Integrating the food, energy and water nexus on urban rooftops

Susana Toboso Chavero

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Doctoral thesis

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A thesis submitted in fulfilment of the requirements for the Doctoral degree in Environmental Sciences and Technology

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THIS THESIS HAS COST:

kg CO_2 eq	€
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The present thesis entitled "Integrating the food, energy and water nexus on urban rooftops" has been carried out at the Institute of Environmental Science and Technology (ICTA-UAB) at Universitat Autònoma de Barcelona (UAB) by Susana Toboso Chavero

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Cristina Madrid López　　　Gara Villalba Méndez　　　Xavier Gabarrell Durany

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“Carpe diem! seize the day, make your lives extraordinary!”

Dead Poets Society

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Abbreviations

ALO	Agricultural Land Occupation
AMB	Metropolitan Area of Barcelona
B	Building
CC	Climate Change
CE	Circular Economy
CEEAH	Ethics Committee on Animal and Human Experimentation
CED	Cumulative Energy Demand
CPBT	CO_2 Payback Time
D	Demand
DSM	Digital Surface Model
E	Energy
EI	Environmental indicator average
E-LCA	Environmental Life Cycle Assessment
EPBT	Energy Payback Time
ET	Ecotoxicity
EU	European Union
F	Flow
FAO	Food and Agriculture Organisation
FE	Freshwater Eutrophication
FEW	Food-Energy-Water
FRS	Fossil Resource Scarcity
FU	Functional Unit
G	Energy generation
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GIS	Geographic Information System
GLO	Global
GR	Green Roof
GTAP	Global Trade Analysis Project
GW	Global Warming
HA	Human Activity
HE	Housing Estates
HH	households
IAP2	The International Association for Public Participation
I	Installation
ICTA	Environmental Science and Technology Institute
IG	Global Irradiance

IN	Average indicator
ISO	International Standards Organization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LIDAR	Light Detection and Ranging System
LO	Land Occupation
MET	Marine Ecotoxicity
MCDM	Multicriteria Decision-Making
MuSIASEM	Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism
N	Neighborhood
NA	Not available
NGO	Non-governmental Organization
NIMBY	Not in my back yard
OAF	Open-Air Farming
OD	Ozone Depletion
OF	Originary Fabrics
P	Production
PDU	Metropolitan Urban Master Plan
PIs	Performance Indicators
PLU	Local Urban Plan in France
PNOA	National Plan of Aerial Orthophotography
PV	Photovoltaic panels
RCE	Public Research Centers in Spain
ROW	Rest of the World
RTG	Rooftop Greenhouse
RWH	Rainwater Harvesting
SDG	Sustainable Development Goals
SETAC	Society of Environmental Toxicology and Chemistry
SF	Single-Family housing
SHDB	Social Hotspots Database
SIGI	Social Institutions and Gender Index
S-LCA	Social Life Cycle Assessment
SSN	Self-Sufficiency indicator
ST	Solar Thermal panels
T	Transport
TA	Terrestrial Acidification
TB	Total number of buildings

TBL	Triple Bottom Line
TET	Terrestrial Ecotoxicity
U	Unit product
UA	Urban Agriculture
ULO	Urban Land Occupation
UM	Use & Maintenance
UN	United Nations
UNEP	United Nations Environment Programme
URF	Urban Rooftop Farming
V	Vegetables
W	Water
WAVE+	Water Accounting and Vulnerability Evaluation Model
WC	Water Consumption
WD	Water Depletion
WE	Wind Energy
WHO	World Health Organization

UNITS

cm^3	cubic centimeter
DALY	Disability-Adjusted Life-Year
€	euro
g	gram
h	hours
kg	kilogram
kh	kilo hours
km^2	square kilometer
kt	kiloton
KWh	Kilowatt hour
hh	household
ha	hectare
inh	inhabitant
L/l	liter
m^2	square meter
m^3	cubic meter
M	million
MJ	Mega Joule
y	year

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Summary

Sustainable urban strategies are worldwide spreading with the common goal of improving the habitats where most population lives, i.e., cities. These strategies cover many different fields, such as mobility, air pollution, resources provision, etcetera, and are key to transforming cities into healthier, fairer, and greener sites. By the same token, metropolises require an array and large quantities of resources to meet the needs of their citizens. Cities are often based on a linear economy system, the traditional system of *"take-make-dispose",* and three of the most essential resources required in urban areas are food, energy and water (FEW). Hence, cities must find circular solutions, closing loops of energy and materials, avoiding long distances and the generation of waste and emissions. However, cities have several limitations to apply certain types of strategies, but still, there are more viable ones, such as the use of underutilized rooftops to implement the production of vegetables, energy or rainwater harvesting, i.e., the Roof Mosaic approach named by authors. Accordingly, the present thesis hypothesizes that the use of rooftops can offer environmental, social and economic benefits in urban areas aiming to optimize FEW resources and enhance city sustainability. To this end, four main research questions are posed throughout the thesis:

- **Question 1:** What are the environmental and socio-economic impacts, and the benefits of the implementation of food production, renewable energy infrastructures and rainwater harvesting, on available rooftops for the purpose of self-sufficient cities?

- **Question 2:** To what extent does this new urban-nexus system contribute to a future self-sufficient city?

- **Question 3:** How can this new urban-nexus system be implemented in different contexts and scales?

- **Question 4**: What is the social perception and acceptance of this new urban-nexus system?

The subsequent sections summarize the relevant contribution of this dissertation in the context of sustainable urban strategies.

Materials & methods. Innovation in the methodological combination

This dissertation includes a set of different methodologies from different fields. The innovation of this thesis lies in the combination of different consolidated methods that have rarely been used together. These mixed methods provided a more comprehensive analysis of this urban strategy. We combined urban metabolism tools with a life cycle assessment approach or a sustainability assessment with public participation. We also assessed the Roof Mosaic from an environmental, social and economic perspective. The scales of analysis also incorporated different levels: building, group of building, neighborhood and municipalities and different urban fabrics:

housing estates, originary fabrics and single-family housing areas. Consequently, the outcomes are more robust and consistent having applied this diversity of methods and scales.

A guideline for the implementation of the Roof Mosaic

The main goal of this dissertation is to advance in the use of urban rooftops as a potential space for producing food, energy and water in cities, and to alleviate exports of these resources. Thus, a guideline for the implementation of the food-energy-water on rooftops is compulsory to progress in this type of urban strategy. We present a complete guide to its implementation in cities, from the technical aspects to environmental, social and economic indicators to be measured. Urban planners and policymakers can use this guideline to select the type of system(s) to implement in their urban area more accurately and in a stakeholder-oriented way.

An integrated participatory assessment of the use of rooftops in different urban areas

To assess the Roof Mosaic, we applied it at different scales and different urban areas. The two first studies were based on housing estates, and the third was based on a municipality with three characteristic urban forms. We evaluated the food-energy-water metabolism of these urban areas, concluding that housing estates had the lowest electricity metabolic rate (0.75-0.82 MJ/hour) and the lowest vegetable and water metabolic rates in one of the two housing estates studied. In contrast, the single-family housing areas displayed the highest rates in vegetable and electricity metabolic rates.

Regarding the different sustainability indicators, we found a relevant share of self-sufficiency in vegetable supply, from 17 to 115% through the implementation of open-air farming or greenhouses on roofs, also in energy production with percentages of 7-71% depending on the scenario implemented. In the case of water self-sufficiency, the coverage was lower than the other two resources; only for irrigation of crops, the percentage is high 66-227% but for specific uses, such as flushing and laundry the percentages are low, from 18-38% for single use, or laundry or flushing.

In terms of environmental indicators, scenarios with more rooftops implementing photovoltaic panels depict high CO_2 savings but simultaneously high environmental impacts in their construction phase (98 kg CO_2 eq/m^2/year). Scenarios implementing productive green spaces unveiled a relevant increase of these spaces from1.7 to 4.7 m^2/inhabitant, which is for example higher than the city of Barcelona's target of increasing 1 m^2/inhabitant by 2030. Socio-economic indicators illustrate that these new food-energy-water systems could cover between 9-71% and 7-18% of energy and water poverty, respectively. Concerning monetary savings, households could save between 335-1801 €/year depending on the scenario implemented, which is a significant saving, especially for vulnerable groups.

To engage stakeholders in the design of future scenarios, we evaluated the public perception of these strategies through participatory processes and surveys, revealing that most residents preferred to implement photovoltaic panels on their rooftops (65-77%). This is a more accepted system to implement among citizens; however, for the implementation of urban rooftop farming, the percentage willing to accept was lower. In one of the municipalities only 7%, and in the second one the proportion augmented to 20-21%. Therefore, there is a necessity for policies aimed at the use of rooftops for other systems than photovoltaic panels such as open-air farming, rooftop greenhouses, green roofs or rainwater harvesting.

Future challenges in cities

This dissertation has laid the foundations for future research lines related to the use of rooftops as an "urban space of production". Imagine what it could be like to live in a city with green and productive spaces, producing its energy and using rainwater to irrigate its crops. Therefore, the next logical step is to set up different pilot projects in different urban forms and types of residents, aiming to monitor and test the Roof Mosaic, and to gain a better understanding of the limitations and benefits that these new spaces can bring. New spaces providing not only resource production but also social cohesion spaces, biodiversity, and other types of ecosystem services in cities such as the enhancement of heat island effect or air pollution. Furthermore, it is indispensable to include all stakeholders in the design of urban strategies to match their preferences and needs with effective climate change solutions in cities.

Resum

Les estratègies urbanes sostenibles s'estan estenent per tot el món amb l'objectiu comú de millorar els hàbitats on viu la major part de la població, és a dir, les ciutats. Aquestes estratègies impliquen molts camps diferents, com la mobilitat, la contaminació atmosfèrica, la provisió de recursos, etcètera, i són clau per transformar les ciutats en llocs més sans, justos i ecològics. D'altra banda, les metròpolis necessiten una gran quantitat de recursos per satisfer les necessitats dels seus ciutadans. Les ciutats es basen en un sistema d'economia lineal, el tradicional "prendre-fer-rebutjar", i tres dels recursos més essencials que es requereixen a les zones urbanes són els aliments, l'energia i l'aigua (FEW de les seves sigles en anglès). Per això, les ciutats han de trobar solucions circulars, tancant els cercles d'energia i materials, evitant les llargues distàncies i la generació de residus i emissions. No obstant això, les ciutats tenen diverses limitacions per aplicar cert tipus d'estratègies, però així i tot, hi ha algunes més viables, com l'ús de les cobertes infrautilitzades per implementar la producció d'hortalisses, energia o recollida d'aigua de pluja, és a dir, l'enfocament de les cobertes mosaic, anomenat així pels autors. En conseqüència, la present tesi planteja la hipòtesi que l'ús de les cobertes pot oferir beneficis ambientals, socials i econòmics a les zones urbanes, per tal d'optimitzar els recursos de FEW i millorar la sostenibilitat de les ciutats. Per a això, al llarg de la tesi es plantegen quatre preguntes principals d'investigació:

- **Pregunta 1**: Quins són els impactes mediambientals i socioeconòmics, així com els beneficis de la implantació de la producció d'aliments, les infraestructures d'energia renovable i la recollida d'aigua de pluja, a les cobertes disponibles per tal d'aconseguir ciutats autosuficients?
- **Pregunta 2**: En quina mesura contribueix aquest nou sistema urbà-nexe a una futura ciutat autosuficient?
- **Pregunta 3**: Com es pot aplicar aquest nou sistema urbà-nexe en diferents contextos i escales?
- **Pregunta 4**: Quina és la percepció i acceptació social d'aquest nou sistema urbà-nexe?

Les seccions següents resumeixen la contribució rellevant d'aquesta dissertació en el context de les estratègies urbanes sostenibles.

Materials i mètodes. Innovació en la combinació metodològica

Aquesta tesi inclou un conjunt de diferents metodologies procedents de diferents camps. La innovació d'aquesta tesi rau en la combinació de diferents mètodes consolidats que poques vegades s'han utilitzat conjuntament. Aquests mètodes mixtos proporcionen una anàlisi més completa d'aquesta estratègia urbana. Combinem eines de metabolisme urbà amb un enfocament d'avaluació del cicle de vida o una avaluació de la sostenibilitat amb participació pública. També vam avaluar les cobertes mosaic des d'una perspectiva ambiental, social i

econòmica. Les escales d'anàlisi també es van incorporar a diferents nivells: edifici, grup d'edificis, barri i municipis i diferents teixits urbans: polígons d'habitatges, teixits originaris i àrees d'habitatges unifamiliars. En conseqüència, els resultats són més sòlids i consistents a l'haver aplicat aquesta diversitat de mètodes i escales.

