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The potential of local food, energy, and water production systems on urban rooftops considering consumption patterns and urban morphology

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ABSTRACT

The external resource dependency of urban areas results in the externalization of environmental and socioeconomic impacts. Implementing food, energy and water production systems on urban rooftops (roof mosaics) can potentially help cities become more self-sufficient but depends on the city's urban morphology. We studied the supply potential and impacts of four roof mosaic scenarios for different urban forms in Cerdanyola, a 58 thousand-inhabitant town in the metropolitan area of Barcelona. We combined spatial analysis of potential rooftops, metabolism analysis, and social and environmental impacts. The municipality has an average rooftop/household potential of 31 m^2 on which to implement any of the mosaic scenarios, with the highest potential in the single-family housing typology. The highest level of vegetable self-sufficiency was found in housing estates (32%), and the lowest in originary fabrics (28%). Regarding electricity and water self-sufficiency, the highest self-sufficiency level was found in the single-family housing typology (51% and 14%, respectively) and the lowest in housing estates (26% and 8%, respectively). Regarding impacts, the implementation of the electricity and rainwater harvesting systems depicts the most positive indicators in single-family housing areas. However, for housing estates and originary fabrics typologies, the best performance is shown to be in the implementation of rooftop farming systems.

1. Introduction

Cities are spaces with high population densities that are intrinsically dependent on imported resources to function (Agudelo-Vera, Leduc, Mels, & Rijnaarts, 2012; Bai, 2007). Import dependency results from the occupation of spaces for housing and services, increasingly densified for a growing urban population that triggers a myriad of environmental, social and economic issues. Northern America (83%), Latin America and the Caribbean (81%) and Europe (75%) already have a high rate of urbanization, with most people living in urban centers. In the future, 96% of urban growth will be centered in the African and East and South Asian regions (UN-Habitat, 2020). In Europe, urban dwellers are exposed to harmful concentrations of air pollutants that are well above the stringent recommendation of the World Health Organization (WHO) (European Environment Agency (EEA), 2020). This is particularly relevant in cities of middle- and low-income countries in which the highest exposure to air pollutants (e.g., PM_{10}, $PM_{2.5}$, O_3, NO_2) has been found (World Health Organization, 2018).

Unequal and sometimes difficult access to resources (particularly energy, water and food) is also an issue that springs from urbanization

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(UN-Habitat, 2020). In Europe, urban households use the most energy (27%, only 17.9% for heating/cooling and other activities in households), and energy production (for all types of activities, not only household activities) is the second highest consumer of energy (19.8%); therefore, both activities account for almost 46.8% of Europe's total energy consumption (Eurostat, 2020). Agriculture is still the largest consumer of water in European cities (40%), especially in southern countries, followed by energy production, mining and manufacturing, and household use (12% - 144 l/person/day) (EEA, 2018). Food provision is a challenge in urban areas, particularly as European kcal intake has increased, especially the intake of meat, sugars, salt and fats (Willett et al., 2019), reaching 13% of the total annual household expenditure and representing the second highest expense after housing, water, electricity and gas (23.5%) (Eurostat, 2019).

In this context, Europe's organization of urban spaces allows for a more efficient means of taking action to tackle climate change. Historically, European cities have been traditionally compact, dense and walkable, mostly with well-organized public transportation systems (Timothy Beatley, 2000). However, strategies that aim to increase the availability of resources from local sources find the variety of building typologies and urban forms that can be found in European cities to be a challenge. Indeed, features such as size, shape, distribution of open spaces and type of rooftops can considerably affect the success of climate change mitigation measures in urban areas (Jenks & Colin A, 2010; Oliveira, 2016). Consequently, urban morphology, i.e., the discipline of urban planning that studies the physical dimension of the built environment (Oliveira, 2016), can play a role in the improvement of the coordination and deployment of sustainable urban initiatives (Fang, Wang, & Li, 2015). In a morphology study, cities are split into smaller subsystems based on urban forms, fabrics or tissues to find similar solutions to their environmental and social performance. Due to the complexity and heterogeneity of metropolises, smaller sections such as urban fabrics, which are a physical expression reflecting specific features, can help to characterize the type of residents that live in these cities, finding common environmental and social issues in sites with similar structural conditions (Braulio-Gonzalo, Ruá, & Bovea, 2020).

The urban morphology discipline therefore offers an integrated view of the analysis and implementation of climate change solutions (Lamb, Creutzig, Callaghan, & Minx, 2019). Several studies have proposed urban morphology as a key factor to assessing different sustainable urban strategies when developing geospatial models. Braulio-Gonzalo and Colleagues (2020) developed a methodology for breaking cities down into small pieces in order to deploy urban initiatives. Jabareen (2006) analyzed the best urban forms for sustainability, and Oliver-Solà et al. (2011) proposed a method that combines different urban morphologies with environmental data to aid urban planners in making decisions based on environmental criteria. Energy aspects and urban morphology have been widely studied for various purposes, namely, to link energy systems more efficiently for renewable energy and urban archetypes (Perera, Coccolo, & Scartezzini, 2019) or to understand the energy demand and promote energy renovation scenarios (Middel, Häb, Brazel, Martin, & Guhathakurta, 2014; Rode, Keim, Robazza, Viejo, & Schofield, 2014). Furthermore, in the design of sustainable transport, urban forms play a vital role (Babalik-Sutcliffe, 2013; Feng, Fujiwara, & Zhang, 2008).

Local resource production as single systems on rooftops has been addressed in many different studies but without considering together the three main consumed resources in cities (food, energy, and water), or presenting an integrated approach. Rooftop food production has been extensively studied worldwide (Appolloni et al., 2021; F. Orsini, Dubbeling, De Zeeuw, & Gianquinto, 2017). There are many studies devoted to food self-sufficiency in cities in different urban spaces and different types of cultivation (open-air farming or/and rooftop greenhouses), such as Berlin (Germany) (De Simone, Pradhan, Kropp, & Rybski, 2023), Boston (United States of America) (Saha & Eckelman, 2017), Barcelona (Spain) (Sanyé-Mengual, Cerón-Palma, Oliver-Solà, Montero, & Rieradevall, 2015; Zambrano-Prado et al., 2021), Quito (Ecuador) (Nadal et al., 2019), Bologna (Italy) (Francesco Orsini et al., 2014) or Lisbon (Portugal) (Benis, Turan, Reinhart, & Ferrão, 2018) among others. The production of energy has also been widely explored at the country scale (Ramirez Camargo, Nitsch, Gruber, & Dorner, 2018), city scale (Barragán-Escandón, Zalamea-León, Terrados-Cepeda, & Vanegas-Peralta, 2020; Bazán, Rieradevall, Gabarrell, & Vázquez-Rowe, 2018; Chung, 2018; Jurasz, Dąbek, & Campana, 2020; Villa-Arrieta & Sumper, 2019; Zhu et al., 2022) community scale (Awad & Gül, 2018; Mehta & Tiefenbeck, 2022) or building scale (Fardi Asrami, Sohani, Saedpanah, & Sayyaadi, 2021; Luthander, Nilsson, Widén, & Åberg, 2019; Menoufi, Chemisana, & Rosell, 2013), using different methodologies and approaches. In a similar vein, the use of rainwater has been analyzed in different ways and with different purposes in cities (de Sá Silva, Bimbato, Balestieri, & Vilanova, 2022), such as agriculture (Hume, Summers, & Cavagnaro, 2022), domestic applications (Angrill et al., 2016; Ortiz, de Barros Barreto, & Castier, 2022; Vargas-Parra, Rovira, Gabarrell, & Villalba, 2014) or a mix of them (Ali & Sang, 2023; Farreny, Gabarrell, & Rieradevall, 2011).

