vegetable expenses, and consumption pattern profile such as vegetable consumption (kilogram of vegetables) per household. We validated these outcomes with the average values of official statistics (see expanded information in Supporting Information S1).

2.2 | The multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM)

The MuSIASEM (Giampietro et al., 2012, 2013) is a method for the assessment of metabolic patterns of complex systems that considers different dimensions and analytical levels. We used this methodology to identify the constraints of different types of roof mosaic on HEs. To this end, we establish a multi-level link, in quantitative terms, between the metabolic patterns of individual buildings and those of the housing estate and analyze the current situation and future scenarios comparing their end-use (Velasco-Fernández, 2017) and supply (Ripa and Giampietro, 2017) matrixes.

The development of the MuSIASEM involved the following:

2.2.1 | System definition

The definition of analytical levels for an MuSIASEM is based on the spatial scale of the studied municipality (Figure 4). The ecosystem level ($n + 1$) is the broader context from which the municipality extracts resources and to which the municipality returns waste. The municipality (level n) and different typologies of type A, B, C, and D buildings (level $n - 1$) have a structural definition. The household level ($n - 2$) follows a functional definition that considers the consumption patterns and employment status of components. The fund element to which metabolic pattern indicators are related is the human activity of households at level $n - 2$.

TABLE 1 Definition of indicators and dataset used for the analysis of metabolic patterns of the HEs and the proposed rooftop scenarios

Matrix	Levels (scales)	Fund elements	Indicators (flow elements and flow/fund elements)	Units	Calculation/source
END USE	n (municipality)	human activity (HA)/year of household activities	**extensive indicators**		
			vegetables total consumption (VTC)	kg/year	Survey
	n-1 Buildings A Buildings B Buildings C Buildings D		electricity total consumption (ETC)	kWh/year	city council data [1]
			heating total consumption (HTC)	MJ/year	city council data [1]
			water total consumption (WTC)	m³/year	company data [2]
			intensive indicators		
			vegetables metabolic rate	g/hour	VTC/HA
			electricity metabolic rate	MJ/hour	ETC/HA
			heating metabolic rate	MJ/hour	HTC/HA
			water metabolic rate	L/hour	WTC/HA
SUPPLY	n (municipality)	human activity (HA)/year of rooftop uses (maintenance of FEW systems)	vegetables losses (VL)	kg/year	Food and Agriculture Organisation of the United Nations (FAO) [3]
	n (decentralized scenarios in the municipality) Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5		electricity losses (EL)	kWh/year	previous study [4]
			water losses (WL)	m³/year	company data [2]
			vegetable total requirement	kg/year	VTC + VL
			electricity total requirement	kWh/year	ETC + EL
			water total requirement	m³/year	WTC + WL
			vegetables savings	%	(VTS/VTC)*100
				kg/household/year	VTS/HH
			electricity savings	%	(ETS/ETC)*100
				kWh/household/year	ETS/HH
			water savings	%	(WTS/WTC)*100
				m³/household/year	WTS/HH

[1]Ajuntament de Badia del Vallès (2019); [2]Sorea (2019); [3]FAO (2011); [4]Domene and García (2017). Sources are underlined in the table. VTS, Vegetable total supply; ETS, Electricity total supply; WTS, Water total supply; HH, Number of households.

2.2.2 | Fund, flow, and indicator definition

We consider flows of end use and the supply of vegetables, energy (electricity and natural gas), and water. The end users are the households of the buildings, and their human activity budget in hours is the proxy for our fund element. We define indicators of end use in flow units per hour of household HA for different activities. Indicators of supply are defined in flow units per hour of HA devoted to the rooftops by actors from building households. A detailed list of the indicators and data sources is given in Table 1.