Una guia per a la implantació de les cobertes mosaic

L'objectiu principal d'aquesta tesi és avançar en l'ús de les cobertes urbanes com a espai potencial per a la producció d'aliments, energia i aigua a les ciutats, i alleujar les exportacions d'aquests recursos. Per tant, una guia per a la implementació de aliments-energia-aigua a les cobertes és obligatòria per progressar en aquest tipus d'estratègia urbana. Presentem una guia completa per a la seva implantació a les ciutats, des dels aspectes tècnics fins als indicadors ambientals, socials i econòmics que s'han de mesurar. Els planificadors urbans i els responsables polítics poden utilitzar aquesta guia per seleccionar el tipus de sistema(s) a implantar a la seva zona urbana amb més precisió i orientada a les parts interessades.

Una avaluació participativa integrada de l'ús de les cobertes en diferents zones urbanes

Per avaluar les cobertes mosaic, aquest va ser aplicat a diferents escales i en diferents zones urbanes. Els dos primers estudis es van basar en polígons d'habitatges, i el tercer en un municipi amb tres formes urbanes característiques. Avaluem el metabolisme d'alimentació-energia-aigua d'aquestes zones urbanes, concloent que els polígons d'habitatges van obtenir la taxa metabòlica d'electricitat més baixa (0,75-0,82 MJ/hora) i les taxes metabòliques d'hortalisses i aigua més baixes en un dels dos polígons d'habitatges estudiats. Per contra, les zones d'habitatges unifamiliars van mostrar els índexs més alts en les taxes metabòliques d'hortalisses i electricitat.

Respecte als diferents indicadors de sostenibilitat, es va trobar una quota rellevant d'autosuficiència en el subministrament d'hortalisses, del 17 al 115% mitjançant la implantació de cultius a l'aire lliure o hivernacles a les cobertes, també a la producció d'energia amb percentatges del 7-71% depenent de l'escenari implantat. En el cas de l'autosuficiència d'aigua, la cobertura va ser menor que la dels altres dos recursos; només per al reg dels cultius, el percentatge és alt 66-227%, però per als usos específics, com fer la bugada i el de les cisternes del vàter, els percentatges són baixos, del 18-38% per a un únic ús.

En termes d'indicadors ambientals, els escenaris amb més cobertes que implementen panells fotovoltaics mostren un alt estalvi de CO_2, però simultàniament un alt impacte ambiental en la seva fase de construcció (98 kg CO_2 eq/m^2/any). Els escenaris que implementen espais verds productius revelen un augment rellevant d'aquests espais d' 1,7 a 4,7 m^2/habitant, que és per exemple superior a l'objectiu de la ciutat de Barcelona d'augmentar 1 m^2/habitant per 2030. Els indicadors socioeconòmics il·lustren que aquests nous sistemes d'alimentació-energia-aigua podrien cobrir entre el 9-71% i 7-18% de la pobresa energètica i d'aigua, respectivament. Pel que fa a l'estalvi monetari, les llars podrien estalviar entre 335-1801 €/any en funció de l'escenari aplicat, el que suposa un estalvi important, especialment per als grups vulnerables.

Per involucrar les parts interessades en el disseny de futurs escenaris, vam avaluar la percepció pública d'aquestes estratègies a través de processos participatius i enquestes, revelant que la majoria dels residents preferien implementar panells fotovoltaics en les seves cobertes (65-77%). Aquest és un sistema més acceptat pels ciutadans; però, per a la implantació de l'agricultura urbana en les cobertes, el percentatge disposat a acceptar va ser menor. En un dels municipis només el 7%, i en el segon la proporció va pujar al 20-21%. Per tant, calen polítiques dirigides a la utilització de les cobertes per a altres sistemes diferents dels panells fotovoltaics, com l'agricultura i hivernacles en les cobertes, els sostres verds o la recollida d'aigua de pluja.

Reptes futurs en les ciutats

Aquesta tesi ha posat les bases per a futures línies d'investigació relacionades amb l'ús de les cobertes com a "espai urbà de producció". Imaginem com podria ser viure en una ciutat amb espais verds i productius, produint la seva energia i utilitzant l'aigua de pluja per regar els seus cultius. Per això, el següent pas lògic és posar en marxa diferents projectes pilot en diferents formes urbanes i tipus de residents, amb l'objectiu de controlar i provar les cobertes mosaic, i conèixer millor les limitacions i beneficis que poden aportar aquests nous espais. Aquests espais proporcionen no només la producció de recursos, sinó també espais de cohesió social, biodiversitat i altres tipus de serveis ecosistèmics a les ciutats, com la millora de l'efecte illa de calor o la contaminació de l'aire. A més, és indispensable incloure a totes les parts interessades en el disseny de les estratègies urbanes per fer coincidir les seves preferències i necessitats amb les solucions efectives al canvi climàtic a les ciutats.

Resumen

Las estrategias urbanas sostenibles se están extendiendo por todo el mundo con el objetivo común de mejorar los hábitats donde vive la mayor parte de la población, es decir, las ciudades. Estas estrategias abarcan muchos campos diferentes, como la movilidad, la contaminación atmosférica, la provisión de recursos, etcétera, y son clave para transformar las ciudades en lugares más sanos, justos y ecológicos. Por otra parte, las metrópolis necesitan una gran cantidad de recursos para satisfacer las necesidades de sus ciudadanos. Las ciudades se basan en un sistema de economía lineal, el tradicional "tomar-hacer-desechar", y tres de los recursos más esenciales que se necesitan en las zonas urbanas son los alimentos, la energía y el agua (FEW). Por ello, las ciudades deben encontrar soluciones circulares, cerrando los círculos de energía y materiales, evitando las largas distancias y la generación de residuos y emisiones. Sin embargo, las ciudades tienen varias limitaciones para aplicar cierto tipo de estrategias, pero, aun así, hay otras más viables, como el uso de las cubiertas infrautilizadas para implementar la producción de hortalizas, energía o recolección de agua de lluvia, es decir, el enfoque de las cubiertas mosaico, llamado así por los autores. En consecuencia, la presente tesis plantea la hipótesis de que el uso de las cubiertas puede ofrecer beneficios ambientales, sociales y económicos en las zonas urbanas, con el fin de optimizar los recursos de FEW y mejorar la sostenibilidad de las ciudades. Para ello, a lo largo de la tesis se plantean cuatro preguntas principales de investigación:

- **Pregunta 1**: ¿Cuáles son los impactos medioambientales y socioeconómicos, así como los beneficios de la implantación de la producción de alimentos, las infraestructuras de energía renovable y la recogida de agua de lluvia, en las cubiertas disponibles con el fin de lograr ciudades autosuficientes?
- **Pregunta 2**: ¿En qué medida contribuye este nuevo sistema urbano-nexo a una futura ciudad autosuficiente?
- **Pregunta 3**: ¿Cómo puede aplicarse este nuevo sistema urbano-nexo en diferentes contextos y escalas?
- **Pregunta 4**: ¿Cuál es la percepción y aceptación social de este nuevo sistema urbano-nexo?

Las secciones siguientes resumen la contribución relevante de esta disertación en el contexto de las estrategias urbanas sostenibles.

Materiales y métodos. Innovación en la combinación metodológica

Esta tesis incluye un conjunto de diferentes metodologías procedentes de distintos campos. La innovación de esta tesis radica en la combinación de diferentes métodos consolidados que rara vez se han utilizado conjuntamente. Estos métodos mixtos proporcionan un análisis más completo de esta estrategia urbana. Combinamos herramientas de metabolismo urbano con un

enfoque de evaluación del ciclo de vida o una evaluación de la sostenibilidad con participación pública. También evaluamos las cubiertas mosaico desde una perspectiva ambiental, social y económica. Las escalas de análisis también incorporaron diferentes niveles: edificio, grupo de edificios, barrio y municipios y diferentes tejidos urbanos: polígonos de viviendas, tejidos originarios y áreas de viviendas unifamiliares. En consecuencia, los resultados son más sólidos y consistentes al haber aplicado esta diversidad de métodos y escalas.

Una guía para la implantación de las cubiertas mosaico

El objetivo principal de esta tesis es avanzar en el uso de las cubiertas urbanas como espacio potencial para la producción de alimentos, energía y agua en las ciudades, y aliviar las exportaciones de estos recursos. Por lo tanto, una guía para la implementación de la alimentación-energía-agua en las cubiertas es obligatoria para progresar en este tipo de estrategia urbana. Presentamos una guía completa para su implantación en las ciudades, desde los aspectos técnicos hasta los indicadores ambientales, sociales y económicos que deben medirse. Los planificadores urbanos y los responsables políticos pueden utilizar esta guía para seleccionar el tipo de sistema(s) a implantar en su zona urbana con mayor precisión y orientada a las partes interesadas.

Una evaluación participativa integrada del uso de las cubiertas en diferentes zonas urbanas

Para evaluar las cubiertas mosaico, este fue aplicado a diferentes escalas y en distintas zonas urbanas. Los dos primeros estudios se basaron en polígonos de viviendas, y el tercero en un municipio con tres formas urbanas características. Evaluamos el metabolismo de alimentación-energía-agua de estas zonas urbanas, concluyendo que los polígonos de viviendas obtuvieron la tasa metabólica de electricidad más baja (0,75-0,82 MJ/hora) y las tasas metabólicas de hortalizas y agua más bajas en uno de los dos polígonos de viviendas estudiados. Por el contrario, las zonas de viviendas unifamiliares mostraron los índices más altos en las tasas metabólicas de hortalizas y electricidad.

En cuanto a los diferentes indicadores de sostenibilidad, se encontró una cuota relevante de autosuficiencia en el suministro de hortalizas, del 17 al 115% mediante la implantación de cultivos al aire libre o invernaderos en las cubiertas, también en la producción de energía con porcentajes del 7-71% dependiendo del escenario implantado. En el caso de la autosuficiencia de agua, la cobertura fue menor que la de los otros dos recursos; solo para el riego de los cultivos, el porcentaje es alto 66-227 %, pero para los usos específicos, como el lavado de ropa y el de la cisterna del inodoro, los porcentajes son bajos, del 18-38% para un uso único.

En términos de indicadores ambientales, los escenarios con más cubiertas que implementan paneles fotovoltaicos muestran un alto ahorro de CO_2, pero simultáneamente un alto impacto ambiental en su fase de construcción (98 kg CO_2 eq/m^2/año). Los escenarios que implementan espacios verdes productivos desvelan un aumento relevante de estos espacios de 1,7 a 4,7

m^2/habitante, que es por ejemplo superior al objetivo de la ciudad de Barcelona de aumentar 1 m^2/habitante para 2030. Los indicadores socioeconómicos ilustran que estos nuevos sistemas de alimentación-energía-agua podrían cubrir entre el 9-71% y el 7-18% de la pobreza energética y de agua, respectivamente. En cuanto al ahorro monetario, los hogares podrían ahorrar entre 335-1801 €/año en función del escenario aplicado, lo que supone un ahorro importante, especialmente para los grupos vulnerables.

Para involucrar a las partes interesadas en el diseño de futuros escenarios, evaluamos la percepción pública de estas estrategias a través de procesos participativos y encuestas, revelando que la mayoría de los residentes preferían implementar paneles fotovoltaicos en sus cubiertas (65-77%). Este es un sistema más aceptado por los ciudadanos; sin embargo, para la implantación de la agricultura urbana en las cubiertas, el porcentaje dispuesto a aceptar fue menor. En uno de los municipios solamente el 7%, y en el segundo la proporción subió al 20-21%. Por lo tanto, son necesarias políticas dirigidas a la utilización de las cubiertas para otros sistemas distintos de los paneles fotovoltaicos, como la agricultura al aire libre, los invernaderos en las cubiertas, los techos verdes o la recogida de agua de lluvia.

Retos futuros en las ciudades

Esta tesis ha sentado las bases para futuras líneas de investigación relacionadas con el uso de las cubiertas como "espacio urbano de producción". Imaginemos cómo podría ser vivir en una ciudad con espacios verdes y productivos, produciendo su energía y utilizando el agua de lluvia para regar sus cultivos. Por ello, el siguiente paso lógico es poner en marcha diferentes proyectos piloto en distintas formas urbanas y tipos de residentes, con el objetivo de controlar y probar las cubiertas mosaico, y conocer mejor las limitaciones y beneficios que pueden aportar estos nuevos espacios. Estos espacios proporcionan no solo la producción de recursos, sino también espacios de cohesión social, biodiversidad y otros tipos de servicios ecosistémicos en las ciudades, como la mejora del efecto isla de calor o la contaminación del aire. Además, es indispensable incluir a todas las partes interesadas en el diseño de las estrategias urbanas para hacer coincidir sus preferencias y necesidades con las soluciones efectivas al cambio climático en las ciudades.