Some studies have assessed the three resources (FEW) from different perspectives, such as from a technical point of view (Zambrano-Prado et al., 2021), using system dynamics modeling analysis (Valencia, Hossain, & Chang, 2022), addressing only urban metabolism in urban growth models (Chang, Hossain, Valencia, Qiu, & Kapucu, 2020), and from a circular city perspective, concluding that a circular city is plausible but needs a multidisciplinary analysis (Valencia et al., 2022). Studies strongly advocate considering environmental, social, economic, spatial and cultural dimensions based on participatory process and appropriate methodologies to progress in sustainable and inclusive development (Garcia & You, 2016; Kundu, Sietchiping, & Kinyanjui, 2020). Therefore, in our study we intend to cover all these aspects. The FEW implementation literature in cities has a significant gap in most studies which is the scant consideration given to the multifaceted nature of resource production in cities. Often, studies only focus on a single vector (energy or food production, or rainwater harvesting), disregarding the three pillars of sustainability - environmental, economic, and social - and failing to take a systemic and multidisciplinary approach that accounts for pattern consumption (using local and specific data), urban form, and rooftop resident preferences. To the best of our knowledge, no studies have comprehensively evaluated the urban strategy for sustainable local production of food, energy and water which incorporate the physical, socio-economic, and resident preference components on a city scale. Three crucial factors are necessary for the successful implementation of any urban strategy, and they are relevant to city councils, urban planners, and organizations alike. In this paper, we assess the implementation of a sustainable urban strategy in a mid-sized city with different urban forms by quantifying the potential production of food, energy and rainwater harvesting (FEW) on urban rooftops (termed the roof mosaic by authors (Toboso-Chavero et al., 2019)).

This implementation of a sustainable urban strategy will reduce the consumption and exploitation of external resources and increase the self-sufficiency of the city. To do so, we geospatially assess the potential rooftops of the municipality and characterize their urban forms to implement the production of food, energy and water (FEW) and compare them to current consumption. Finally, we assess the feasibility and desirability of future roof mosaic scenarios.

The present paper is structured into four major sections, beginning with the introduction and objectives, after Section 2 on methods, Section 3 (results and discussion) provides five different sub-sections. Firstly, the resource rooftop supply potential by urban form, secondly and thirdly, the consumption and production characterization of the municipality and urban forms, fourthly the resource potential supply vs consumption considering urban morphology; and fifthly, the sustainability performance per scenario. We also added some concluding remarks and further research in Section 4.

2. Materials and methods

The methodology is organized into three steps (Fig. 1). First, a geospatial model was developed to characterize rooftops and urban forms, i.e., the morphological characterization (Section 2.2). The study area covers 31 km^2, holding 3,583 buildings and 23,726 households. Second, we characterized the households of the municipality according to their consumption patterns and rooftop use preferences (Sections 2.3 and 2.4). A comparison between the potential resource supply and the consumption patterns helped us define viable scenarios of rooftop uses (Section 2.5).

2.1. Study area

Cerdanyola del Vallès (from now on Cerdanyola) is a medium-sized city of approximately 58 thousand inhabitants (IDESCAT, 2020) and is located in the metropolitan area of Barcelona (AMB; 36 municipalities and of 5.4 million inhabitants) (Catalonia; Spain). The municipality has a Mediterranean climate with mild winters and hot summers, a seasonal rain pattern that averages 610 l/m^2/year and an average global solar radiation of 4.56 kWh/m^2/day (AEMET, 2006). Cerdanyola also has an average of 1,478 heating degree days (base temperature 18°C) and 384 cooling degree days (base temperature 21°C) (based on the 2022 year) (Eurostat, 2023). The municipality was chosen because its urban forms are well differentiated and representative of those that can be found in other European cities: i) a dense historic center, ii) suburban extension, iii) different areas of housing estates, iv) dispersed single-family housing areas and v) isolated industrial parks (PDU, 2017). In this study, the historic center and suburban extension were grouped with the originary fabrics spatial pattern. A more accurate definition of each of the fabrics can be found in Table 1.

2.2. Estimation of the potential supply

2.2.1. Identification of suitable rooftops

The identification of suitable rooftops was conducted using different geoprocessing and spatial analyst tools in QGIS (version 3.22.2) and ArcMap (10.7.1) software (ESRI Inc.) following the methodology of Montealegre, García-Pérez, Guillén-Lambea, Monzón-Chavarrías, & Sierra-Pérez (2021). We used airborne laser scanning (ALS) data to build a digital surface model (DSM) of the city with a 1-meter cell size. These remote sensing data were captured by the National Plan of Aerial Orthophotography (PNOA ©Instituto Geográfico de España – Institut Cartogràfic de Catalunya) in September 2016 using a Leica ALS50 discrete return sensor with an average density of 0.5 points/m^2. The DSM was essential to deriving the rooftop slope, azimuth, shading and solar radiation, which were later used to select suitable rooftops for agriculture and photovoltaic (PV) panels via a multicriteria decision analysis in a geographic information system (GIS). See supplementary data 1 for details.

2.2.2. Estimation of the potential supply

2.2.2.1. Food: Urban agriculture. The installation of urban rooftop farming, in general, requires a load capacity of higher than 200 kg/m^2 on a flat roof (surface slope ≤10°) and insolation equal to or higher than 3.61 kWh/m^2/day (Nadal et al., 2017). For growing vegetables, a roof surface of at least 13 m^2 is needed, which can meet the vegetable consumption requirements for one person using soilless cultivation systems (Zambrano-Prado et al., 2021). Also, the selected vegetables are proven to be grown in this type of climate (Boneta, Rufí-Salís, Ercilla-Montserrat, Gabarrell, & Rieradevall, 2019).

2.2.2.2. Energy: Photovoltaic. We assumed that multicrystalline silicon (multi-Si) photovoltaic panels were installed and that the annual electricity (Ee obtained in kWh/year (y)) produced on each rooftop was calculated as:

$$Ee = IG \cdot \eta PV \cdot APV \cdot PR \tag{1}$$

Where IG is the global annual irradiance in kWh/m^2/y, Ƞ PV is the PV panel efficiency, APV is the area of the installed PV panels in m^2, and PR is the PV system performance ratio.

The global irradiance (IG) received for the panels depends on the PV tilt angle. We assume that the panels will be mounted following the rooftop slope if it is ≥38° or at the optimal angle for energy production (38°) for lower slopes and will be considered an increasing coefficient of 1.19 for solar irradiance, obtained from the PVGIS interactive tool (https://re.jrc.ec.europa.eu/pvg_tools/en/#PVP). The module's efficiency (Ƞ PV) was 16%, which is a typical value for crystalline silicon modules. The system performance ratio (PR) coefficient includes the losses in the system caused by cables, power inverters, dirt, etc. and by the modules, because they tend to lose power over the lifetime of the