2.2.3 | Matrix

The end-use matrix (see the template in Table S1-2 in Supporting Information S1) covers current consumption patterns of the study area. It shows in rows the components of the system at the different analytical levels and in columns the flow, fund, and metabolic indicators for end use. We include two structural levels in the end-use matrix municipality (n) and buildings ($n - 1$) and a functional level for households ($n - 2$). We assessed five extensive variables, including one fund (human activity in h/year) and four flows. Flow variables of end use are defined as the total consumption of each resource per year: vegetables (kg/year) using the consumption pattern survey, electricity (kWh/year), and heating (natural gas) (MJ/year) retrieved from city council data—modeled with EnergyPlus©, and water (m^3/year) stemmed from current water consumption (Sorea company). We also calculated four intensive variables of metabolic rate as the quantity of flow consumed in 1 year per hour of human activity: vegetables (g/h), electricity (MJ/h), heat (MJ/h), and water (L/h).

The supply matrix covers the potential supply of FEW for different roof mosaic scenarios. We calculated the human activity budget needed to maintain the new rooftop uses as well as the potential flow production (savings) for the roof mosaic scenarios (decentralized systems) for the same flows included in the end-use matrix. The HA for rooftop use was retrieved from real data for the Barcelona region for open-air farming (OAF) (11.55 h/m^2/year) (Boneta et al., 2019) and rooftop greenhouses (RTGs) (6.72 h/m^2/year) (Rufí-Salís et al., 2020) and for companies specialized in the implementation and maintenance of remaining systems (PV) (2.77 E-05 h/m^2/year), green roofs (GRs) (0.24 h/m^2/year), and rainwater harvesting (RWH) (44 h/tank/year). For GRs, we only consider the energy savings resulting from implementing them on roofs founded on 2% of energy savings (Sailor, 2008), and we also explore the increase of green spaces (m^2/inhabitant) generated by new rooftop uses. We calculated the losses generated for centralized systems. The vegetable losses were based on FAO data for Europe of agricultural production, postharvest, and distribution excluding consumption losses (FAO, 2011) The electricity losses stemmed from a study performed in the AMB electricity network (Domene and García, 2017), which the municipality belongs, and validated for the Catalan Energy Institute (ICAEN) (Generalitat de Catalunya, 2019). The water losses were supplied by the Sorea water company for a timeframe of 6 years (2013–2018) (see Supporting Information S2). The total requirement is the resource consumption (end use) adding the losses.

These results are illustrated in Figures 5 and 6 and in Table 2 in Section 3.

2.3 | Participatory roof mosaic scenario design

To ensure that the chosen MuSIASEM indicators and rooftop mosaic scenarios are indeed relevant for decision-making, we integrate, as a further contribution, a participatory process in formalization steps of the MuSIASEM quantitative analysis, founded on the World Café methodology (Brown, 2005). The method involves several rounds of small group discussion to identify different opinions and perspectives in a relaxed environment with a host that tries to interfere as less as possible, giving the prominence to the participants, and record all the conversation of the topic proposed. This method was employed to capture the residents' preferences in terms of implementing food, energy, or/and water systems on the roofs. The participants were called for participation by the city council and neighborhood association in December 2018. Fourteen randomly selected residents older than 18 years of age from the four typologies of buildings participated in this process. We collected and scrutinized the data based on grounded theory methods (Corbin and Strauss, 1990), data were coded and key concepts were extracted from the responses given. The design protocol for the participatory process can be checked in Supporting Information S1.

After this participatory process, the roof mosaic approach (Toboso-Chavero et al., 2019) was applied to assess the technical feasibility of the roofs. For this approach, there are three main basic requirements for the integration of different systems on roofs. The first is legal and planning criteria and the produce exploitation model. For the studied HE, there are no legal issues related to implementing such systems, as they are used for self-sufficiency purposes. The second requirement concerns the selection of systems to implement. In this study, no solar thermal panels or mini wind turbines were used due to technical limitations of the studied residential area, which includes high-rise apartment blocks of several stories (Bond et al., 2013; Buker and Riffat, 2015). The most suitable systems for this area were, however, identified as PV panels, GRs, OAF, RTGs, and RWH. Vegetable crop yield was determined from real data of hydroponic crops (soilless system with perlite substrate) for the Barcelona region (10.6 kg/m^2/year for OAF (Boneta et al., 2019) and 14.16 kg/m^2/year for RTGs (Rufí-Salís et al., 2020)). Electricity (PV) and water (RWH) outputs are based on our own calculations and measured at 75.8 kWh/m^2/year and 0.52 m^3/m^2/year, respectively (see Supporting Information S2). The third requirement is related to technical viability, for which different criteria must be considered for roofs: (i) direct solar radiation, (ii) roof inclination and resistance, and (iii) if systems are to be combined on the same roof or not.