Preface

The present doctoral thesis was elaborated, from October 2017 to August 2021, in compliance with the PhD program in Environmental Science and Technology of the Universitat Autònoma de Barcelona (UAB) within the research group of Sustainability and Environmental Prevention (Sostenipra; SGR 1683) at the Institute of Environmental Science and Technology (ICTA-UAB). It includes an international research stay at the Technical University of Berlin (Germany) and teaching assistance at the Department of Chemical, Biological and Environmental Engineering (DEQBA). This thesis was supported by a pre-doctoral fellowship by the Spanish Ministry of Science, Innovation and Universities, grant FPU16/03238; The thesis was also funded within the Fertilecity II project (2017-2019) (CTM2016-75772-C3-1-R) "Invernaderos integrados en azoteas: simbiosis de energía, agua y emisiones de CO_2 con el edificio - Hacia la seguridad alimentaria urbana en una economía circular" (IP: Xavier Gabarrell i Durany) and also the "María de Maeztu" Unit of Excellence in R&D (MDM-2015- 0552 / CEX2019-000940-M) of the ICTA-UAB.

This dissertation addresses the development of sustainable urban strategies to provide food, energy and water in cities by using underutilized urban rooftops, and seeks to advance in sustainable urban solutions to tackle climate change and external resource dependency in urban areas. We proposed new spaces of production and assess them to find the best possible future scenarios by applying different innovative combinations of methodologies.

Structure of the dissertation

The dissertation is organized into five main parts and eleven chapters as shown in the following table:

PART 1 – Background and methodological framework

Chapter 1- Introduction

Chapter 2- Motivations, hypothesis, research questions and objectives

Chapter 3- Materials and methods

PART 2 – The Roof Mosaic strategy: a guideline for its implementation

Chapter 4- Towards productive cities: Environmental assessment of the food-energy-water nexus of the urban Roof Mosaic

PART 3 – Assessment of the implementation of the Roof Mosaic in urban areas

Chapter 5- More than the sum of the parts: System analysis of the usability of roofs in housing estates

Chapter 6- Incorporating user preferences in rooftop food-energy-water production through integrated sustainability assessment

Chapter 7- Consumption pattern profiles versus the potential of the local food-energy-water production on urban rooftops in three characteristic urban forms

PART 4 – Assessment of the components of the implementation of the Roof Mosaic

Chapter 8- Environmental and social life cycle assessment of growing media for urban rooftop farming

PART 5 – Discussion and general conclusions

Chapter 9- Discussion of the main contributions

Chapter 10- Conclusions

Chapter 11- Suggestions for future research

The dissertation is organized into five main parts and eleven chapters as shown in the previous table:

PART 1: Background and methodological framework

This section provides a thorough description of the state-of-the-art urban strategies for sustainable, healthy and just cities, urban metabolism and the use of rooftops to produce basic resources (**Chapter 1**). **Chapter 2** states the motivation of this dissertation, the research questions it aims to answer, and the objectives formulated. Finally, **Chapter 3** lays out the methods used and the case studies that apply the innovative methods.

PART 2: The Roof Mosaic strategy: a guideline for its implementation

Chapter 4 proposes a guideline for the implementation of the Roof Mosaic, i.e., the production of food, energy and harvesting rainwater on urban roofs. This guideline was applied to a housing estate in Barcelona at building and group of building scales. This first study sets the beginning for the application of an urban strategy: the Roof Mosaic.

PART 3: Assessment of the implementation of the Roof Mosaic in urban areas

This part expands the application and assessment of the Roof Mosaic in different case studies. Before each chapter, a brief introduction to the innovation of the combination of different methodologies is presented.

Chapter 5 evaluates the food-energy-water (FEW) pattern consumption profiles of the residents of a municipality for the accurate implementation of FEW systems on roofs. **Chapter 6** develops the complete methodology to implement FEW systems on roofs by using participatory processes to include the collaboration of residents in the design of sustainable urban strategies, the urban metabolism and life cycle assessment. **Chapter 7** expands the implementation of FEW on roofs in a municipality with three characteristic urban forms: housing estates, originary fabrics and single-family housing areas to test the Roof Mosaic in different urban forms and types of residents.

PART 4: Assessment of the components of the implementation of the Roof Mosaic

This section presents the environmental and social life cycle assessment of different growing media constituents used for urban rooftop farming (**Chapter 8**).

PART 5: Discussion and general conclusions

This part is the final section of this thesis. **Chapter 9** discusses the main outcomes obtained in the previous chapters and highlights the main contributions in the field of sustainable urban strategies. **Chapter 10** includes the main conclusions of this dissertation by answering the research questions posed in Chapter 2. The last chapter, **Chapter 11**, proposes future research lines related to the search for sustainable solutions for cities by decreasing their external dependency on resources and producing their food, energy and water using underutilized rooftops.

Dissemination and training

This thesis is based on a group of peer-reviewed papers:

- **Toboso-Chavero, S.,** Nadal, A., Petit-Boix, A., Pons, O., Villalba, G., Gabarrell, X., Josa, A. & Rieradevall, J. (2019). Towards productive cities: environmental assessment of the food-energy-Water Nexus of the urban Roof Mosaic. Journal of Industrial Ecology, 23(4), 767-780. (doi: https://doi.org/10.1111/jiec.12829) and also at Science of Environmental Policy, European Commission DG Environment News Alert Service, edited by SCU, The University of the West of England, Bristol (https://ec.europa.eu/environment/integration/research/newsalert/pdf/urban_self_sufficiency_how_rooftops_could_contribute_to_cities_energy_food_and_water_demands_524na1_en.pdf)
- **Toboso-Chavero, S**., Villalba, G., Gabarrell Durany, X., & Madrid-López, C. (2021). More than the sum of the parts: System analysis of the usability of roofs in housing estates. Journal of Industrial Ecology (doi: https://doi.org/10.1111/jiec.13114)
- **Toboso-Chavero, S**., Madrid-López, C., Durany, X. G., & Villalba, G. (2021). Incorporating user preferences in rooftop food-energy-water production through integrated sustainability assessment. Environmental Research Communications, 3(6), 065001. (doi: https://doi.org/10.1088/2515-7620/abffa5)
- **Toboso-Chavero, S**., Madrid-López, C., Villalba, G., Gabarrell Durany, X., Hückstädt A.B., Finkbeiner, M., Lehmann A. (2021). Environmental and social life cycle assessment of growing media for urban rooftop farming. International Journal of Life Cycle Assessment. Accepted (26/08/2021) (open access)

Some preliminary outcomes were presented in international conferences:

- **Susana Toboso-Chavero**, Xavier Gabarrell, Gara Villalba, Mario Giamprieto, Cristina Madrid-Lopez. Transforming Cities: The Food-Energy-Water Nexus Implementation on Rooftops. International Sustainable Production and Consumption Conference 2018. The Institution of Chemical Engineers (IChemE). Manchester (UK).
- **Susana Toboso-Chavero**. "Como planificar la ciudad Mosaico". Visiones de la ciencia:" Agricultura urbana y despilfarro alimentario". Bibliotecas de Barcelona. Barcelona (2018).
- **Susana Toboso-Chavero**, Xavier Gabarrell, Gara Villalba, Cristina Madrid-Lopez. Improving the Socio-economic Metabolism in Neighborhoods: Climate Change Action Plans. The 13th Conference of the International Society for Industrial Ecology (ISIE) - Socio-Economic Metabolism Section, 2019. The International Society for Industrial Ecology. Berlin (Germany).
- **Susana Toboso-Chavero**, Xavier Gabarrell, Gara Villalba, Cristina Madrid-Lopez. Enhancing Cities' Performance: The Water-Energy-Food Nexus Implementation on Rooftops. 10th International Conference of the International Society for Industrial Ecology, 2019. The International Society for Industrial Ecology. Tsinghua University, Beijing, China.

- **Susana Toboso-Chavero**, Xavier Gabarrell, Gara Villalba, Cristina Madrid-Lopez. Productive Neighborhoods- Environmental Assessment of the Urban Roof Mosaic. La VIII Conferencia Internacional de Análisis de Ciclo de Vida en Latinoamérica, CILCA 2019. Red Iberoamericana del Ciclo de Vida. Cartago, Costa Rica.
- **Susana Toboso-Chavero**, Xavier Gabarrell, Gara Villalba, Cristina Madrid-Lopez. New strategy for Sustainable Urban Areas: The Water-Energy-Food Nexus Implementation on Rooftops. The 19th European Roundtable on Sustainable Consumption and Production (ERSCP). Circular Europe for Sustainability: Design, Production and Consumption, 2019. The Institute for Sustainability Science and Technology of the Universitat Politècnica de Catalunya – BarcelonaTech. Barcelona (Spain).
- **Susana Toboso-Chavero**. Fundamentals of Life Cycle Assessment. Life Cycle-Wie grün sind Erneuerbare und Elektromobilität wirklich? (2019) Foundation of SPD Friedrich Ebert Stiftung. Berlin (Germany).
- Xavier Gabarrell, Ertuğrul Örücü, **Susana Toboso-Chavero**, Burçin Atilgan Türkmen. Introducing Life Cycle Assessment and Industrial Processes in Sustainable Chemical Engineering Education: A case study in the automotive sector. V Congreso de Innovación Docente en Ingeniería Química (2020). Universidad de Santiago de Compostela (Spain).
- **Susana Toboso-Chavero**, Xavier Gabarrell, Gara Villalba, Cristina Madrid-Lopez. Social Assessment of Growing Media for Rooftop Farming. The 7th International Conference on Social Life Cycle Assessment (2020). KTH – Royal Institute of Technology and Chalmers University of Technology. Gothenburg (Sweden).
- **Susana Toboso-Chavero**, Xavier Gabarrell, Gara Villalba, Cristina Madrid-Lopez. How can we use rooftops for “urban productivity” of energy, food and water?. 3rd International Society of Industrial Ecology Americas Conference - ISIE Americas 2020. Pontificia Universidad Católica del Perú. Lima (Perú).
- **Susana Toboso-Chavero.** "Dónde vivimos y como viviremos". Conferencias del Aula de Extensión Universitaria, 2020. Aulas de Extensión Universitaria. Ripollet (Spain).
- **Susana Toboso-Chavero**, Xavier Gabarrell, Gara Villalba, Cristina Madrid-Lopez. Rooftop Mosaics: Environmental Implications to Multifunctional Roofs. FoodE Winter School "Sustainability Assessment of City-Region Food Systems 2021. Barcelona (Spain).

Additionally, the author of this dissertation did a research stay at the Technical University of Berlin (TU Berlin) in the Chair of Sustainable Engineering (SEE) under the supervision of Prof. Dr. Matthias Finkbeiner and Dr.-Ing. Annekatrin Lehmann.

Additional training was obtained through different courses, scientific activities and collaborations in projects, books and articles.

Relevant courses:

- o **Teacher Training Program in Higher Education** (FDES) (175 hours) at the Universitat Autònoma de Barcelona (UAB).
- o **Advanced Life Cycle Assessment** course at the Aalborg University (6 ECTS).

Collaboration in projects:

- o Fertilecity II (CTM2016-75772-C3-1-R, AI/UE-Feder). Agrourban sustainability through rooftop greenhouses. Integrated rooftop greenhouses: symbiosis of energy, water and CO2 emissions with the building – Towards urban food security in a circular economy. MINECO funds.
- o Interreg V NWE - GROOF: Greenhouses to Reduce CO2 on roofs. EU funds.
- o URBAG: Integrated System Analysis of Urban Vegetation and Agriculture. EU funds.
- o FoodE: European Union's Horizon 2020 research and innovation programme under grant agreement No 862663 (FoodE). EU funds.
- o Pandèmies 2020: "Municipis resilients a les pandèmies mitjançant el nexe de l'agricultura de proximitat, energia, aigua i residus. Del pilot al municipi." (AGAU 2020 PANDE 00021). Secretaria d'Universitats i Recerca del Departament d'Universitats i Recerca.

Participation in articles to complement this thesis:

- o Salvador, D. S., **Toboso-Chavero, S.,** Nadal, A., Gabarrell, X., Rieradevall, J., & da Silva, R. S. (2019). Potential of technology parks to implement Roof Mosaic in Brazil. Journal of Cleaner Production, 235, 166-177. (https://doi.org/10.1016/j.jclepro.2019.06.214).
- o Bonilla-Gámez, N., **Toboso-Chavero, S.,** Parada, F., Civit, B., Arena, A. P., Rieradevall, J., & Durany, X. G. (2021). Environmental impact assessment of agro-services symbiosis in semiarid urban frontier territories. Case study of Mendoza (Argentina). Science of The Total Environment, 774, 145682. (https://doi.org/10.1016/j.scitotenv.2021.145682).
- o Vittuari, M., Bazzocchi, G., Blasioli, S., Cirone, F., Maggio, A., Orsini, F., Antonella Samoggia, ...**Toboso-Chavero, S**.,… & De Menna, F. (2021). Envisioning the future of European food systems: Approaches and research priorities after COVID-19. Frontiers in Sustainable Food Systems, 5, 58. (https://doi.org/10.3389/fsufs.2021.642787).
- o Muñoz-Liesa, J., **Toboso-Chavero, S.,** Beltran, A. M., Cuerva, E., Gallo, E., Gassó-Domingo, S., & Josa, A. (2021). Building-integrated agriculture: Are we shifting environmental impacts? An environmental assessment and structural improvement of urban greenhouses. Resources, Conservation and Recycling, 169, 105526. (https://doi.org/10.1016/j.resconrec.2021.105526).
- o Zambrano-Prado, P., Pons-Gumí, D., **Toboso-Chavero, S.,** Parada, F., Josa, A., Gabarrell, X., & Rieradevall, J. (2021). Perceptions on barriers and opportunities for integrating urban

agri-green roofs: a European Mediterranean compact city case. Cities, 114, 103196. (https://doi.org/10.1016/j.cities.2021.103196).