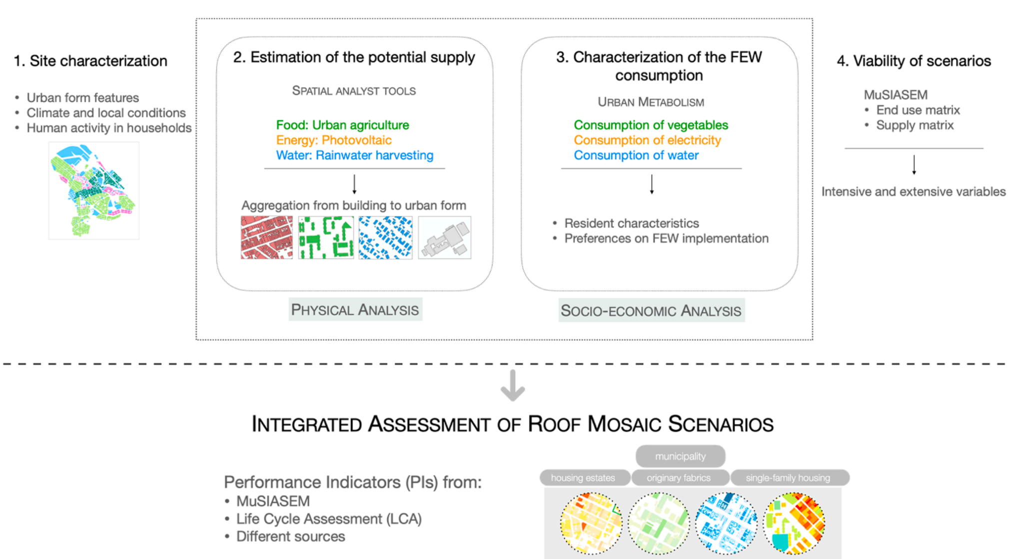
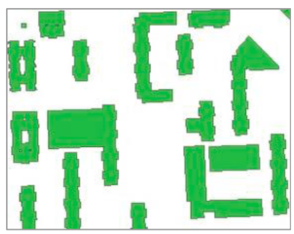
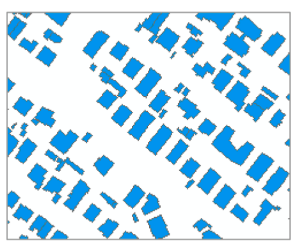
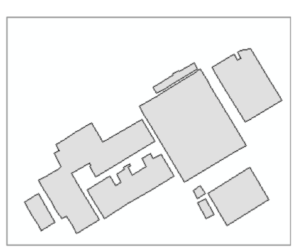


Fig. 1. Diagram of the main steps of the applied methodology. FEW: food-energy-water; MuSIASEM: Multi-scale Integrated Analysis of Societal and Ecosystem Metabolism.

Table 1
Urban morphologies of the study area.

Morphology	Description	Spatial pattern
Originary fabrics	These plots have experienced a strong process of densification. Continuing the compact city is the suburban extension. This is a morphology whose planning gives rise to an ordered road system, and a subdivision of plots whose development is focused on the alignment of the street. The result is the dense and compact perimeter block.	
Housing estates	The sprawl city is based on slab-like developments. Among the slabs, a first distinction is made between those which form part of unitary organizations, but which are not aligned with the street network. This category includes the well-known massive housing estates.	
Single-family housing areas	Single-family housing areas are represented by unitary organization slabs aligned to the street network, such as the contemporary suburban perimeter blocks. As part of single-family morphologies, the following are included: those that generate isolated buildings on plots or more compact fabrics, such as those produced by grouped terraced houses.	
Nonresidential uses	Public and private facilities, industrial parks or other buildings that do not fit the patterns described above have been considered as 'others'.	

system, depending also on the module working conditions and the temperature. The value obtained from PVGIS for this coefficient is 0.79 for flat and 0.76 for sloped roofs. If the slope value was greater than 38°, the pixel value assigned was 0.76 (sloped roof), if not, 0.79 (flat). Furthermore, the area solar radiation model uses a monthly resolution to summarize the annual global radiation. See additional details in supplementary data 1.

2.2.2.3. Water: rainwater harvesting. The only condition for water harvesting is the load capacity of the roof, which must be able to hold the weight of the water tank that has to be installed on the rooftop. However, the water tank's weight limit can be optimized depending on the roof and building and can be placed in different places (on the roof, on a lower story or underground) (Toboso-Chavero et al., 2019).

2.2.3. Aggregation: from building to urban morphologies

The building areas (i.e., roofs) were provided from the Spanish Cadastre (land registry) in shapefile format as polygon geometries (Dirección General del Catastro, 2014). After grouping the building footprints according to cadastral reference and height attributes, a 1-meter inside buffer was applied to the building polygons.

Rooftops were grouped according to their urban form following the categorization done by the future Metropolitan Plan (Metropolitan Urban Master Plan (PDU, currently under development)) (PDU, 2017). The morphological categories used in this study are defined based on their growth pattern and the evolution of the urban form (see Table 1).

2.3. Characterization of food, energy, and water (FEW) consumption

Domestic energy and water consumption was supplied by the distribution companies for 2018, 2019 and 2020 (note that the coronavirus pandemic started on 14 March 2020). An average of these three years was used. Data by street and number addresses of buildings with five or more households were aggregated by urban form and municipality.

Vegetable consumption was surveyed during April of 2021 (more than one year since the start of the coronavirus pandemic) along with the residents' preferences for the use of their rooftops (Table 2). The survey used a stratified random sample by urban form typology, i.e., housing estates, originary fabrics (including historic centers and suburban extensions) and single-family housing areas. The survey was answered by 1100 residents (raw data in open access: 10.5565/ddd.uab.cat/267206; see outcomes in supplementary data 2). We validated the results with the average values from official statistics.

2.4. Checking the viability of scenarios

We used the supply and end-use matrices from the multiscale integrated analysis of societal and ecosystem metabolism (MuSIASEM) (Giampietro, Mayumi & Ramos-Martin, 2009) to assess the viability and self-sufficiency of each urban morphology as defined by Toboso-Chavero, Villalba, Gabarrell Durany, & Madrid-López, (2021). Flow variables are defined as the total end use of each resource per year for each urban form and the municipality. The intensive variables were calculated based on human activity (hours, h) per type of household, determined by the working status and number of people per household as a proxy using the official time use survey (Generalitat de Catalunya, 2011). A detailed list of the analytical levels and the variables used is displayed in Table 3.

The FEW consumption was crossed with the potential rooftop production at the municipality and urban form levels to obtain resource self-sufficiency.

2.5. Integrated assessment of roof mosaic scenarios

To assess the different viable rooftop mosaic scenarios, we analyzed them in terms of their sustainability performance, i.e., environmental, social and economic performance. The performance indicators (PIs) defined are covered in Table 4 based on previous studies, residents' concerns – retrieved from the survey- and the most used on this topic (Toboso-Chavero, Madrid-López, Gabarrell, & Villalba, 2021; Toboso-Chavero et al., 2019).

Table 2
Datasets and sources for the current study of the socioeconomic profile of residents.

DATASETS	Consumption of vegetables	Consumption of energy	Consumption of water	Work status	Household occupation	Human activity	Preferences for the rooftop's systems
SOURCES	Survey (open access data)	Distribution company (confidential data)	Distribution company (confidential data)	Survey (open access data)	Survey (open access data)	Official statistics (Generalitat de Catalunya, 2011)	Survey (open access data)

Table 3
Definition of end-use and supply matrices and variables. Resources: vegetables (kilogram, kg); gram, g), electricity (kWh; MJ), and water (cubic meter, m^3; liter, l).

	Levels (scales)	Fund elements	Variables
end-use matrix	municipality (*n*)	human activity (HA)/year of household activities	*extensive variables*
	n-1 [housing estates originary fabrics single-family housing]		resource total consumption (kg; kWh; m^3)/year *intensive variables* resource metabolic rate (resource consumption (g; MJ; l)/hour of household activities)
supply matrix	municipality (*n*)	human activity (HA)/year of rooftop uses (maintenance)	resource losses (kg; kWh; m^3)/year
	n-1 [housing estates originary fabrics single-family housing]		resource total requirement (kg; kWh; m^3)/year resource savings (kg; kWh; m^3)/year

Table 4
Performance indicators (PIs) applied in the case study and the type, source or method proposed of these indicators.