An uncertainty analysis is presented for the different scenarios to capture the variability of the inputs. The uncertainty analysis is developed for the vegetable crop yield variability, for OAF is 8–13 kg/m^2/year and for RTG is 12–18 kg/m^2/year. For the PV panels performance two variables are introduced, the global solar radiation (4.30–4.67 kWh/m^2/day) based on data from the last 10 years, and the PV panels' efficiency (10–20.4%) founded on the current and future efficiencies in the market (Ludin et al., 2018). Besides, the uncertainty analysis was also performed for RWH, inserting the rainfall variability of the last 10 years in the area (327–919 L/m^2/year). The uncertainty is illustrated in Figure 6 with black bars and Table 2 with absolute values in brackets. Details of the uncertainty analysis can be found in Supporting Information S2.

Our HE roofs receive direct solar radiation and are flat; this was determined from a high-density airborne LIDAR sensor with a resolution of 0.5 m^2/pixel and validated via Google Earth and in the municipality (Zambrano-Prado et al., 2020) (Figure S1-4 in Supporting Information S1). They have a load capacity of higher than 300 kg/m^2 (Serrat and Vicens, 2016), and thus any system can be implemented (Toboso-Chavero et al., 2019), and because there is enough space, we combine in the same roof PV panels with RWH or green/productive spaces (GRs, OAF, and RTGs) with RWH. These outcomes were crossed with residents' preferences and MuSIASEM results to propose suitable scenarios.