Books:

- Solucions Eixverd, S. L., Calvo, L., Bermejo, J., Arranz, L., Jimeno, A., Rieradevall Pons, J., Gabarrell, X., ...**Toboso-Chavero, S**… & Pons, D. (2019). Barreres i oportunitats de les cobertes mosaic. ISBN: 978-84-09-15094-6 (https://5.135.88.25/jspui/bitstream/11703/116237/1/Cobertes_Mosaic.pdf).

Collaboration in different scientific activities:

- **Teaching practical classes in "Bojos per la terra"** course about urban agriculture to high school students. Fundació Catalunya la Pedrera.
- **Coach of the Urban Greenhouse Challenge 2020**. Wageningen University and Research.
- **GROOF project guidelines**: Member of the team that designed the social aspects of the guidelines for the implementation of rooftop greenhouses in the European project GROOF. See details in **Appendix 6.**
- **FoodE project: a literature review of social indicators.** Member of the team to carry out a literature review of social indicators in City/Region Food Systems (CRFS), it is still in progress.

Participation in journals:

- Collaboration with the Journal of Industrial Ecology in the translation of the abstracts from English to Spanish, from October 2017 to October 2018.


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- 2 peer-reviewed were done for the Environmental Research Letters journal.

Collaboration in teaching assistance:

- “Industrial Ecology” subject in the master’s degree in Interdisciplinary Studies in Environmental, Economic and Social Sustainability. Academic years: 2017-2018, 2018-2019; 2019-2020.
- “Environmental Management Tools in Business and Public Administration” subject in the bachelor’s degree in Environmental Science. Academic years: 2018-2019, 2019-2020, 2020-2021.
- “Environmental Management and Energy Resources” in the bachelor’s degree “Management of Smart and Sustainable Cities”. Academic years: 2019-2020.

Collaboration as a master’s thesis supervisor:

- “Sustainability Analysis of an urban rooftop mosaic (water, energy and food). Legal framework analysis” by Belén Bruzual. Supervisors: **Toboso- Chavero, S**; Gabarrell, X. Academic year: 2017-2018.
- “Economic and Environmental Analysis of Hydroponic Benches” by Benedikt Flock. Supervisors: **Toboso-Chavero, S**; Rufí-Salís, M; Gabarrell, X. Academic year: 2017-2018
- “Urban planning strategies: implementation of open-air farming on hotel rooftops” by María Alexandra Poveda. Supervisors: Rufí-Salís, M; **Toboso- Chavero, S**; Gabarrell, X. Academic year: 2018-2019.
- “Could cork granulates contribute to a local more sustainable hydroponic crop production?” by Ramón Santiago. Supervisors: **Toboso-Chavero, S**, Arcas-Pilz, V, Villalba, G. Academic year: 2018-2019.
- “Barriers and opportunities for Urban Agri-Green Roofs in Mediterranean cities. Case study of Barcelona” by David Pons. Supervisors: **Toboso- Chavero, S**; Parada, F, Rieradevall, J, Gabarrell, X. Academic year: 2018-2019.
- “Environmental impact assessment of the agro-services symbiosis in frontier territories. Case study Mendoza (Argentina)” by Natalia Bonilla Gámez. Supervisors: **Toboso- Chavero, S**; Parada, F, Rieradevall, J, Gabarrell, X. Academic year: 2019-2020.
- “Life Cycle Analysis comparison of permacultural production systems: the case study of Mas les Vinyes” by Sara Molins Cabaní. Supervisors: **Toboso-Chavero, S**, Arcas-Pilz, V, Muñoz, P. Academic year: 2019-2020.
- “Modelling building energy savings for alternative rooftop uses in the Mediterranean climate” by Sofie de Brabander. Supervisors: Muñoz, J, **Toboso-Chavero, S**, Gabarrell, X. Academic year: 2019-2020.

- “Social assessment of urban rooftop agriculture projects” by Jana Gansen. Supervisors: **Toboso- Chavero, S**; Gabarrell, X. Academic year: 2020-2021.

Background and methodological framework

1

Chapter 1

Introduction

1. Introduction

The need to enhance sustainability in cities is key, particularly in the provision of three basic resources: food, energy, and water (FEW). First, sustainable urban strategies proposals are discussed in the context of adapting cities to climate change and dependency on external resources. Second, the metabolism of cities and the external dependency on the FEW supply are presented. Third, the use of roofs to supply these necessities and the potential of urban roofs to play a key role in a more sustainable future in metropolises are examined.

1.1 Urban strategies for sustainable, healthy and just cities

More than half of the world population (4.3 billion citizens) dwell in urban areas (UN-Habitat, 2020). These urban settlements started many centuries ago in Mesopotamia when people concentrated to work the fields together during the agricultural revolution. The food surpluses from agriculture allowed congregating inhabitants in large communities, and specialized in other activities and services, creating more complex social units (Adams, 1960). Presently, cities account for more than 80% of the gross domestic product (GDP) (World Bank, 2015), occupy only 3% of the earth's surface (UNEP, 2012) but consume most of the global resources (UN-Habitat, 2020). For all these reasons, cities are key in advancing towards more sustainable living and improving quality of life. The challenges to more environmental, social and economic sustainability must be tackled first and foremost in urban areas.

1.1.1 The future of cities

Metropolises have a principal role in mitigating and adapting to climate change. They are part of the problem, but simultaneously part of the solution since cities offer many possibilities for mitigation and adaptation strategies. They have the required capacity to implement solutions at scale, having enough population, assets and knowledge. Urbanization will continue to grow in all the regions to a greater or lesser degree. The current urbanized areas will slow their urban growth rate; however, less developed regions of Africa and Asia will cope with most of this urban growth by 96% (UN-Habitat, 2020). Thereby urban growth should go through applying a set of conditions to follow a sustainable pathway and enhance the most populated areas of the globe.

The future of our cities should be based on different factors:

a) **Urban planning and design.** Urban planning must adapt to the climate change crisis, reversing old preconceptions on how cities are, and move forward to a paradigm shift focusing on better places to live for all the residents, from children, elderly, migrants and so on (UN-Habitat, 2020). This renovated urban planning has to be centered in all types of urban areas, from megacities, medium and small cities to towns aiming to provide access to sustainable, resilient, affordable and equitable infrastructures and services (Marvuglia et al., 2020). Examples include maintaining and promoting cities with a mix of services and infrastructure to keep everything close at hand such as the workplace, residential or commercial areas, and with a minimum level of car dependency. Consequently, encouraging policies related to increased use of public transport, cycling or walking within urban areas (Dulal et al., 2011).

b) **Inclusive prosperity**. The concept of inclusive prosperity, i.e., all the groups, migrants, youth, vulnerable groups, elderly, etc., must be considered to advance in the prosperity of cities but being inclusive, leaving no one behind. Inclusion in cities is a generator of economic prosperity, urban sustainability, equality and quality of life enhancement (Lee, 2019). For example, resources or public transport access for all the citizens will aid in cities to equal opportunities to boost wellbeing and job market access (Glaeser and Joshi-Ghani, 2013; UN-Habitat, 2020); therefore, creating opportunities for all the heterogeneous groups that dwell in a city and not only for the wealthy elite. This inclusion must be incorporated in all the stages of a city's design, from the infrastructure design to the decision-making processes in any new urban proposal by institutions.

c) **Local actions**. Local governments should be the drivers to boost long-term sustainable urban actions. Urban areas can benefit from a wide range of strategies adequate to implement such as improvement of air quality, production of resources, efficient and affordable public transport, green spaces, etc. (Adami et al., 2020). However, in some urban areas, the lack of investment can trigger this evolution to sustainability. Countries should ensure strong multilevel governance for local actions and effective centralized and decentralized policies for sustainable urbanization (Croci et al., 2017). The Covenant of Mayors is a fine representative of local actions, with 21,097 accepted actions in European cities. These actions include a variety of sectors such as agriculture, electricity, heat, residential buildings, public lighting, transport, waste, health, land use planning, water, tourism, etc., all aiming to mitigate and adapt to climate change (Adami et al., 2020).

Since 2008 many different agreements and actions have been focused on tackling climate change and sustainable development future. They are the backbone of international development policy, aims, targets and indicators (see Figure 1.1).

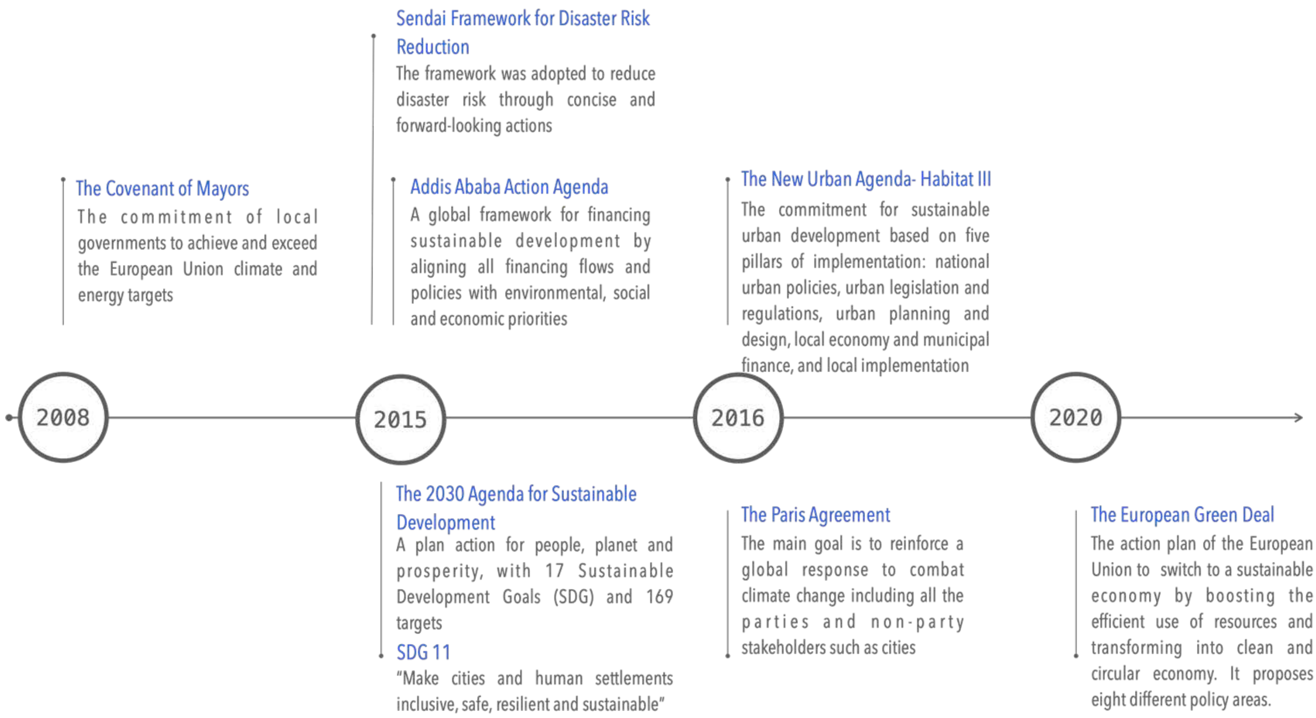


Figure 1.1 Timeline of climate change and sustainable development agreements. Own elaboration from the different agreements and action plans

In 2008, a European initiative – **Covenant of Mayors** for Climate & Energy- involving local governments was launched aiming to commit towards climate change targets. Municipalities are considered key stakeholders to implement a wide range of actions to meet these targets (Kona et al., 2018). As of August 2021, there are more than 10,704 signatories covering 325 million inhabitants from 53 different countries[1] (European Commission, 2008). Subsequently, two different frameworks were signed in 2015**,** the **Sendai framework for disaster reduction risk** and the **Addis Ababa action agenda**. The former one aspires to achieve *"the reduction of disaster risks and losses in lives, livelihoods and health and the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries"* (United Nations, 2015a). The latter one established a global framework to support financially sustainable development (United Nations, 2015b). The same year, one of the most important agendas related to climate change, the **2030 agenda for Sustainable Development**, was approved, with 17 sustainable development goals (SDG) and 169 associated targets (United Nations, 2015c). Among them, goal 11 is focused on cities and human settlements. This goal seeks to make cities *"inclusive, resilient and sustainable"* with 7 different targets ranging from access to safe, affordable and sustainable transport systems to providing green and public spaces for all the citizens (United Nations, 2015c). The following year, the **Paris Agreement**, worldwide new

[1] https://www.covenantofmayors.eu/about/covenant-initiative/covenant-in-figures.html

adoption of climate treaty was signed. The general agreement was *"to reach global peaking of greenhouse gas emissions as soon as possible, making specific reference to the 2°C goal, and even an aspirational reference to the 1.5°C goal"* (Savaresi, 2016). More specific for cities, in the same year, the **New Urban Agenda- Habitat III** was proposed, aiming to settle the standards and principles for the planning, development, construction, management and improvement of urban settlements, proposing the five principal pillars of implementation: "*national urban policies, urban legislation and regulations, urban planning and design, local economy and municipal finance, and local implementation*" (United Nations, 2017). The most recent action plan was adopted in 2020 by the European Union (EU), the Green Deal, founded on fostering a sustainable economy and acting in an array of policy areas such as sustainable food systems, clean energy, building and renovations, etc. (European Commission, 2019).