Type of indicator	Performance indicators	Method/source
Sustainability	% Resource self-sufficiency	MuSIASEM
	Increase of green spaces (m^2)	Taylor et al., 2011; Van Herzele & Wiedemann, 2003
Environmental	kg CO_2 savings/year	LCA- Recipe method (H), Goedkoop *et al* 2013
	Global Warming (kg CO_2 eq)	LCA- Recipe method (H), Goedkoop *et al* 2013
Social	Energy poverty coverage (number of households)	The Green/EFA group of the European Parliament, 2016
	Water poverty coverage (number of households)	Lawrence, Meigh, & Sullivan, 2002
	Maintenance investment (hour/household/year)	MuSIASEM// Project data & Distribution companies
Economic	Investment (€/household)	Distribution companies
	Monetary savings (€/household/year)	Public prices

3. Results and discussion

3.1. Rooftop supply potential by urban form

The municipality depicts, as Fig. 2 illustrates, a historic center surrounded by suburban extension districts and housing estates and also some isolated housing estates mixed with wide extensions of single-family housing areas. The historic center and suburban extension districts, i.e., originary fabrics, occupy almost the same amount of land as the housing estates - approximately 70 hectares (ha) - and have a similar number of households, 7,619 and 7,637, respectively. In contrast, the single-family housing areas occupy almost four times more land (253 ha) than the other two urban forms and have only 11% more households. This greater occupation of land means that approximately 45% of the gross floor area of the municipality is colonized by single-family housing areas.

The municipality has a total of 72.7 ha of rooftops (Table 5) to be exploited for different purposes. All of them can be used for rainwater harvesting, as it is feasible to collect rainwater on any typology of roofs (Angrill et al., 2016). In terms of urban forms, single-family housing areas have a great potential due to the area of the rooftops (13,6 ha; 19%); however, out of these three urban forms, the "others" category (nonresidential uses) has the highest potential, with an area of 31.2 ha, which is 43% of the total potential roof area in the municipality. The rooftops of the municipality represent an average of 18.4% of the total land area. Comparing the percentage of rooftop surface to land occupied by urban form, the originary fabrics have the highest ratio (19.5%), while the lowest ratio is for single-family housing areas (7.5%). Therefore, more land area is needed in single-family housing areas, and in contrast, there are fewer open spaces (i.e., space between buildings) in the originary fabrics. Housing estates (12.3%) are in between these two urban forms.

We observed that only 46% of the total rooftop area of the municipality has potential for the implementation of PV panels, since the rest of the rooftops are not suitable due to either their slope or orientation. In this respect, originary fabrics and single-family housing areas reduce rooftop potentiality for PV panels to 45 and 46%, respectively, whereas housing estates leave a slightly less room for PV panels, reducing their potentiality of use to 42%. Potential rooftop areas for growing vegetables were reduced to 8% in the municipality. Regarding urban forms, the reduction was insignificant for housing estates (-4%), but there was a very relevant decrease in roof surface area for originary fabrics (-49%) and single-family housing (-57%); this means that level, well-oriented roofs are more common in housing estates than in the originary fabrics and single-family housing areas.

The comparison of supply and consumption reflects differences among urban forms (Fig. 2). Concerning vegetables, the situation of maximum production and minimum consumption is mainly identified in housing estates and some areas of the originary fabrics. On the other hand, single-family housing areas are characterized by medium to high production but also by high consumption. In relation to energy and water resources, the behavior is slightly different, as housing estates depict the highest production and the lowest consumption, while single-family housing and originary fabrics display high production but also high consumption of both energy and water. The category "others" exhibits the optimal case of minimum consumption and maximum production, but this is a consequence of accounting only for household consumption without including the nonresidential uses. Specific details

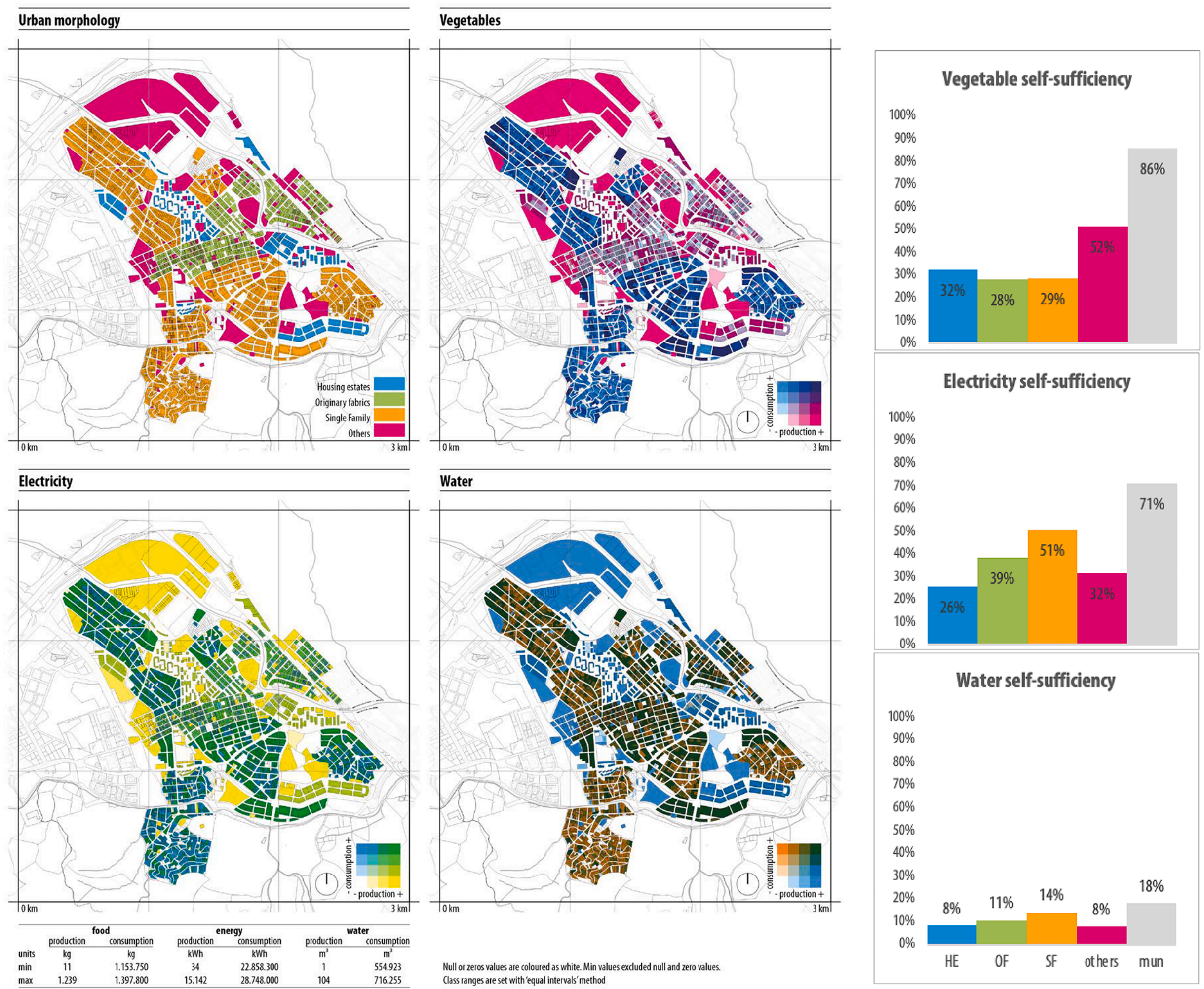


Fig. 2. Food, energy, and water consumption vs. production on rooftops. The first map identifies the three urban forms, e.g., housing estates, originary fabrics and single-family housing areas, as well as the others category. The rest of the maps represents the consumption vs. production of food, energy and water. The bar charts show the resource self-sufficiency by urban form and the total of the municipality. HE: housing estates; OF: originary fabrics; SF: single-family housing areas; others: public and private facilities and industrial parks; mun: municipality.