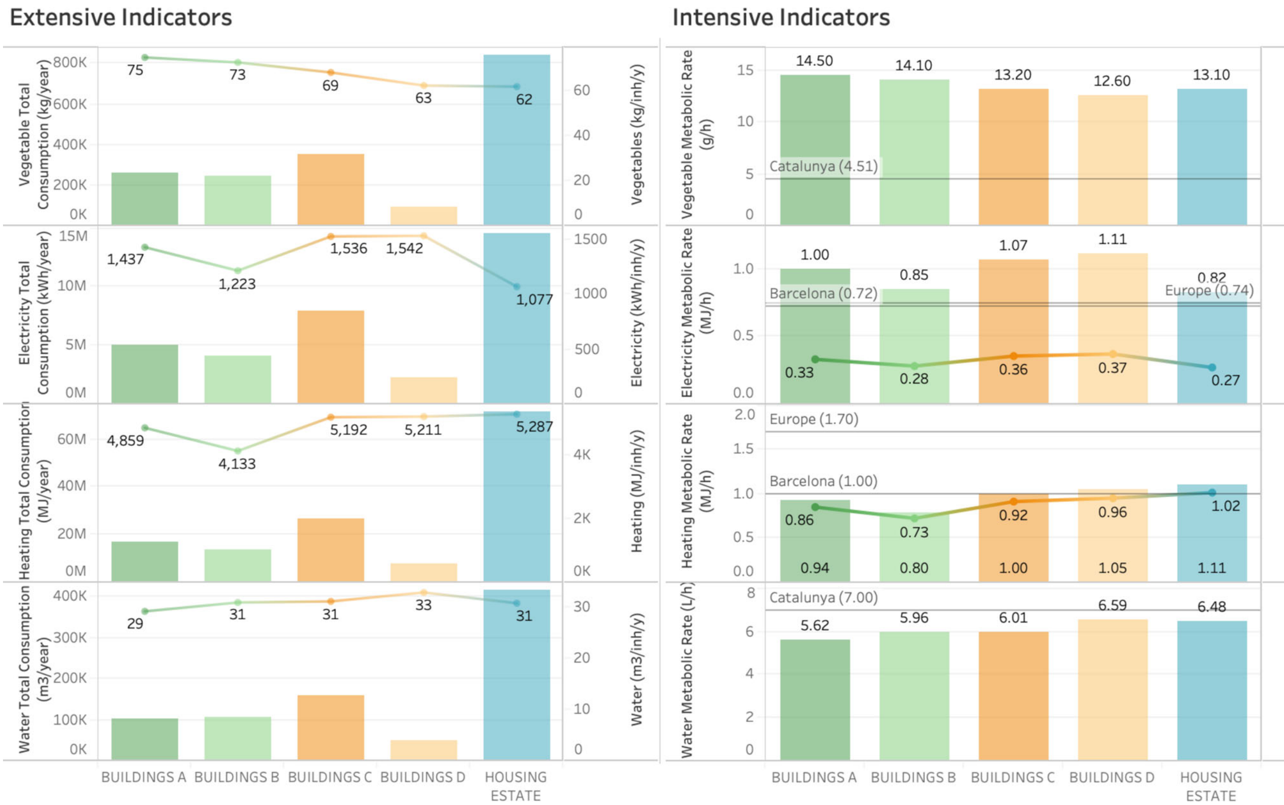


FIGURE 5 End-use matrix indicators (extensive indicators and resource consumption per capita (line chart) are shown on the left and intensive indicators are shown on the right) by building and municipality compared with averages for Barcelona, Catalunya, and Europe (horizontal lines) (Pérez-Sánchez et al., 2019; Madrid and Cabello, 2011; Velasco-Fernández, 2017). The two line charts (right side) show electricity and heating metabolic rates for climatic conditions in households (cooling and heating). Inh, inhabitant; h, hour; y, year. Underlying data used to create this figure can be found in Supporting Information S2

3 | RESULTS

3.1 | Characterization of the current metabolic pattern of housing estates

Figure 5 provides a comprehensive account of the metabolism of the municipality and of building types in the form of end-use extensive and intensive indicators.

3.1.1 | Total end use by building (level $n - 1$)

Type C has the highest value of total end uses for FEW (Figure 5, left side) and the highest residential capacity. However, when these flows are disaggregated per capita, the highest consumption levels are found for buildings D for energy (electricity and natural gas) and water, and for buildings A for vegetable consumption. Buildings A and B show similar total consumptions caused by an analogous number of households of this type of construction. However, buildings B consume less electricity and natural gas per capita and show lower metabolic rates (0.85 and 0.80 MJ/h, respectively).

3.1.2 | Metabolic rate in buildings (level $n - 1$)

HE buildings required 0.85-1.11 MJ of electricity and 0.80-1.05 MJ of heat (natural gas) per hour spent indoors. We can conclude that all of the studied buildings have very similar metabolic rates in terms of vegetables, electricity, heating, and water. We found differences of 1–15% for all flows except for buildings B in energy flows with differences of 26–28%. We have proved the homogeneity of the housing estate form, resulting in similar metabolic rates. Hence, different types of buildings with different shapes and numbers of stories do not show significant metabolic pattern shifts, demonstrating the strength of other parameters such as social status in the determination of the metabolic patterns.

3.1.3 | The HE as a whole (level *n*)

The total electricity metabolic rate of the whole municipality was found to be lower than those of the different types of buildings, which ranged from 3.5% to 26%. Metabolic rates show differing results between levels where the electricity metabolic rate for the municipality is lower than the metabolic rates of the buildings. This could be attributed to illegal connections to the electricity network. By contrast, the heating metabolic rate shows more linear behavior and the municipality scale has similar value or is slightly higher than the building scale, leading to quantitative scale mismatches. Additionally, the energy metabolic pattern of climatic conditions in households (only cooling and heating) represented by line charts in Figure 5 (right side) contributes in a third part of the total electricity metabolic rate and almost equal to the heating metabolic rate which means that households use predominantly natural gas for heating. Finally, vegetable and water metabolic rates are similar among scales.

We provide these technical coefficients for energy, vegetables, and water for housing estates. To the best of our knowledge, this is the first study to characterize the metabolic profiles of such areas.

3.2 | Roof mosaic scenario definition

According to the preferences of participants of our workshop carried out without previous information provided, different scenarios were developed. Related to the implementation of these new systems, that is, food and energy production and RWH on roofs, the residents mainly prefer energy production and electricity in particular due to the high price of this resource, which averages at 50–80 euros per month/family (Table S1-4 in Supporting Information S1). The limitations residents perceived are related to the monetary investments of different systems and to the maintenance (time required) of agricultural systems on rooftops, for example, whether neighbors take care of crops. Conversely, the participants agreed that these new uses for roofs could ensure money and resource savings for the municipality, empowering them to manage and secure these resources.