1.1.2 Sustainable urban strategies

Future cities have an array of challenges to overcome, among them, ensuring a cohesive and diverse city, eradicating energy and water poverty and spatial exclusion, adapting the city to all the different vulnerable groups and remodeling into a greener and healthier site (European Commission, 2011). Taking into consideration the fundamentals drivers of change: policy and legislation, governance, financing and urban planning and design, a wide spectrum of topics related to sustainable urban strategies have been proposed in cities (Lamb et al., 2019) (see Figure 1.2).

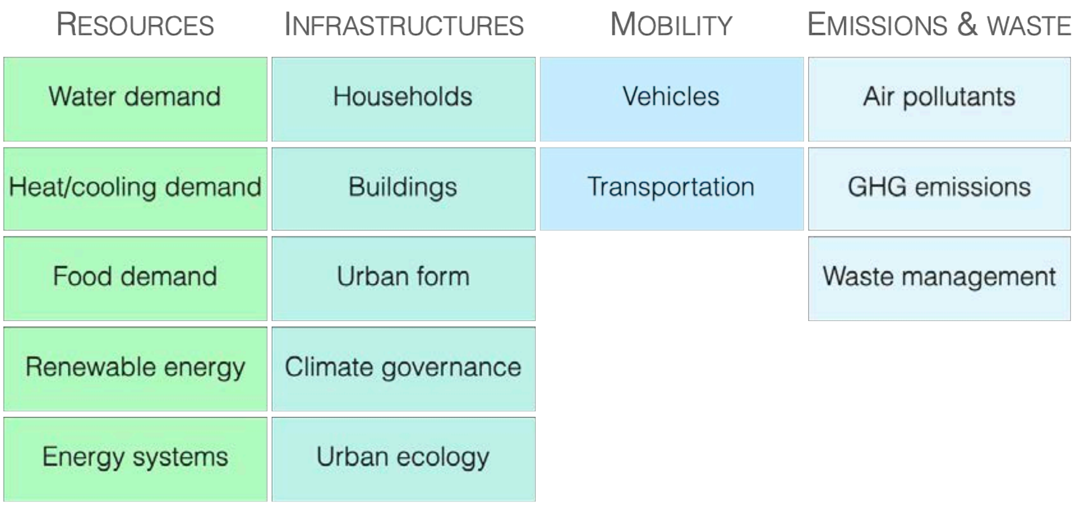


Figure 1.2 Main topics related to sustainable urban strategies proposed in cities around the globe. Adapted from Lamb et al., (2019)

As can be observed from Figure 1.2 many of these urban strategies are related mainly to four main themes: resources, infrastructures, mobility, emissions and waste. Two of the major themes studied in urban environments are related to renewable energy systems such as integrated urban energy systems and sustainable built environment such as net-zero buildings, heat consumption and low-carbon high-rise buildings (Marvuglia et al., 2020); however, diverse types of solutions have been proposed throughout history. Therefore, many fruitful and sustainable strategies have been implemented in cities. Concerning energy systems can be found energy-efficient renovations, heat recovery from sewage networks, biogas production, district heating and cooling, LED street lighting, etc. Waste-wide, examples include door-to-door waste collection, municipal or home composting and waste treatment facilities. Regarding food, urban agriculture, food waste reuse and food sharing are fine representatives. Mobility-wise, strategies comprise bike and car sharing, electric vehicles, etc. (Petit-Boix and Leipold, 2018). These plausible urban strategies can have a triple gain: provide economic, social and environmental benefits, prevent future losses and disasters, and increase productivity (UN-Habitat, 2020); therefore, the selection of the most suitable strategies in urban areas is crucial.

1.2 Urban Metabolism: Food-Energy-Water nexus

The present section introduces the concepts of urban metabolism and FEW nexus, required concepts for a previous analysis in cities so that later urban strategies will be carried out.

1.2.1 Urban metabolism. Linear versus circular cities

The concept of **urban metabolism** was coined by Wolman (1965). He proposed to analyze the city as an organism that metabolizes inputs and excrete outputs; thus, it could be defined as the quantification of all the inputs and outputs and storage of food, energy, water, materials and waste within an urban area (Kennedy et al., 2007). Therefore, it is essential to analyze all the resources indispensable to sustain lives in cities, understanding and quantifying all the interactions between flows and associated environmental issues. This analysis leads to a more integrated vision of the functioning, the demand of the urban areas and aid in applying more accurate strategies and policies. Many diverse studies have analyzed the urban metabolism of cities, such as Brussels (see Figure 1.3), Tokyo (Hanya and Ambe, 1976), Toronto (Sahely et al., 2003), Sydney (Newman, 1999), Vancouver (Moore et al., 2013), London (Chartered Institute of Wastes, 2020), etc.

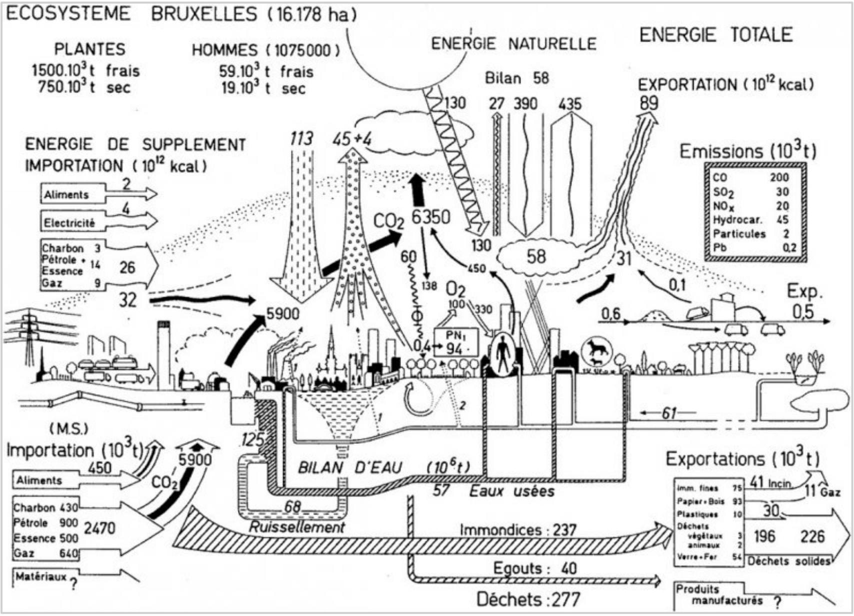


Figure 1.3 The urban metabolism of Brussels in the 1977. Source: Duvigneaud and Denayeyer-De Smet, 1977.

Most of the urban metabolism is based on a linear economy system, i.e., the traditional system of *"take-make-dispose".* However, **circular economy (CE)** and its analogous, circular cities are currently gaining momentum. The CE is based on closing loops of energy, materials avoiding wastes and emissions and promoting resource efficiency (Pearce and Turner, 1990). In the same context, a circular city is defined as "*a city that practices circular economy principles to close resource loops, in partnership with the city's stakeholders (citizens, community, business and knowledge stakeholders), to realize its vision of a future-proof city*" (Prendeville et al., 2018). Following the RESOLVE framework proposed by Ellen Macarthur Foundation (2017a), six actions have been presented within the CE: regenerate, share, optimize, loop, virtualize and exchange. How cities become more circular and implement CE strategies is essential for the cities' sustainability and decreasing demand for resources. Circular cities rely on three main principles: i) design out waste and pollution, ii) products, components, and materials are maintained at their highest value and in use, iii) restore natural systems. Thereby a circular city targets to create prosperity, boost the quality of life, and enhance resilience for residents and urban areas, while aspiring to reduce the consumption of non-renewable resources (Ellen Macarthur Foundation, 2017b).

1.2.2 Food-Energy-Water nexus

Having all these premises in mind, this thesis focuses their attention on three main basic resources in cities, which are food, energy and water, because almost any type of human activity requires either food, energy, water, or the combination of them. The interconnection of these three resources is referred to as the **FEW nexus** (Garcia and You, 2016). In this context, cities consume 70% of the global energy (IEA, 2015) and 70% of the global imported food (FAO, 2017). Furthermore, cities are the third major water consumers (11%) after industry (19%) and agriculture (70%) (Ritchie and Roser, 2017), which is also correlated with the increase of food demand that is expected to continue growing by 30% the next 30 years (Alexandratos and Bruinsma, 2012). Additionally, cities are also responsible for 75% of global carbon emissions (United Nations, 2021).

Due to the high population concentration in urban centers, not all the required FEW can be supplied close by; therefore, **imported resources from longer and longer distances are needed**, for example, United Kingdom imports apples from New Zealand (14,000 miles) or green beans from Kenya (4,000 miles) (Paxton, 2011), etc. Equally, for supplying energy and water more resources and networks are needed, with the associated losses to the transformation and distribution of these resources have, being an average of 8% for global electric power transmission and distribution losses (The World Bank, 2018) and 37% for vegetables and fruits (FAO, 2011). This situation diminishes the self-sufficient and food security, i.e., "*a situation that exists when all people, at all times have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life*" (Burton et al., 2013), of cities and make them more dependent on external markets (Godfray et al., 2010). This dependency was aggravated during the lockdown in the COVID-19 pandemic crisis when some basic products were out of stock for weeks (Vittuari et al., 2021).

Cities will continue growing, the urban population will expand, more resources will need to sustain these lives, and accordingly, more associated impacts will occur. Therefore, new sustainability strategies to produce resources within cities should be proposed and broadened. It seems imperative that cities should be more resilient, self-sufficient and healthy, in consequence, the provision of these three resources (FEW) within urban areas is crucial to enhance food, energy and water security and the implication of reducing their associated impacts due to faraway markets or centralized and conventional networks of distribution.

Some advances have been made in that sense; **urban agriculture (UA)** is an example. Many different UA projects have bloomed across the globe. UA provides not only food security within urban areas but also a wide range of ecosystem services such as provisioning services, from food to medicinal plants, regulating services and the quality of air, storing greenhouse gas emissions, habitat services offering biodiversity within the city and cultural services such as recreation, social cohesion, mental and physical health, etc. (Orsini et al., 2020). Likewise, the production of energy in cities has been expanded during decades, mainly with the installation of photovoltaic and solar thermal panels and to a lesser extent, with urban wind turbines (Keirstead et al., 2012). Regarding rainwater harvesting, the expansion of this strategy is unevenly distributed across cities. While the global south relies more on this strategy to harvest water (Furlong, 2014; Teston et al., 2018), in the global north its use tends to be occasional (García Soler et al., 2018), despite a myriad of studies and pilot projects has been carried out over the last decades (Rashidi Mehrabadi et al., 2013; Steffen et al., 2013). These systems, different from UA, contribute mainly to the self-sufficiency of cities to ensure their availability and not depend on external resources.

The present dissertation pursues the implementation of FEW in cities, in particular in underutilized urban rooftops. The following sections introduce the use of rooftops and the framework for their successful implementation.

1.3 Urban design: The use of urban rooftops

The implementation of the production of resources within cities must be scrutinized accurately within the urban design and planning. There are two types of cities disperse and compact (Artunduaga and Ríos, 2017). Disperse cities (or diffuse or sprawl cities) are considered horizontal cities spread throughout the territory, divided in specialized areas, such as residential areas, business areas, etc., while compact cities are characterized by a higher density of buildings and people, and mixture of activities and services. It usually results in more efficient urban planning and transportation (Jabareen, 2006; Nechyba and Walsh, 2004). In this dissertation we have focused our research on compact cities, due to is where more concentration of population inhabits and where land is scarce and expensive. Within compact cities different morphologies can be found, the most common are housing estate fabrics, historic center fabrics, suburban extension districts and single-family housing fabrics (see Figure 1.4) (Oliveira, 2016).