Table 5
Characterization of the rooftops at the municipality and urban form scales. Note the category others refers to public and private facilities and industrial parks.

	Municipality (total)	URBAN FORMS housing estates	originary fabrics	single-family housing	others
m^2 rooftop vegetables	274,707	35,251	31,885	37,752	165,185
m^2 rooftop electricity	334,245	36,907	63,095	88,506	145,738
m^2 rooftop water	727,254	87,664	136,118	191,054	312,418
m^2 land	5,650,695	714,910	696,334	2,532,754	1,706,697
number of households	23,726	7,619	7,637	8,470	0
m^2 rooftop/m^2 land (vegetables)	0.049	0.049	0.046	0.015	0.097
m^2 rooftop/m^2 land (electricity)	0.059	0.052	0.091	0.035	0.085
m^2 rooftop/m^2 land (water)	0.129	0.123	0.195	0.075	0.183
m^2 rooftop/household (vegetables)	11.6	4.6	4.2	4.5	7.0
m^2 rooftop/household (electricity)	14.1	4.8	8.3	10.4	6.1
m^2 rooftop/household (water)	30.7	11.5	17.8	22.6	13.2

can be found in an open access map https://uab.maps.arcgis.com/apps/mapviewer/index.html?webmap=7e72e430e1204418b3ceb6257d27e4ae

Assessing the availability of rooftops per household (Table 5), the municipality has an average of 31 m^2 rooftop/household (hh), including the "others" category that contributes to 13.2 m^2/hh for the entire municipality, approximately 42% of the total. By urban form, single-family housing obtained the highest value (22.6 m^2/hh), and the lowest was for housing estates (11.5 m^2/hh), caused by a higher density of households in housing estates and, therefore, less availability of roofs. For PV implementation (municipality:14.6 m^2/hh), the tendency was the same, but this availability was reduced by more than half, which means only 4.8 m^2 for housing estates, 8.3 m^2 for originary fabrics and 10.4 m^2 for single-family housing areas. As for the amount of space available for growing vegetables, the trend changes and housing estates have the highest ratio with 4.6 m^2/hh and the lowest is for the originary fabrics (4.2 m^2/hh).

3.2. Consumption characterization of the municipality and urban forms

The total consumption of residents in the different urban forms reveals remarkable differences in the extensive indicators (Fig. 3). Single-family housing areas account for 11% more dwellings than the originary fabrics and housing estates; however, vegetable consumption is 16% and 21% higher than in the originary fabrics and housing estates, respectively. The same is true for electricity consumption, where consumption is also 14% and 26% higher, respectively. Concerning water consumption, single-family housing areas consume a quarter more than housing estates, but no more than the originary fabrics, which is only 8% lower when there are 11% fewer households.

Comparing housing estates and originary fabrics, which have a similar number of households, the vegetable, electricity, and water consumptions are higher in the originary fabrics by 4%, 10% and 20%, respectively, suggesting higher consumption of all measured resources.

Examining the metabolic rates among people living in these urban forms, the highest rates of vegetable and electricity consumption correspond to the single-family housing areas (11.4 g/hour (h) and 0.85 MJ/hour, respectively) and the lowest to the housing estates (10.5 g/h and 0.75 MJ/h, respectively). Single-family housing areas consume approximately 8.6% more vegetables, 13% more electricity and 20% more water than housing estates do, which serves as a relevant reference for resource consumption in these single-family housing areas. The originary fabrics exhibit a more heterogeneous behavior. Inhabitants of these areas consume less vegetables and electricity than inhabitants of single-family dwellings but consume almost the same amount of water. The originary fabrics are usually an amalgam of different types of buildings, from low-rise apartment blocks to single-family housing; thus, consumption tends to be more variable compared to that of housing estates and single-family housing areas, which are more homogeneous urban forms.

When these outcomes are compared with those of other studies, some differences can be highlighted. The vegetable metabolic rate within this municipality is higher than that of Catalunya and lower than that of a nearby municipality (Badia del Vallès) composed only of housing estates, 9.9 g/h versus 13.1 g/h (Toboso-Chavero et al., 2021).The electricity metabolic rate, the results (municipality: 0.81 MJ/h) are similar to those of Barcelona (0.72 MJ/h), Europe (0.74 MJ/h) and the aforementioned municipality (0.82 MJ/h) (Pérez-Sánchez, Giampietro, Velasco-Fernández, & Ripa, 2019; Toboso-Chavero et al., 2021; Velasco-Fernández, 2017). In this case, the municipality has a lower water metabolic rate than Catalunya and Badia del Vallès (Madrid & Cabello, 2011; Toboso-Chavero et al., 2021).

3.3. Production characterization of the municipality and urban forms

Three possible resources (vegetables, electricity and water) for

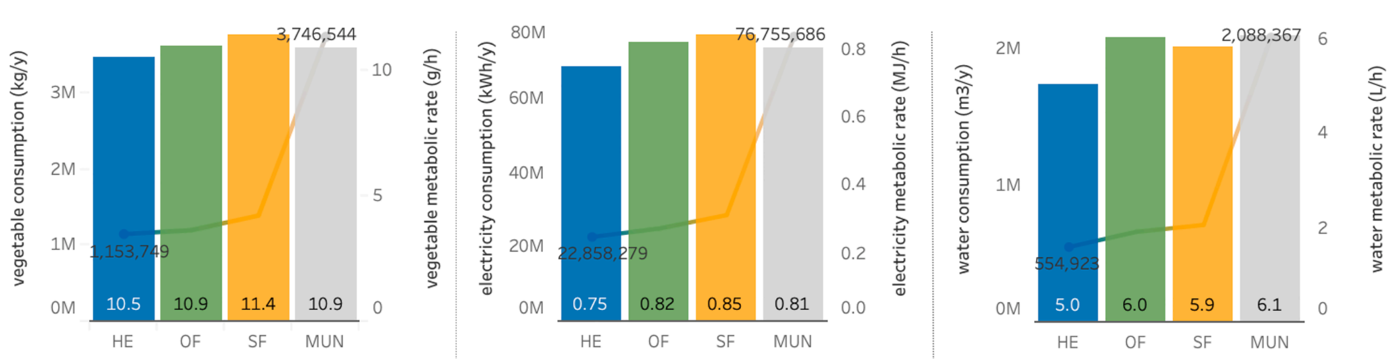


Fig. 3. Resource consumption (lines; extensive variable) and resource metabolic rate (bars; intensive variable) of the municipality and the different urban forms derived from the end-use matrix (see supplementary data 1). HE: housing estates; OF: originary fabrics; SF: single-family housing areas; MUN: municipality; h: hour; y: year; M: million.

potential rooftop production were assessed (Table 6). The combination of energy or vegetable production with rainwater harvesting is possible because no additional space is needed, and only a water tank is required, which can be placed on the roof, in other parts of the building or underground (Angrill et al., 2012).

The viability assessment returns, depending on the type of urban rooftop farming, between 78% (open-air farming, OAF) and 104% (rooftop greenhouses, RTG) of consumption supplied by rooftop production for the main vegetables consumed in Cerdanyola: tomatoes, lettuces, peppers, and green beans (59 kg/person/year). However, when each urban form is assessed on its own, these percentages decrease considerably because most available areas appear to be in the "others" category. The FEW consumption of the "others" category is not included, and only household consumption is included. The highest self-sufficiency is detected in housing estates, both in OAF (32% of self-sufficiency) and RTG (43% of self-sufficiency), due to their lower vegetable consumption; the highest vegetable total production is identified in single-family housing areas (535 tons), due to their having a greater surface area of rooftops.