The participatory process was essential for the proposal of different scenarios, as many of them can be implemented but a limited number are compliant with the residents' priorities. Correspondingly, five different scenarios were proposed (S1 [100% PV and RWH], S2 [50% PV + 50% GR and RWH], S3 [50% PV + 50% OAF and RWH], S4 [50% PV + 50% RTG and RWH], and S5 [25% PV + 25% GR + 25% OAF + 25% RTG and RWH]) (Table 2) with PV panels supplying electricity in all options because it is the residents' main preference. RWH is also included in all scenarios because it does not occupy room on roofs and only tanks are required to store rainwater. The other scenarios are combined with productive systems such as OAF and RTGs, and GRs are used as a more manageable option because they require little maintenance and infrastructure.

While other scenarios could be developed, the proposed scenarios fulfil three relevant premises. First and foremost, they satisfy the preferences of local residents and considers the area's distinctiveness. Second, they are in harmony with the roof mosaic approach where the multi-functionality of roofs makes them more synergetic and efficient (Toboso-Chavero et al., 2019). Third, they are at the municipality scale and technically viable. Therefore, we design scenarios based on residents' preferences and concerns, empowering local citizens through participation in decisions that affect their community. This is in line with different studies advocating for public participation for more acceptance of the implementation of new technologies (Bidwell, 2016; Walker and Devine-Wright, 2008).

3.3 | Metabolic patterns of scenarios: Centralized systems versus savings in decentralized systems

Centralized vegetable system shows losses in the harvesting and distribution of produce of roughly 37%, which is wasted through the supply chain. Hence, if one of scenarios 3–5 is implemented on rooftops (Figure 6 and Table 2), they could ensure half (between 42% and 53% [65.5–87.6 kg/household/year]) the consumption of tomatoes, lettuce, green beans, and peppers, reducing dependence on external markets and related losses. This would result in a shift from long food miles with considerable impacts (Paxton, 2011) to almost no impacts producing vegetables in the same buildings.

Electricity is the centralized system with the highest share of losses, which are caused by energy transformation, transmission and distribution networks (Domene and García, 2017) and account for 63%. As a result, decentralized systems on rooftops would reduce the consumption of conventional networks by 35% (937 kWh/household/year) if PV panels were deployed on all roofs to a minimum of one-tenth of the electricity consumed in the fifth scenario (248 kWh/household/year).

The centralized water system is a more efficient system than those for electricity and vegetables, representing 17% of total requirements. Under decentralized systems, scenario 1 would replace the flushing of toilets, reducing the consumption of this resource by 38% (6.4 m^3/household/year) and by 8% of total losses. However, the infrastructure required to implement this scenario has more technical issues than the other scenarios (2–5), where rainwater is used for crop irrigation, which is more feasible to install and consumes less materials than flushing. This use would not decrease end uses or losses of the municipality under current circumstances.

Building an uncertainty assessment, we could capture that the five scenarios are considerably reliant on vegetable crop yield variability, PV panel efficiency, and rainfall variability. For food self-sufficiency, the crop yield influences directly to this value. Hence, low yields show low self-sufficiency ratios. The average data for this study (OAF: 10.6 kg/m^2/year and RTG: 14.16 kg/m^2/year) stem from real data for 3 years of hydroponic crops in urban areas which have demonstrated their regularity but with not very high productivity. For example, higher crop yields have been reported in greenhouses (Sanyé-Mengual et al., 2015), therefore, there is room for improvement. For electricity self-sufficiency, the variability of the global solar radiation is almost irrelevant and does not affect significantly to the outcomes. Conversely, high PV panels' efficiencies would double the production of electricity, which means that PV panels with 20.4% efficiency could provide half of the total consumption of the municipality (1300 kWh/household/year). Consequently, future PV technologies (Ludin et al., 2018) can enhance these outcomes substantially. Concerning water self-sufficiency, the rainfall variability influences this ratio directly. The rainfall had high variability in the last 10 years (327–919 L/m^2/year). However, the forecast for the Mediterranean region, specifically in Catalonia, is a reduction in precipitations up to 30% and the intensification of heavy rainfall events (Cramer et al., 2018), therefore these self-sufficiency percentages will decline. Nevertheless, this further reinforces the goal of exploiting any form of water in this future context.