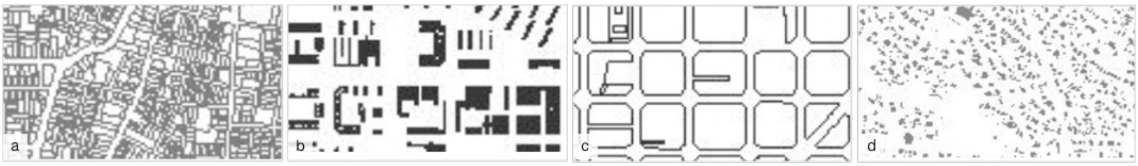


Figure 1.4 Four different urban morphologies in compact cities: a) historic center fabric, b) housing estate fabric, c) suburban extension district fabric, d) single-family housing fabric. Source: PDU, (2017)

In these types of urban forms, rooftops are very diverse; however, various options can be implemented and adaptable to almost any range of roofs. Table 1.1 depicts an overview of the different uses a rooftop can host. For energy systems, active systems can be applied, i.e., photovoltaic (PV) and solar thermal (ST) panels to mini wind turbines (WE). For passive systems, the options are green roofs (GR), white-painted roofs, etc. Likewise, rooftops can be used to catch and store rainwater and to place various types of equipment, or as a social space. Another use on rooftops is the implementation of green infrastructures such as green roofs, open-air farming (OAF) and rooftop greenhouses (RTG). However, all the rooftops cannot be used for placing all these systems. Therefore, depending on the type of roof features one system or another will be able to implement.

Table 1.1 Diagram of the different uses that can be implemented on urban rooftops.

TYPE OF SYSTEMS					
Energy systems	*Active*	Photovoltaic panels	Wind energy	Solar thermal panels	Aerothermal
	Passive	Green roofs	Ventilated roof	White-painted roof	
Rainwater harvesting systems	Catchment	Storage			
Food and biodiversity systems	Green roofs	Rooftop greenhouses	Open-air farming		
Social use systems	Recreation	Businesses	Schoolyards	Culture	
Other Uses	Equipment				

Table 1.2 illustrates the set of considerations to place various rooftop system types. As shown in the table, the most versatile systems to implement on a rooftop are PV and ST panels, because they can be installed in any slope and type of surface material, and the load capacity required is minimal. However, to implement rooftop farming (OAF and RTG) is needed a flat roof and a minimum of solar radiation to grow vegetables. For RWH less space is needed to place the water tank; in contrast, the roof load capacity is a critical point, in this case, to place the water tank because of the weight of rainwater.

Table 1.2 Technical requirements for rooftop systems

Requirement	Criterion	Specification	Rooftop systems					
			RWH	PV	ST	WE	OAF	RTG
Technical	Solar radiation	Area receives direct radiation	N/A	Suitable (Parida et al., 2011)	Suitable	N/A	Suitable (minimum 13-14 $MJ/m^2/day$) (Nadal et al., 2017a)	Suitable (minimum 13-14 $MJ/m^2/day$) (Nadal et al., 2017a)
	Slope	Flat (≤10º)	Suitable (Farreny et al., 2011)	Suitable for any slope	Suitable for any slope	Suitable (Ledo et al., 2011)	Suitable	Suitable (Sanyé-Mengual et al., 2015b)
	Load capacity	Depends on roof system	Depends on water tank location	≈12.5 kg/m^2 (SEAI, 2010)	≈12.5 kg/m^2 (SEAI, 2010)	Depends on wind turbine weight and location[4]	80 -100 kg/m^2 (hydroponics) 200 kg/m^2 (whole system) (Nadal et al., 2017a)	200 kg/m^2 (Nadal et al., 2017a; Sanyé-Mengual et al., 2015a)
	Surface material	Tiles	Suitable[1]	Suitable[1]	Suitable[1]	Suitable[5]	It should be evaluated[2]	It should be evaluated[2]
		Gravel	Suitable[1]	Suitable[1]	Suitable[1]	Suitable[5]	Suitable[1]	Suitable[1]
		Others[3]	Depends on the type of material	Depends on the type of material	Depends on the type of material	Depends on the type of material	Depends on the type of material	Depends on the type of material

N/A means that they are not affected by this criterion. RWH: rainwater harvesting, PV: photovoltaic, ST: solar thermal, WE: wind energy, OAF: open-air farming, RTG: rooftop greenhouse. [1] Sedlbauer et al., 2010. ; [2] It depends on type of tiles; [3] This specification is geographically-sensitive; it would be necessary to evaluate the materials used in the area under study. [4] Abohela et al. 2013; Ledo et al. 2011. [5] Cace et al. 2007.

1.3.1 Potential of the use of rooftops in cities

The potential of the use of rooftops has been studied in many different cities because the space they provide is an asset for urban areas that is often not exploited. Figure 1.5 displays the surface available from unused rooftops of some global cities, compiled from several studies. High population density and compact cities have significant roof space available, such as New York City with 15,482 hectares (ha) or Toronto with almost 5,000 ha. In Europe, Berlin has a higher potential than the rest of European cities shown, which have between 51 to 3,000 ha of plausible rooftops to implement any of these FEW systems.

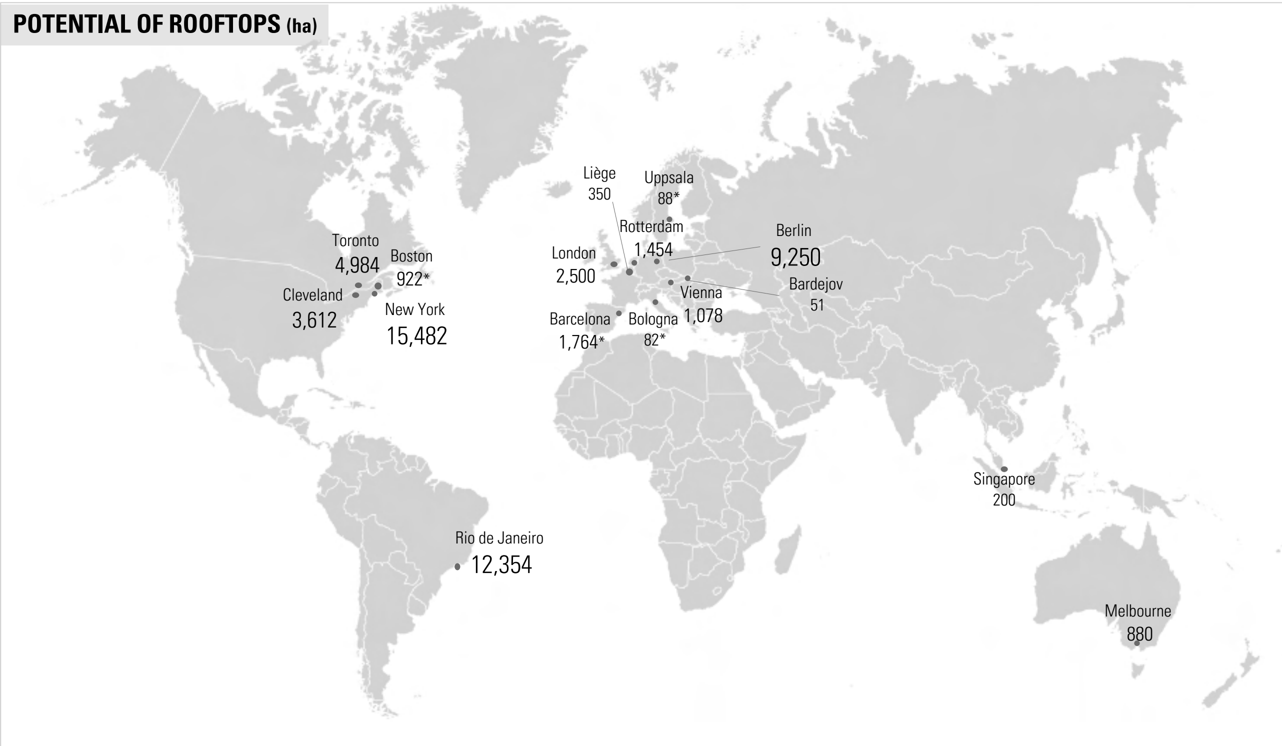


*Figure 1.5 World map with the potential rooftops in hectares (ha) to implement FEW systems in some cities. * Only flat roofs. Own elaboration based on the following references: (Banting et al., 2005; BCNecologia, 2010; Berlin City Council, 2021; Dang and Sampaio, 2020; Department of Environment and Primary Industries, 2013; Gemeente Rotterdam, 2015; Grewal and Grewal, 2012; Harada and Whitlow, 2020; Hofierka and Kaňuk, 2009; Joshi et al., 2020; Orsini et al., 2017, 2014; Rodríguez, 2009; Saha and Eckelman, 2017; Sinha Roy, 2020; Smart Cities Connect- Media & Research, 2017; Stott, 2009). Bigger numbers mean higher potential.*

In this context, there is a plethora of literature available that explores the potential of rooftops in cities to implement different production systems (Table 1.3). These studies have usually concentrated on only one single system on rooftops, such as the application of solar panels, the production of vegetables or rainwater harvesting, as can be seen from Table 1.3. However, none of these studies explored the combination of systems that provide food, energy and water (FEW) as a more synergetic and optimized use of rooftops.

Table 1.3 Studies related to the implementation of different systems on rooftops

ENERGY SYSTEMS	
Description	*References*
The implementation of PV panels on rooftops of commercial buildings was proved to be a feasible investment.	(Armendariz-Lopez et al., 2016)
The authors proposed 12 different scenarios for the optimal implementation of PV panels on the gable roof of military facilities.	(Jeong et al., 2015)
The authors compared PV and ST systems at the household scale, where ST systems delivering more favorable indicators.	(Carnevale et al., 2014)
The implementation of PV systems on a 100 m2 flat rooftop of a Norwegian residential building in Oslo was calculated, resulting in an energy payback time of 3.9 years.	(Madessa, 2015)
The potential of electricity self-sufficiency production on rooftops of three medium-sized cities in Peru could save 112 ton CO_2eq to over 523 kton CO_2eq.	(Bazán et al., 2018)
FOOD AND BIODIVERSITY SYSTEMS	
Description	*References*
The study determined the great potential of the implementation of RTGs in the city of Bologna, which could provide 12,000 ton/year vegetables, satisfying 77 % of the inhabitants' requirements.	(Orsini et al., 2014)
In this study 922 ha of rooftop were identified, representing 7.4% of the total land area in Boston.	(Saha and Eckelman, 2017)
The research analyzed food production versus photovoltaic (PV) energy generation on rooftops in a mixed-use neighborhood in Lisbon.	(Khadija Benis et al., 2018)
The implementation of an RTG in a building in the Barcelona region can produce 30.2 kg/m^2 of tomato over 15.5 months.	(Sanjuan-Delmás et al., 2018)
The authors compared the environmental impacts associated with two types of rooftop systems: RTGs and PV panels.	(Corcelli et al., 2019)
RAINWATER HARVESTING SYSTEMS	
Description	*References*
The implementation of RWH systems was evaluated as the decentralized urban water infrastructures for the city of Toledo (Ohio).	(Tavakol-Davani et al., 2013)
The environmental assessment and the life cycle cost of implementing RWH for toilet flushing and irrigation were analyzed at the building scale.	(Devkota et al., 2015)
The selection of an environmentally optimal RWH strategy on rooftops in residential buildings for laundry emerged to be roof tanks in detriment to underground tanks.	(Angrill et al., 2016)
The authors compared the environmental performance of implementing RWH systems in American and European cities. These systems were able to supply 75% of the rainwater demand for laundry and toilet flushing.	(Petit-Boix et al., 2018a)

The joint use of multifunctional rooftops that creates collective benefits has been little explored. In this dissertation, ***the Roof Mosaic approach*** *(from now on the Roof Mosaic)* is proposed, which makes use of suitable and available rooftops at urban scale (i.e., neighborhoods, districts, industrial and retail parks) to provide local food, energy, and water as an alternative to centralized networks of distribution. Furthermore, the Roof Mosaic aims to contribute to environmental, social, and economic benefits and to promote self-sufficiency and self-production 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.

1.3.2 Urban planning and design: Environmental, social and economic perspective

As any innovative urban strategy, the implementation of the Roof Mosaic should be analyzed from a systemic and holistic approach, engaging stakeholders for their design and co-creation. Sustainability and participatory assessments for these urban strategies are mandatory to assure forward-looking and integrated assessments (Kloepffer, 2008; Kühnen and Hahn, 2019). Sustainability assessments that integrate environmental, social and economic aspects, provide multi-criteria and not single-issue perspective. They are multi-dimensional and multi-disciplinary, guided by a stakeholder-driven approach and are based on finding integrated solutions to complex systems that are socially acceptable (Finkbeiner et al., 2010; Zamagni, 2012).