The municipality has the potential to supply 36-71% of the total electricity. However, the largest potential is again in "others", at almost half (16-32%) of the potential production of electricity in the municipality. Comparing by urban form, the self-sufficiency of this resource in single-family housing doubles (25-51%) that in housing estates (13-26%), while the originary fabrics are somewhere in between (19-39%).

The municipality has the potential to collect approximately 377,699 m^3/year of rainwater. For potential rainwater harvesting, combining it with electricity production, this rainwater could be utilized for toilet flushing, covering 18% of the municipality's total requirements. In the case of crop irrigation in combination with urban rooftop farming (OAF and RTG), self-sufficiency soars to 101 and 129% in OAF and RTG, respectively. Again, the larger total surface area of rooftops in single-family dwellings means that they have the highest potential for harvesting rainwater and also in terms of self-sufficiency. Nevertheless, in all urban forms, the crops could be irrigated exclusively with rainwater, and there would even be a surplus for other uses.

Apart from the potential production of these resources in the municipality, it is also necessary to account for losses arising from conventional and centralized systems (Table 6), i.e., losses from the transformation and distribution of centralized electricity systems, losses from harvesting, transportation of centralized food and water distribution losses. The highest losses are assigned to conventional electricity systems by 63% (Domene & García, 2017), followed by vegetable losses by 25% related to harvesting and distribution (Caldeira, De Laurentiis, Corrado, van Holsteijn, & Sala, 2019) and water centralized systems by 7.4% (retrieved from a water distribution company). Consequently, all of these losses from centralized systems could also be reduced by applying strategies of local production in municipalities, i.e., the roof mosaic that we propose.

3.4. Food, energy, and water potential supply vs. consumption considering urban morphology

The urban forms analyzed in this study are characterized by different features that affect the implementation of the roof mosaic. Housing estates areas are distinguished by more extensive and flatter roofs than the other urban forms. The effect of this feature was demonstrated by the small difference between roofs available for energy and those for growing vegetables (only flat roofs), reducing their potential by only 4%. However, in the other urban forms, the reduction was approximately 50%. Likewise, the average roof surface in housing estate buildings is 420 m^2, which is almost three times larger than that of the other two urban forms. Housing estate buildings have remarkable potential for implementing rooftop farming, although these areas display viable open space between buildings that could also be used for urban farming, i.e., soil-based agriculture. Therefore, from an environmental point of view, flat roofs have more potential for implementing any type of FEW resource, so the promotion of flat roofs in new constructions could lead to more suitable exploitation of these spaces; evidently, other technical, social and economic criteria should also be considered.

Housing estates have the lowest ratio of m^2 of rooftops per household (11.5 m^2/household (hh)) and have the smallest apartments, averaging 86 m^2. Hence, there is an actual need to provide additional common spaces for these families. On the other hand, originary fabrics have more heterogeneous buildings, rooftops and consumption patterns than housing estates because of the combination of different constructions, mixing the old and new constructions of blocks and houses, and type of household. This urban form shows the lowest ratio of rooftops and open space, meaning that it is the most compact area, with few intermediate spaces between buildings and no possibility for further construction. The average rooftops are 127 m^2; therefore, some will be too small to implement rooftop farming. However, the best solution would be to use these rooftops for green infrastructures to grant these areas more green spaces. Regarding single-family housing areas, rooftops are the most limited, averaging 104 m^2, but they have the highest open spaces between buildings and are the largest households (102 m^2) with the highest FEW consumption. It would be more viable to implement PV panels in single-family housing areas due to the open space they have to use for soil-based agriculture and their characteristic small and sloping roofs. Therefore, urban forms are the key to implementing the most suitable systems on roofs as climate change adaptation strategies.

Considering the physical characteristics of these urban forms would make it easier to promote a strategy for self-sufficiency in these areas. However, consumption is another key parameter to consider when proposing a suitable strategy. This study was conducted under coronavirus pandemic conditions; therefore, time use or resource consumption could be influenced by these conditions. To account for the electricity and water consumption patterns, the average of three years, 2018, 2019 and 2020, was used. The difference between electricity consumption in 2018 and 2019 entailed an increase in total consumption of 0.77%, and between 2019 and 2020 there was an increase of 0.79%; energy consumption during both periods increased by nearly the same amount, although 2020 was the pandemic year with a lockdown lasting almost two months. In terms of water consumption, the differences were more relevant between years. The difference between 2018 and 2019 entailed a decrease of 0.9% in water consumption, while the difference between 2019 and 2020 was an increase of 7.8%. Therefore, a considerable rise in water consumption can be detected in the lockdown year (2020).

Housing estates have an average electricity consumption of 3,000 kWh/hh/year, originary fabrics of 3,290 kWh/hh/year and single-family housing areas of 3,394 kWh/hh/year. These consumption levels are similar to the Catalan average (3,400 kWh/hh/year) (Generalitat de Catalunya, 2020a), and below the Spanish average (3,918 kWh/hh/year), and the European average (3,700 kWh/hh/year) (Enerdata, 2020). In the municipality (88 m^3/hh/year), the lowest average water consumption is in housing estates (73 m^3/hh/year), and the originary fabrics and single-family housing areas are very similar (87 and 85 m^3/hh/year, respectively). Compared with the average in Spain (130 m^3/hh/year (2017)) or the European average (111 m^3/hh/year), there is a significant difference (The European Federation of National Associations of Water Services, 2017). The municipality's vegetable consumption (59 kg/person/year) is higher than the Catalan average (32 kg/person/year) (Generalitat de Catalunya, 2020b). Therefore, the self-sufficiency of each urban form depends not only on the availability of rooftops but also on the type of resident.

3.5. Municipality and urban form performance per scenario

According to the survey outcomes, most of the residents (77% total; women: 74.5%, men: 80%) would prefer to implement the production of electricity on their roofs (see details of the survey in supplementary data 2), thus choosing the most conservative and nondisruptive option.

Table 6
Supply matrix with the different resources (vegetables, electricity, and water at the municipality (MUN) and three urban forms. PV: photovoltaic panels; OAF: open-air farming; RTG: rooftop greenhouses; RWH: rainwater harvesting. NA: not available; SV: same value as each scenario; kh: kilohours; M: million.