Table 2 displays savings per household and levels of human activity, that is, annual maintenance time of rooftop uses. Substantial differences are identified among systems. Concerning the implementation of PV panels, the human budget for their maintenance is marginal. The RWH system needs more dedicated time (10,890 h/year), and farming systems are the most demanding, requiring between 223,000 and 384,000 h/year. The number of hours required per household is almost irrelevant for scenarios 1 and 2 and greater for the other scenarios. When we intersect human activity needed for scenarios 4, 5, and 6 with human activity available from the inactive and unemployed (Figure 3), this only represents 2, 1.2, and 1.6 h/person/week, respectively. This large quantity of residents with the most human activity dedicated leisure activities in households depicts a population structure characterized by a large inactive and ageing population, creating a large human budget for investing in recreational activities such as caring for vegetable gardens. Other considerations for the enforcement of rooftop scenarios include the rise of green spaces depending on the scenario (from 2.5 to 3.7 m^2/inhabitant) and the type of infrastructure required to implement such systems.

4 | DISCUSSION

4.1 | Metabolic profile of housing estates

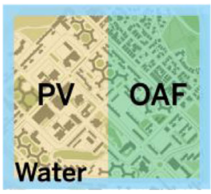
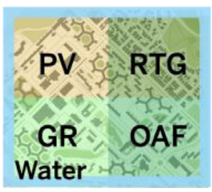
In comparing the metabolic rates of our municipality with those identified by prior studies of residential areas with combinations of urban forms, we found one for Barcelona (Pérez-Sánchez et al., 2019) and another for the European Union (Velasco-Fernández, 2017). The studied HE exhibits a higher electricity use metabolic rate. However, population differences and variability in developments larger than HEs must be considered. Unfortunately, no studies of the neighborhood or municipality scales for drawing comparisons to the present study were found. In contrast, heating metabolic rates are similar to or lower than (for buildings A and B) Barcelona's and 35–53% lower than those for Europe, respectively, which translates into a significantly lower heating metabolic pattern for HEs (Figure 5, right side).

Conversely, for the vegetable metabolic rate, the municipality consumes more than three times the Catalan average. This discrepancy could be attributable to different reasons. The first reasons are related to the fact that the Spanish population over 50 years of age consumes 50% more vegetables than the population younger than 50, and lower social classes purchase less quantity of meat (20%) than higher social classes (Ministerio de Agricultura y Pesca Alimentacion, 2018). In the studied municipality a significant proportion of residents (40%) are older than 50 years of age, and most families have limited incomes (Figure S1-1 and Table S1-4 in Supporting Information S1). Another reason may relate to the use of different methodologies to estimate vegetable consumption. Our results stem from a survey conducted in the municipality (see survey results in Table S1-4 in Supporting Information S1 and open access at: https://doi.org/10.5565/ddd.uab.cat/226152) while those from Catalonia are based on the shopping habits of representative families (Figure S1-6 in Supporting Information S1). Nonetheless, aggregated data for Catalan vegetable consumption could lead to inaccurate results when an analysis is founded on local areas such as municipalities as in our case.

The general idea is that the consumption of energy and water in housing estates is much higher than in other constructions due to the low energy and water efficiency of their obsolete constructions (Hess et al., 2018). Nonetheless, we detected low heat and water consumption compared to levels for Barcelona and Europe, potentially due to the types of family units that live in the studied municipality, where roughly 60% of families have family incomes of less than 1,660 €/month (Table S1-3 in Supporting Information S1) and the annual average income per capita in the municipality is 30% lower than in Barcelona (Institut d'Estadística de Catalunya, 2018). Moreover, 10% of the surveyed residents have needed social service support to pay their energy and water bills over the last 5 years (Ajuntament de Badia del Vallès, 2019). Energy poverty can be correlated with low-income households, low energy efficiency among households, and high energy prices (Boardman, 2012). Therefore, the municipality does not consume less due to building efficiency but rather at the expense of "cold homes" (Anderson et al., 2012). Cardiovascular and respiratory diseases