Few studies related to the implementation of systems on rooftops embark on conducting a sustainability assessment and focus their attention on only one pillar of the sustainability, i.e., calculating the environmental impacts (Lamnatou et al., 2016; Menoufi et al., 2013; Sanyé-Mengual et al., 2013), or the social perception and constraints (Cerón-Palma et al., 2012; Zambrano-Prado et al., 2021b) or the economic feasibility (Armendariz-Lopez et al., 2016; Wang et al., 2016). However, in this thesis, we tried to cover all these three different approaches.

From a social perspective, it is essential to include citizen's preferences and perceptions because of the relevance in defining strategy alternatives according to stakeholders' objectives and needs. Public participation aids to a transparent choice of future strategies and policies, to empower citizens, being part of the decision-making, who are strongly affected by a decision, to effectively implement a new strategy or policy, to ensure more successful application of a strategy or policy with the participation of all stakeholders (Burton and Mustelin, 2013; Hügel and Davies, 2020). Furthermore, different organizations have included the public participation in their goals, such as the European Union with the green and white papers on Citizen Science (European Commission, 2015, 2014) or the SDGs, in Goal 11 (Sustainable Cities and Communities): *"Target 11.3 By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries"* (United Nations, 2019). Therefore, for implementing these FEW systems in residential areas the public participation, through participatory processes and surveys, is key for a more democratic and open selection of climate change mitigation and adaptation scenarios. Thus giving voice to residents results in more effective research for the social acceptance of novel strategies (O'Faircheallaigh, 2010). Different participatory processes can be adopted to engage stakeholders. The International Association for Public Participation (IAP2) suggests an array of public participation forms (Table 1.4). The ranking ranges from the lowest levels of participation, "informing" to the highest level, "empowering" (International Association of Public Participation, 2020).

Table 1.4 The spectrum of public participation of the International Association for Public Participation. Source: adapted from International Association of Public Participation (2020)

IAP2	inform	consult	involve	collaborate	empower
Public Participation Goal	To provide the public with objective information	To obtain public feedback	To work directly with the public throughout the process	To partner with the public in each aspect of the decision	To place final decision-making in the hands of the public
Example Tools	- Websites - Factsheets	- Focus groups - Surveys	- Workshops	- Participatory decision-making	- Citizen juries - Delegated decisions

Therefore, an integrated participatory sustainability assessment to capture the local context from environmental, social and economic perspectives should be the most viable pathway for the implementation of the Roof Mosaic strategy.

Chapter 2

Motivation, hypothesis, research questions and objectives

2 Motivations, hypothesis, research questions and objectives

2.1 Motivations of the dissertation

This dissertation seeks to advance urban strategies to enhance the resilience of cities, i.e., *"the ability of a system to resist and/or adapt to a particular disturbance and recover its normal functioning or state of balance, which may set the initial baseline or a new situation"* (Ribeiro and Pena Jardim Gonçalves, 2019), by taking advantage of underused rooftop spaces. These rooftops can be spaces of urban productivity that would aid urban areas to tackle climate change and evolve into more self-sufficient, healthy and just areas.

Rooftops are underutilized spaces in cities that can be used for different purposes. Table 1.1 depicts the multiple uses that can be placed on rooftops, from spaces of energy production to social interaction spots.

The implementation of these systems offers great potential for cities. For this reason, this dissertation is focused on the use of rooftops and their development in urban areas in order to:

a) **Enhancing urban sustainability.** In Europe, three out of four dwellers live in cities (UN-Habitat, 2020). Given this tendency, the consumption of resources and the dependence on external sources of resources will continue to increase. Therefore, new urban strategies to revert this situation must be proposed. One of these emergent strategies is the production of energy and food and the harvest of water on rooftops that can help to reduce this external dependency and transform cities into more circular urban areas (Figure 2.1). Most urban areas are linear cities which means that they have a metabolism based on importing energy, water, and other resources and exporting emissions, waste and goods (Echarri and Brebbia, 2016). In this dissertation, we propose to transform the metabolism of the cities into circular, i.e., producing their own food, energy and harvesting water and simultaneously reducing their emissions and waste.

b) **Using spaces underutilized in cities.** As a general trend, free spaces in cities are rare. Cities are formed of buildings, streets, parks, car parks, industrial parks, etc. Therefore, it is complex to add more services or infrastructures in urban areas. However, there are still some unused spaces such as abandoned spots or rooftops that could be exploited. Rooftops can comprise up to 32% of the horizontal surface of built-up areas (Frazer, 2005), and examples of their potential can be found in many compact cities, such as Berlin, Paris, New York, Barcelona, etc. (see Figure 1.5). Therefore, these assets can be excellent sites to exploit in cities where land is scarce and expensive that can be used as productive spaces of basic resources for citizens' self-sufficiency.

c) **Proposing the FEW implementation on roofs where it is most needed in cities**. The implementation of the Roof Mosaic in urban areas should not be random and should be fostered in areas where is most essential. The Roof Mosaic is focused on the self-production and self-sufficiency of basic resources; therefore, the first beneficiaries should be urban areas with entrenched poverty, social and economic issues, energy and water poverty as well as obsolete infrastructures and lack of investment and need for rehabilitation. One widespread urban form that is often characterised by such issues are housing estates (Monclús et al., 2017). Housing estates, i.e., mass social housing built between the 1950s and 1970s, are mostly spread all over Europe and post-communist countries (Benkő, 2012). In the same way, these urban fabrics are characterised by homogeneous and repetitive buildings and flats roofs that are an advantage for the implementation of the Roof Mosaic (Monclús et al., 2017).

d) **Analysing limitations and benefits from environmental, social and economic perspectives** of this urban strategy. When a new strategy is proposed and will affect the daily life of residents and their interaction in their building and surroundings, the analysis should be multi-dimensional to capture all the perspectives and nuances. Different methodologies from the Industrial Ecology can be applied, one of the most widespread methodologies is the life cycle assessment for the accounting of environmental impacts, and its analogous methods the social life cycle assessment and life cycle costing deriving in a life cycle sustainability assessment (Finkbeiner et al., 2010). In this dissertation, we used life cycle thinking to analyse the impacts of these new systems as well as their benefits.

e) **Involving stakeholders in the selection of future changes in urban planning**. In the same line, to propose the best future Roof Mosaic scenarios for metropolises, it is indispensable to engage citizens of the area under study. If the aim is to implement successful strategies in urban areas, stakeholders are necessary to help codesign the scenarios, to select the indicators to use, etc., to align urban sustainable strategies with the necessities and concerns of residents. Therefore, participatory processes, surveys, and other methodologies that involve citizens are fundamental to the social acceptance of the production of resources on the roofs of our cities (Joshua P. Newell et al., 2019).

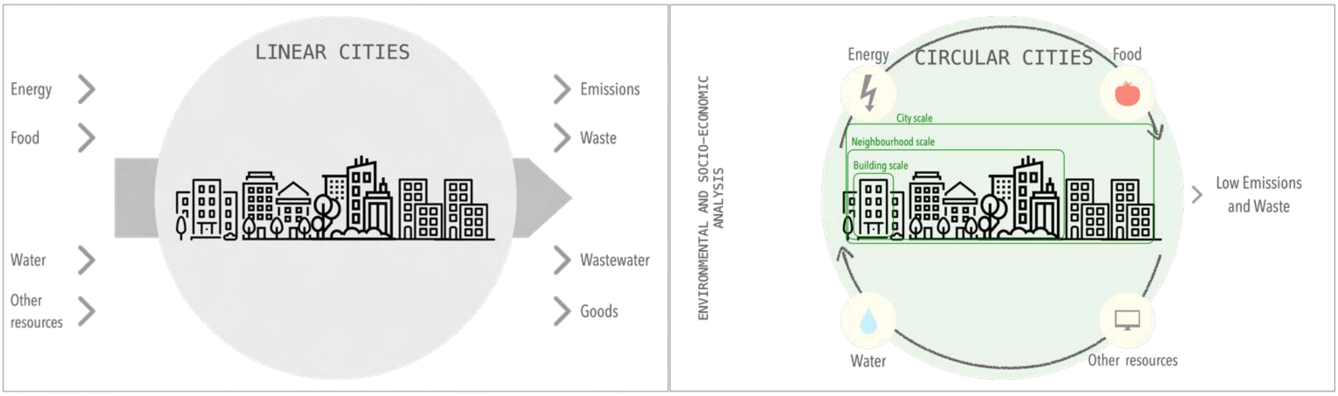


Figure 2.1 Simplified diagrams of linear cities and circular cities metabolism

Considering all these arguments, this dissertation aims to propose a new approach for the sustainability of three basic resources (food-energy-water) in cities, where is most needed, coping with all the perspectives and guided by a stakeholder-driven strategy. We proffer all the instruments to policymakers so that they make the most appropriate decision for their municipality and advance in the development of these new urban spaces in the near future.

2.2 Hypothesis, research questions and objectives of the dissertation

The present thesis hypothesizes that the use of rooftops can offer environmental, social and economic benefits in urban areas in order to optimize and enhance city sustainability. Our general objective is, therefore, to analyze the environmental and socio-economic impacts, and the benefits of the implementation of food production, renewable energy infrastructures and rainwater harvesting, on available rooftops of urban areas. To do so, four main research questions are addressed throughout the thesis:

- **Question 1:** What are the environmental and socio-economic impacts, and the benefits of the implementation of food production, renewable energy infrastructures and rainwater harvesting, on available rooftops for the purpose of self-sufficient cities?

- **Question 2:** To what extent does this new urban-nexus system contribute to a future self-sufficient city?

- **Question 3:** How can this new urban-nexus system be implemented in different contexts and scales?

- **Question 4**: What is the social perception and acceptance of this urban-nexus system?

To explore these research questions following specific objectives were thoroughly studied:

	Objective	*Research question*	*Chapter*
I	To design a comprehensive approach that helps to evaluate the technical feasibility and environmental implications of applying the Roof Mosaic in urban areas.	1,2,3	4
II	To characterize the FEW metabolism of a housing estate and evaluate the robustness of some Roof Mosaic scenarios to improve self-sufficiency and resource security in urban areas.		5
III	To propose a participatory integrated sustainability assessment for this urban strategy: the implementation of FEW production on roofs in a municipality.	1,2,4	6
IV	To propose the best scenarios of production of food-energy-water on rooftops in a municipality and in three different urban forms (housing estates, originary fabrics and single-family housing areas).	1,2,3,4	7
V	To perform a comprehensive environmental and social assessment of the various extended soilless systems to grow vegetables on urban roofs.	1	8

Chapter 3

Materials and Methods

3 Materials and methods

This section presents the methods applied and the cases studies proposed in this dissertation.

3.1 Method overview

An innovative and unique combination of previously established methodologies was applied to integratively quantify the environmental, social and economic aspects of the Roof Mosaic and with the participation of stakeholders (Figure 3.1). To assess the Roof Mosaic various environmental and socio-economic tools were applied. Furthermore, to analyze the social perception and acceptance and the barriers and opportunities of this urban strategy, quantitative and qualitative methods were employed such as surveys and participatory processes. The Roof Mosaic was implemented at different scales from buildings to municipalities and using geographic information systems (GIS) for the geospatial representation.

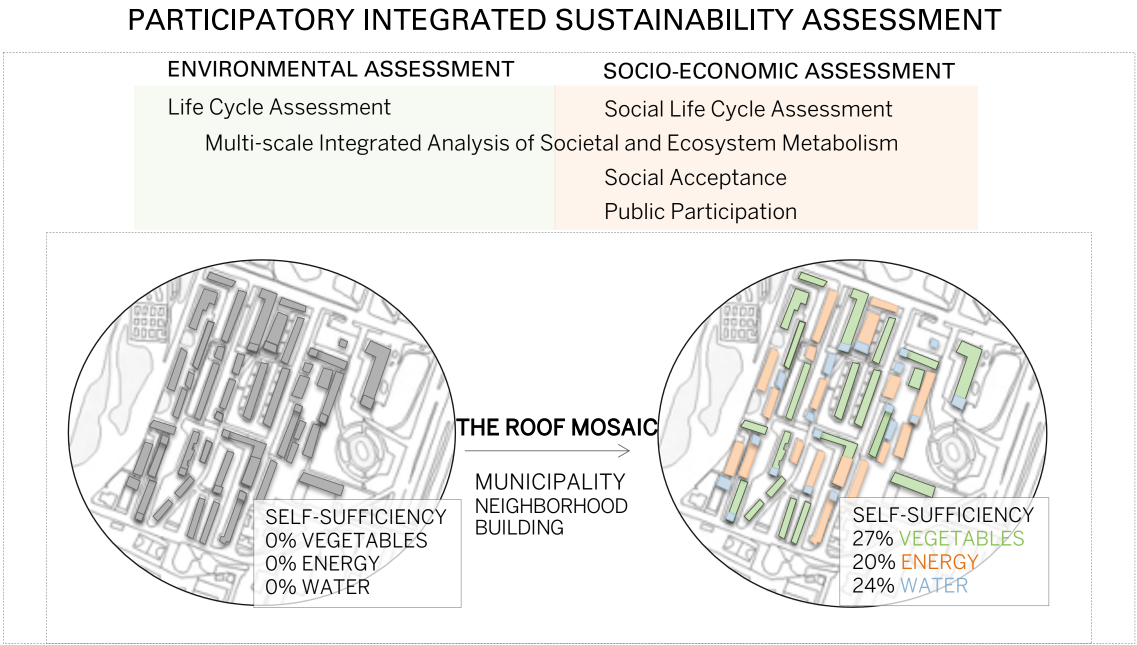


Figure 3.1 General overview of the methods used, and scales applied

The extent to which each method was employed is displayed in Table 3.1. All the chapters incorporated environmental tools, **Chapter 4, 6 and 8** incorporated environmental life cycle assessment (LCA from now on) to assess the performance of the case study, and **Chapters 5 and 7** was applied the multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM) to analyze the metabolic profile of these urban areas. Except for **Chapter 4,** all the chapters include somehow social aspects and geographic information systems (GIS) tools. **Chapter 5** is based on the urban metabolism of a municipality using participatory processes, a survey and environmental and social indicators. **Chapter 6** integrated a sustainability assessment (assessing environmental, social and economic indicators) and participatory processes and a survey to propose the best future Roof Mosaic scenarios. **Chapter 7** also applied social and economic indicators, and surveys to obtain the potentials of using rooftops to produce basic resources at three urban forms and municipality scales. We performed a social life cycle assessment (S-LCA) at different scales of a component (growing media) of a system of the Roof Mosaic in **Chapter 8**.