SUPPLY MATRIX		FLOWS											
		VEGETABLES				ELECTRICITY				WATER			
		End use (kg/year)	Human activity (kh/year)	Savings (kg/year)	% Self-sufficiency	End use (kWh/year)	Human activity (kh/year)	Savings (kWh/year)	% Self-sufficiency	End use (m^3/year)	Human activity (kh/year)	Savings (m^3/year)	% Self-sufficiency
Centralized	Imported resource	3.742.841	NA	0	0	76.755.686	NA	0	0	2.088.367	NA	0	0
Centralized	Exported resource	0,00	NA	0	0	0	NA	0	0	0	NA	0	0
Decentralized	PV + RWH (municipality)		0				0,0093	54.693.528	71%		175	375.699	18%
	housing estates						0,0010	5.911.321	26%		21	45.287	8%
	originary fabrics						0,0017	9.724.183	39%		33	70.318	11%
	single-family housing						0,0025	14.623.427	51%		46	98.698	14%
	others						0,0040	24.434.597	32%		75	161.395	8%
Decentralized	OAF + RWH (municipality)		3.173	2.911.894	78%						175	375.699	101%
	housing estates		407	373.661	32%						21	45.287	95%
	originary fabrics		368	337.981	28%						33	70.318	163%
	single-family housing		436	400.171	29%						46	98.698	194%
	others		1.908	1.750.961	47%						75	161.395	44%
Decentralized	RTG + RWH (municipality)		1.846	3.889.851	104%						175	375.699	129%
	housing estates		237	499.154	43%						21	45.287	121%
	originary fabrics		214	451.492	37%						33	70.318	208%
	single-family housing		254	534.568	38%						46	98.698	246%
	others		1.110	2.339.020	62%						75	161.395	55%
Decentralized	ALL SYSTEMS (municipality)		1.255	1.700.436	45%		0,0046	27.346.764	36%		175	375.699	227%
	housing estates		161	218.204	19%		0,0005	2.955.661	13%		21	45.287	213%
	originary fabrics		146	197.368	16%		0,0009	4.862.092	19%		33	70.318	366%
	single-family housing		172	233.685	17%		0,0012	7.311.713	25%		46	98.698	433%
	others		754	1.022.495	27%		0,0020	12.217.298	16%		75	161.395	97%
Losses		1.105.096	NA	0	0	130.616.756	NA	0	0	168.883	NA	0	0
Total requirement		4.847.936	NA	SV	SV	207.372.442	NA	SV	SV	2.257.250	NA	SV	SV

Rainwater harvesting was accepted by 43% of the residents to implement on their roofs. The last option was rooftop farming (OAF and RTG), which was only accepted by 20-21% of the residents. They opted for more manageable and normalized systems on their roofs such as solar panels. Residents found more organizational and implementation issues with rooftop farming systems. Nonetheless, this proportion increases if the proposal is a combination of all of them (27%), i.e., production of energy and vegetables and rainwater harvesting. The survey conducted confirmed the challenges associated with implementing open-air farming or greenhouse systems on rooftops. While there is a feasible capacity to implement these systems, there are several real-world challenges that must be addressed. These challenges include lack of agreement among neighboring communities, resistance to change, economic difficulties, and other issues. It should be noted that this survey was conducted one year after the start of the coronavirus pandemic and amid the third wave in Catalonia; therefore, some responses could be influenced by these conditions. According to these results, four different scenarios were proposed for this municipality: the combination of electricity production and rainwater harvesting (scenario 1); vegetable production and rainwater harvesting (scenario 2 with OAF and scenario 3 with RTGs); and the combination of all of them, where half of the roofs would produce electricity and the other half vegetables with OAF and RTGs and rainwater harvesting on all roofs (scenario 4).

In consonance with the outcomes of the different indicators by scenario and urban form (Table 7), the highest values in vegetable self-sufficiency appear in scenario 3 (RTG + RWH) and in the housing estates urban form despite the RTG option being less accepted by residents. Accordingly, the largest area of new green spaces is in scenarios 2 and 3 (11.6 m^2/hh) for the municipality, and for housing estates (4.6 m^2/hh) due to a higher number of flat rooftops than in the other urban forms. On the other hand, for energy and water self-sufficiency, the single-family housing areas obtained the highest share because they have more rooftops that are suitable for energy and water production systems, and there are fewer households in these sites. The originary fabrics have more heterogeneous buildings and roofs; therefore, their values are in the middle.

In terms of environmental indicators, the highest CO_2 savings correspond to scenario 1 (PV + RWH) and the single-family housing areas due to a higher number of rooftop surfaces. In contrast, scenario 1 has the highest environmental impact in terms of kg CO_2 eq due to building these new facilities, and scenario 2 (OAF +RWH) and housing estates represent the lowest environmental impact, which means that scenario 2 is the least environmentally impacting system to construct because fewer materials and energy are required.

Concerning social indicators, energy poverty obtains the highest value in scenario 1 and single-family housing areas. This scenario would cover 71% of the household energy requirements in the municipality, and approximately 16,906 households could benefit from these systems. Additionally, for water poverty, all scenarios have the same potential, and the highest share is for single-family housing because of a higher rooftop surface area. The implementation of water systems on roofs would cover the water consumption of approximately 4,268 households, i.e., 18% of the total households. Comparing the maintenance investment of hours for families shows that scenario 1 is the least time-consuming, while scenarios 2 and 3 are the most demanding due to the care of the crops in these systems.

For economic indicators, scenario 3 requires the highest investment for the whole municipality; albeit, by urban form, the highest investment corresponds to single-family housing areas in scenario 1 due to there being more m^2 to cover and fewer families to split the cost. Conversely, the lowest investment in all scenarios, except for scenario 3, is allocated to housing estates due to a larger number of households to share the cost. However, single-family housing areas obtain the highest monetary savings in all scenarios. The highest savings are assigned to scenario 1, i.e., the combination of PV and RWH.

The category "others" has the highest number of roof areas; thus, there is a large area to exploit. However, their FEW consumption is not included in this study, only the municipality's domestic consumption. Additionally, these private and public facilities and industrial uses tend to have roofs with a very low load capacity and are made of metal sheets, fiber cement or other nonresistant materials (Nadal et al., 2017). Thus, this is a limitation to implementing rooftop farming systems.

Scenario 1 (PV+ RWH) obtained the most positive indicators at the municipality level; by urban form, housing estates show better outcomes in scenarios 3 and 4, with both dedicated to vegetable rooftop farming. This urban form has higher self-sufficiency in vegetables and lower monetary investment and environmental impacts. Because these areas have mostly flat roofs, they are ideal for implementing OAF or RTGs; however, these types of production systems were only accepted by 18% of the residents of this urban form. These types of roofs can be found in most housing estates. In contrast, these areas tend to have households at risk of water and energy poverty (Baldwin Hess, Tammaru, & van Ham, 2018). They are also distinguished by large open spaces among buildings that could be used for urban farming. Hence, the most viable option would be a combination of all the systems to alleviate these needs, i.e., the roof mosaic. Single-family housing acquired the most positive indicators. In particular, electricity production could support 51% of electricity requirements if PV panels are installed on all their roofs. These single-family roof areas are usually small and steep; therefore, it is more feasible to implement PV panels than rooftop farming and also because these urban forms have large open space of soil to make better use of it for vegetable farming. Finally, for the originary fabrics, the indicators depict average values; thus, no clear conclusion can be drawn. However, with the physical analysis of these areas, it is evident that they are the ones with the least open spaces. They are compact, so a greater area of green space is required. Therefore, most of these roofs could be used for urban farming (scenarios 2 and 3), or the largest roofs could be used for rooftop farming and the smallest roofs could be used for the implementation of electricity production systems, according to scenario 4. In this urban form, the acceptance of the type of production system was uneven, with 87% acceptance for PV panels and only 24% acceptance for rooftop farming systems. Likewise, all the rooftops of these urban forms can feasibly harvest rainwater.

At the municipality level, the current local government proposed a general action plan for 2020-2023 (Ajuntament de Cerdanyola del Vallès, 2019). Among the policies they proposed for the coming years, it is their intention to install renewable energy production infrastructure in some municipal facilities and to draft a new green infrastructure plan. Consequently, with the new data from this study in hand (see open access map: https://uab.maps.arcgis.com/apps/mapviewer/index.html?webmap=7e72e430e1204418b3ceb6257d27e4ae), both proposals could include more precise planning. Similarly, at the AMB scale through the Metropolitan Urban Master Plan (PDU), of which this municipality is part, the future urban territory is defined and structured, and a connected network of green infrastructures of green avenues, streets, connectors, parks and paths is being proposed (AMB, 2020). According to the outcomes of this study, these proposed green and productive spaces on roofs—applying scenarios 2, 3 or 4—would contribute from 14 to 27 ha to the green network proposed by the AMB. Moreover, following the New Green Deal of the European Union (EU), any of these four scenarios we present are in harmony with the policy areas of the EU action plan, which are farm to fork, sustainable agriculture and clean energy (European Commission, 2019). Thus, this study is an asset for all the proposed policies at the local and supralocal levels to enhance the current and future situation of this and other municipalities.