FIGURE 6 Consumption and losses of centralized systems (current baseline) and savings of decentralized systems (proposed scenarios) by buildings and municipality for different resources, food, energy, and water. Irrigation is marked with diagonal lines because it is not part of current building consumption. Losses are shown in orange in consumption and saving scenarios. Black lines in saving scenarios (decentralized systems) are the uncertainty in each scenario associated with vegetable crop yields, global solar radiation and PV efficiency, and rainfall variability. Electricity production is included for PV panels and energy savings are included for green roofs. S1, scenario 1; S2, scenario 2; S3, scenario 3; S4, scenario 4; S5, scenario 5. TVR, total vegetable requirement; TER, total electricity requirement; TWR, total water requirement. Underlying data used to create this figure can be found in Supporting Information S2

TABLE 2 Part of the supply matrix of the system, including other considerations

Rooftop scenarios	Description	Annual savings/hh	Annual human activity	Annual human activity/hh	Considerations
Scenario 1		Electricity 937 (670–1300) kWh Water 6.4 (3.6–10.2) m^3	Electricity 0.18 kh Water 10.65 kh	2.0 h	No farming systems in this scenario No need for rooftop access
Scenario 2		Electricity 495 (327–712) kWh Water 5.2 (2.9–8.2) m^3	Electricity 0.09 kh Water 10.65 kh	3.5 h	Green spaces: 2.5 m^2/inhabitant No farming systems in this scenario No need for rooftop access
Scenario 3		Vegetables 65.5 (49.5–80.4) kg Electricity 468 (300–685) kWh Water 6.4 (3.6–10.2) m^3	Vegetables 384 kh Electricity 0.09 kh Water 10.65 kh	73.5 h	Green spaces: 2.5 m^2/inhabitant Need for rooftop access
Scenario 4		Vegetables 87.6 (74.2–111.3) kg Electricity 468 (300–685) kWh Water 6.4 (3.6–10.2) m^3	Vegetables 223 kh Electricity 0.09 kh Water 10.65 kh	43.6 h	Green spaces: 2.5 m^2/inhabitant Need for rooftop access
Scenario 5		Vegetables 76.5 (61.8–95.8) kg Electricity 248 (164–356) kWh Water 5.8 (3.3–9.2) m^3	Vegetables 303 kh Electricity 0.05 kh Water 10.65 kh	59.2 h	Green spaces: 3.7 m^2/inhabitant Need for rooftop access

For the full results, see Table S1-4 of Supporting Information S1. The values of the uncertainty assessment are in brackets; hh, household; kh, kilohours. Underlying data used to create this figure included in this table can be found in Supporting Information S2

have been related to cold home temperatures (Howden-Chapman et al., 2007). Serrat (2016) similarly carried out a study in the same municipality and found that 19.6% of these diseases can be related to humid and unsanitary conditions in households.

Therefore, we advocate for characterizing the metabolic patterns of urban areas at different scales and dimensions to avoid possible hidden issues and scale mismatches and to obtain the current state of a system while focusing on what is most needed, our use of the MuSIASEM assists us in this matter.

4.2 | Centralized systems versus decentralized systems

Reporting the losses associated with each resource system is fundamental to accounting for the actual supplies of conventional networks. The throughput is a part of a centralized system and should be addressed when proposing decentralized systems, as both consumption and system losses decline when implementing locally. The FAO has reported vegetable and fruit losses of 38–55% in different regions, which dominate agricultural production phase losses in most of these areas (FAO, 2011). Target 12.3 (responsible production and consumption) of the Sustainable Development Goals (SDGs) (FAO, 2019) calls to halve food losses and waste by 2030. Rooftop food production can help achieve this goal.

In the same vein, electric power transmission and distribution losses account for 8.25% globally, for roughly 6% in the European Union, and for an average of 10% in Spain in current centralized systems (The World Bank, 2018) without considering the transformation losses of each primary energy source. In our case study, this value soars to 63%, as the transformation losses of each source are incorporated. The electricity mix in Catalonia predominantly comes from nuclear sources (70%), and these primary energy sources come with significant transformation losses (roughly 70%) (Domene and García, 2017). The implementation of PV panels would decrease such losses, mitigate residents' financial issues, and increase the share of renewable energy used in the municipality. Target 7.2 of the SDGs (United Nations, 2019) cites this approach as a means to substantially increase the global use of renewable energies.

While water losses are also relevant in centralized systems, in the studied municipality, rainwater would mainly be used to irrigate crops and thus would not be taken from conventional networks, implying the non-use of potable water and derived operations such as potabilization, the use of infrastructure, and so on, enhancing water resource efficiency. Target 6.4 of the SDGs (United Nations, 2019) also advocates for water-use efficiency across all sectors.

Our proposed multi-scale and multi-dimensional analysis method offers valuable, wide-ranging information for planning rooftop uses while other studies restrict their assessments to one scale, one dimension (usually environmental), using average consumption levels to estimate resource self-sufficiency, without taking into account the loss estimation, and no participatory processes or surveys used to acquire data either (Benis et al., 2018a, 2017; Toboso-Chavero et al., 2019). Additionally, the uncertainty analysis aided to draw the plausible resource self-sufficiency (savings) depending on vegetable crop yield, global solar radiation, PV panels' efficiency, and rainfall variability.

5 | CONCLUSIONS

This study assessed the implementation of FEW systems on the rooftops of housing estates (HEs). This strategy can be used to ameliorate the centralized supply of FEW, reducing costs and environmental impacts. We conducted a multi-scale (municipality, building, and household) and multi-dimensional (environmental and social, structural and functional) analysis involving a variety of methods to propose relevant rooftop scenarios for this urban area.

We propose a participatory calculation protocol that involves understanding and quantifying FEW consumption, human activity, and metabolic rates for the area under study. Applying the MuSIASEM method to analyze the metabolic patterns of housing estates via the end-use matrix and using the supply matrix to estimate the losses and actual values of conventional systems when an urban area shifts to a decentralized system, that is, using roofs to produce resources, not only reduces consumption from centralized systems but also decreases losses. Consequently, we provide a means to estimate the technical coefficients of housing estates (12.60–14.50 g/h for vegetables, 0.82–1.11 MJ/h for electricity, 0.80–1.11 MJ/h for heating, and 5.62–6.59 L/h for water) and ways to upscale them. We prove the homogeneity of the housing estate form, resulting in similar metabolic rates among buildings in terms of vegetable, electricity, heating, and water consumption. Nonetheless, different outcomes between the buildings and housing estate scales are found, meaning that effects amount to more than the sum of their parts. For instance, our analysis of different scales reveals differences for building B in terms of heating with respect to the housing estate scale, and for buildings A, C, and D for electricity in relation to the housing estate scale. These outcomes can help focus our endeavors where they are most needed.

The rooftop scenarios proposed in this research were found to improve the resource self-sufficiency of housing estate residents by providing 42–53% of their vegetable consumption, 9–35% of their electricity use, and 38–200% of their water needs depending on the scenario and despite its high population density (14,387 inhabitants/km^2). Our joint use of the MuSIASEM and roof mosaic assists us in generating manageable scenarios to deeply understand the socio-economic and environmental weaknesses of the area, for example, types of families present and their current conditions, time available and time spent on household activities, resource requirements. By incorporating a participatory process into these quantitative methods, the current concerns of residents are detected, and the success of new roof uses is made more robust. For example, efforts can focus on buildings with the highest metabolic rates or on in-demand or more costly resources.

Such a framework can be further applied to other housing estates or municipalities with a mixture of urban forms and social classes, and also plausible forms of governance mechanisms of these new systems on roofs. Essential to replication in urban areas will be access to disaggregated data of different scales of FEW flows and the involvement of stakeholders. This strategy will boost new urban spaces of resource production involving citizens in sites where they face social and economic needs, with the aim to play a crucial role in environmental upgrading, guiding metropolises to evolve to resource more self-producing, socially just, and healthy habitats.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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