4. Conclusions

This study presents the roof mosaic urban strategy and illustrates the current consumption profiles and resource potential production of urban

Table 7
Municipality and urban form performance per scenario proposed; no: number; PV: photovoltaic panels; RWH: rainwater harvesting; OAF: open-air farming; RTG: rooftop greenhouses.

FUTURE SCENARIOS			SCENARIO 1 PV+ RWH	SCENARIO 2 OAF+ RWH	SCENARIO 3 RTG+ RWH	SCENARIO 4 All combined
sustainability indicators	municipality	% vegetables self-sufficiency	0%	78%	104%	45%
	housing estates		0%	32%	43%	19%
	originary fabrics		0%	28%	37%	16%
	single-family		0%	29%	38%	17%
	others		0%	47%	62%	27%
	municipality	% energy self-sufficiency	71%	0%	0%	36%
	housing estates		26%	0%	0%	13%
	originary fabric		39%	0%	0%	19%
	single-family		51%	0%	0%	25%
	others		32%	0%	0%	16%
	municipality	% water self-sufficiency	18%	101%	129%	227%
	housing estates		8%	95%	121%	213%
	originary fabrics		11%	163%	208%	366%
	single-family		14%	194%	246%	433%
	others		8%	44%	55%	97%
	municipality	increase of green spaces (m^2/household)	0	11.6	11.6	5.8
	housing estates		0	4.6	4.6	2.3
	originary fabrics		0	4.2	4.2	2.1
	single-family		0	4.5	4.5	2.2
	others		0	7.0	7.0	3.5
environmental indicators	municipality	tonne CO_2 savings /year	33,323	5,618	7,459	19,931
	housing estates		3,603	720	956	2,221
	originary fabrics		5,926	662	876	3,347
	single-family		8,909	789	1,042	4,912
	others		14,885	3,355	4,462	9,397
	municipality	global warming (tonne CO_2 eq)	32,719	1,337	2,704	17,604
	housing estates		3,617	168	344	1,967
	originary fabrics		6,176	183	342	3,246
	single-family		8,663	233	421	4,527
	others		14,264	736	1,558	7,846
social indicators	municipality	energy poverty coverage (no. households)	16,906	0	0	8,453
	housing estates		1,970	0	0	985
	originary fabrics		2,953	0	0	1,476
	single-family		4,308	0	0	2,154
	others		7,553	0	0	3,776
	municipality	water poverty coverage (no. households)	4,268	4,268	4,268	4,268
	housing estates		622	622	622	622
	originary fabrics		806	806	806	806
	single-family		1,167	1,167	1,167	1,167
	others		1,834	1,834	1,834	1,834
	municipality	maintenance investment (hour/household/year)	5	139	83	58
	housing estates		2	55	33	23
	originary fabrics		3	51	31	22
	single-family		4	55	34	24
	others		2	83	49	34
economic indicators	municipality	investment (€/household)	5,121	3,188	6,424	4,962
	housing estates		1,778	1,261	2,554	1,842
	originary fabrics		3,001	1,269	2,436	2,426
	single-family		3,795	1,418	2,663	2,917
	others		2,229	1,824	3,770	2,512
	municipality	monetary savings (€/household/year)	1,851	335	437	1,118
	housing estates		624	133	174	389
	originary fabrics		1,023	127	164	584
	single-family		1,386	139	179	772
	others		826	196	258	527

rooftops that allow the design of viable future scenarios for implementing food, energy, and water rooftop systems in a medium-sized Mediterranean city. We used a georeferenced physical and socioeconomic analysis to gain an integrated perspective of their potential for a more self-sufficient and less environmentally impacting urban scenario.

The city studied has three main urban forms: housing estates, originary fabrics and single-family housing areas, as well as the “others” category, which includes public facilities and industrial and retail parks. The morphology related to rooftops, buildings, and open space is summarized in Table 8.

Every urban form is distinguished by different features that more or less support the implementation of one or another FEW system. By characterizing the city by urban forms, the analysis is more specific and precise and aids in fostering policies in similar physical areas. This study serves as a reference for other European cities with these urban forms. In Catalonia, many cities are composed of these types of morphologies (PDU, 2017). For instance, Barcelona has a historic center, a vast suburban extension district, housing estates, and some isolated single-family housing areas.

When considering the consumption of these urban forms and their potential production, we can see that the lowest consumption rates are in housing estates, which consequently demonstrate the highest self-sufficiency in vegetable production (19%-43%). However, electricity production does not occur due to the large number of households and less space on roofs. Conversely, single-family housing inhabitants were the highest consumers of vegetables, electricity and water (together with the originary fabrics), but because the buildings only house one family per dwelling, they have a greater roof surface area and therefore would benefit most from self-sufficiency in electricity (25% and 51%) and water (14%-443%). However, not in vegetable self-sufficiency because most of them are steep rooftops on which farming systems cannot be placed. On the other hand, originary fabrics have average values for both consumption and potential production due to the diversity of their buildings, type of families and roofs.

The four scenarios proposed reveal significant shares of self-sufficiency in vegetables (16-104%), electricity (13-71%) and the required irrigation water (13-433%) for the municipality and the different urban forms. It is also important to create new green spaces between 2.1 and 11.6 m^2/hh, with housing estates being the urban form that would benefit the most. In the same way, these scenarios would help to considerably reduce energy and water poverty and their carbon footprints (662-33,323 tonnes CO_2 eq/year) by producing their own FEW resources on-site. Therefore, these scenarios can facilitate the adaptation of municipalities and Catalonia to climate change, where predictions are not very optimistic regarding temperature increase and lack of precipitation (Altava-Ortiz & Barrera-Escoda, 2020). The use of urban forms for assessing consumption patterns could aid us in suggesting more specific urban climate solutions and adapting these areas to climate change accordingly.

Further insights into these urban forms in other small, medium, and large cities using this bottom-up methodology will be useful to evaluate if they follow the same pattern. Similar urban climate solutions can be implemented, leading to further knowledge on the physical and socioeconomic aspects of these urban forms and how to take advantage of their constructions and the type of resident. One of the key challenges is the availability of local data pertaining to consumption patterns, citizens’ preferences, and cadastre (land registry). Nonetheless, the EU is taking steps to overcome this hurdle through the INSPIRE directive, which seeks to establish a comprehensive infrastructure for spatial information in all member states (European Commission, 2023). In addition, a close collaboration among stakeholders (public institutions, inhabitants, academia, businesses, etc.) is crucial for successfully implementing these types of urban solutions. Concerning technical issues related to the implementation of these food-energy-water systems, this methodology serves as a first approach at the neighborhood, community, or urban form level, however, a more specific study of the rooftops under study should be carried out, such as type of rooftop material, load capacity or accessibility. Further efforts should be made to find viable urban mitigation and adaptation strategies to climate change according to urban forms and resident typologies.

Table 8
Summary of the three urban forms in the municipality.

Urban form	Rooftops	Buildings	Open space
housing estates	most of them flat and large	middle and high-rise blocks	open space among constructions
originary fabrics	heterogeneity of roofs	heterogeneity of buildings	compact areas, few open spaces
single-family housing areas	small and steep	semidetached and detached housing	those with the most open spaces

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data are shared with a link in the manuscript and in the supplementary data 1 and 2.

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Supplementary materials

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