Table 3.1 Overview of the methods applied in each chapter of the dissertation. LCA: environmental life cycle assessment; MuSIASEM: Multi-scale integrated analysis of societal and ecosystem metabolism; S&E: social and economic; S-LCA: social life cycle assessment; PP: participatory processes

			LCA	MuSIASEM	S & E indicators	S-LCA	Survey	PP	Scale
PART II	Chapter 4	Towards Productive Cities: Environmental Assessment of the Food-Energy-Water Nexus of the Urban Roof Mosaic							building & group of buildings
PART III	Chapter 5	More than the sum of the parts: System analysis of the usability of roofs in housing estates							group of buildings & municipality
	Chapter 6	Incorporating user preferences in rooftop food-energy-water production through integrated sustainability assessment							group of buildings & municipality
	Chapter 7	Consumption pattern profiles versus the potentiality of the local food-energy-water production on urban rooftops in three characteristic urban forms							urban forms & municipality
PART IV	Chapter 8	Environmental and social life cycle assessment of growing media for urban rooftop farming							product

3.2 Environmental tools: LCA

LCA was employed in most of the studies to analyze the environmental performance of the Roof Mosaic as a tool to obtain environmental indicators. LCA is an internationally standardized methodology recognized by the UNEP (UNEP, 2002) and the European Commission (European Comission, 2001) and is based on the ISO 14040 (International Organization for Standardization, 2006), which determines it as: "*LCA is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (i.e., consecutive and interlinked stages of a product system, from raw materials acquisition or generation from natural resources to final disposal)".*

The LCA methodology is split into four main steps represented in Figure 3.2.

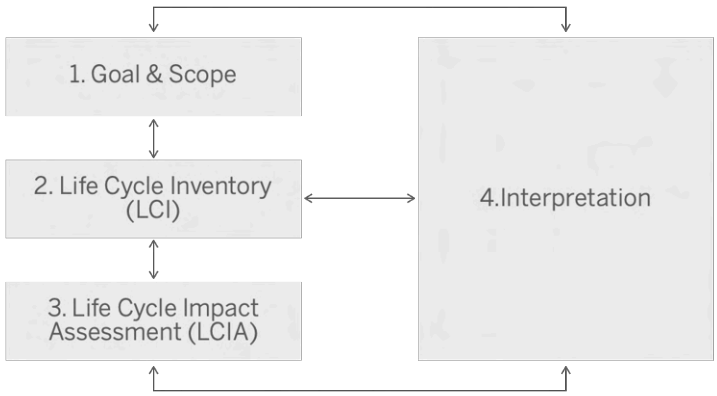


Figure 3.2 Steps of the LCA methodology. Source: Adapted from ISO 14040 (International Organization for Standardization, 2006)

3.2.1 Goal and Scope

The goal and scope are the first stage of an LCA. It comprises the definition of the aim, applications and target audience of the study. The scope includes the description of the system under study such as functional unit (FU), system boundaries, assumptions, limitations and quality of data. Three FUs were defined in this dissertation. The FU is key for a proper comparison among systems, the FU is the reference to compare same type of function in LCA. Due to the Roof Mosaic entails a variety of different systems (food, energy and water), the FU was crucial to compare the same type of functions. **Chapter 4** uses a system expansion, i.e., *"expanding the product system to include the additional functions related to the co-products"* determined in the ISO 14044 (ISO, 2006a); therefore, the FU was to meet the annual FEW demands of an average resident of the neighborhood, using decentralized systems (Roof Mosaic scenarios) and centralized networks. **For Chapter 6 and 7** the FU was the same, which is 1 m^2 of rooftop that supplies different resources, this translates into the supply of electricity (76 kWh/m^2/year), vegetables—tomatoes, lettuces, green beans and peppers—(10.3 kg/m^2/year for OAF) (Boneta et al., 2019) and 14.16 kg/m^2/year for RTGs (Rufí-Salís et al., 2020)), 1 m^2/year GR system and 1 m^3/year of RWH. **Chapter 8** uses a different FU because the study is based on growing media for urban rooftop farming (URF), thereby the FU is 1 m^3 of a growing medium for URF and the reference flow is 1 m^3 of each growing media (perlite, peat and coir).

3.2.2 Life cycle inventory (LCI)

The second step of the LCA is the LCI which consists of the collection of all the inputs from nature (i.e., water) and technosphere (i.e., fuel), and outputs, emissions and waste generated (i.e., GHG emissions, solid waste) according to the established goal of the study and for the entire life cycle of the product or service. The different case studies of this dissertation adapted the inventories from experimental research for foreground data and used secondary data, retrieved from scientific papers, reports and books for background data. These inventories are open access (see them in the corresponding chapter). In this dissertation, the employed database was mainly Ecoinvent 3 (Swiss Center for Life Cycle Inventories, 2015).

The LCI can be modelled from two different perspectives, attributional and consequential. In our case studies, we only performed attributional LCA, the most widespread model, meaning fixed FU and system boundaries (Weidema B, 2018). However, consequential LCA can also be applied as it has been done in other research on waste management (Sevigné-Itoiz et al., 2015) or flood prevention systems (Petit-Boix et al., 2017b).

3.2.3 Life cycle impact assessment (LCIA)

The last calculation step of the LCA is the LCIA (ISO, 2006b). The LCIA consists of the aggrupation of inputs and outputs resulting in an array of impact categories to assess the environmental performance of a product or service. It consists of four different steps: classification, characterization, normalization and weighting. The two first are compulsory in LCA, whereas the other two are optional. The classification phase comprises allocating all the inputs and outputs in impact categories respecting their effect on the environment, then, the characterization step aims to multiply each input/output by the characterization factors. Finally, all the outcomes are aggregated per impact category to have a final score. These impact categories can be at different levels of aggregation which are midpoints (global warming impact category (kg CO_2 eq)), endpoints (human health impact category (disability-adjusted life-year (DALY)) and a single score, which implied less or more uncertainty (Huijbregts et al., 2017a).

In this dissertation, the Recipe method hierarchical (H) was used -only midpoints- (Goedkoop et al., 2009). The climate change/global warming impact category was applied in all three chapters that performed an LCA. On the other hand, the ecotoxicity indicator (ET) is not per se an impact category, it is the aggregation of all three impact categories, including marine, terrestrial and freshwater ecotoxicity. Other environmental indicators were evaluated derived from LCA outcomes, they can be checked in each chapter. Table 3.2 illustrates the impact categories, method, database and software used in each chapter.

Table 3.2 List of software, databases, impact method and impact categories used in each chapter. CC: climate change; OD: ozone depletion; TA: terrestrial acidifications; FE: freshwater eutrophication; TET: terrestrial ecotoxicity; MET: marine eutrophication; ALO: agricultural land occupation: ULO: urban land occupation; GW: global warming; ET: ecotoxicity; FRS: fossil resource scarcity; WC: water consumption

Chapter	Software	Ecoinvent	Impact method	Impact categories
4	Simapro 8.1.4	3.4	Recipe method 2008 (Goedkoop et al., 2009) and Cumulative Energy Demand (CED) (Hischier et al., 2010a)	CC/ OD/ TA / FE/ TET/ MET/ ALO/ ULO
6 & 7	Simapro 9.0	3.5	Recipe method 2016 (Huijbregts et al., 2017a)	GW
8	Simapro 9.0 Gabi 9.1.0.53	3.5	Recipe method 2016 (Huijbregts et al., 2017b) and Cumulative Energy Demand (CED) (Hischier et al., 2010a)	GW/ TA/ FE/ ET/ LO/ FRS/ WC

3.2.4 Interpretation

The last step of the LCA is the interpretation of the results. In this part, the aim is to discuss and provide conclusions, looking for hotspots in the environmental performance and determining critical points to optimize or improve the systems under study.

3.3 Social assessment

In this dissertation, we used a set of social methods and assessments to appraise the social aspects of the implementation of the Roof Mosaic. The following sections depict the different social tools thoroughly.

3.3.1 Social life cycle assessment (S-LCA)

The S-LCA was applied to assess the social and socio-economic impacts (positives and negatives) of a product or service, but could also be an industry, a country, etc., along their life cycle. This methodology builds on the widespread known LCA but dealing with social impacts instead of environmental impacts. It does not have an ISO, but a guideline first launched in 2009 (UNEP/SETAC, 2009) and now gaining maturity with the latest update in December 2020 (UNEP et al., 2020).

The S-LCA follows the same four steps as LCA: goal & scope, LCI, LCIA and interpretation, however because of the nature of social impacts, more factors must be considered. The S-LCA distinguishes different levels: **the first level** is the stakeholders: workers, local community, society, consumers, value chain actors, children – new in the guidelines 2020-. The proposed stakeholders share common concerns and interests. **The second level** is the impact categories: human rights, working conditions, health and safety, cultural heritage, governance, socio-economic aspects, and **the third level** is the impact subcategories, and they are assessed by inventory indicators. Some examples of impact subcategories are community engagement, local employment, and access to material resources, etc (see Figure 3.3 for all the different levels).

They are socially relevant themes and should be classified concerning stakeholders and impact categories (Benoît-Norris et al., 2013).

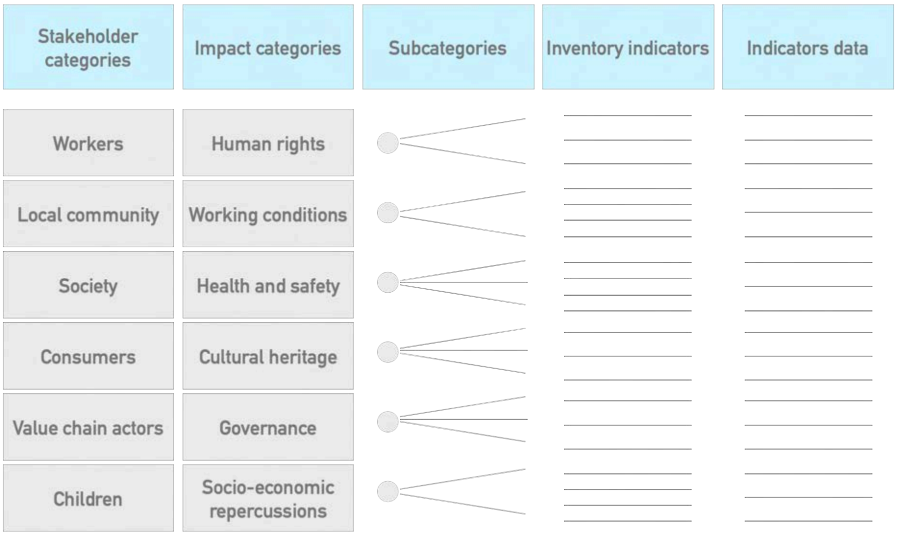


Figure 3.3 Assessment system from categories to inventory data. Adapted from UNEP et al. (2020)

There are two types of S-LCA (see Figure 3.4 for the decision pathway for each type of approach):

Type 1 (or Reference Scale S-LCIA): It is founded on aggregating outcomes of subcategories within each impact category for each stakeholder. It is the most exploited type and aims to focus on its social performance or social risk.

Type 2 (or Impact Pathway S-LCIA): the outcomes are depicted on the casual relationship between subcategories and inventory indicators, it is focused on predicting the aftermaths of the product system (UNEP et al., 2020).

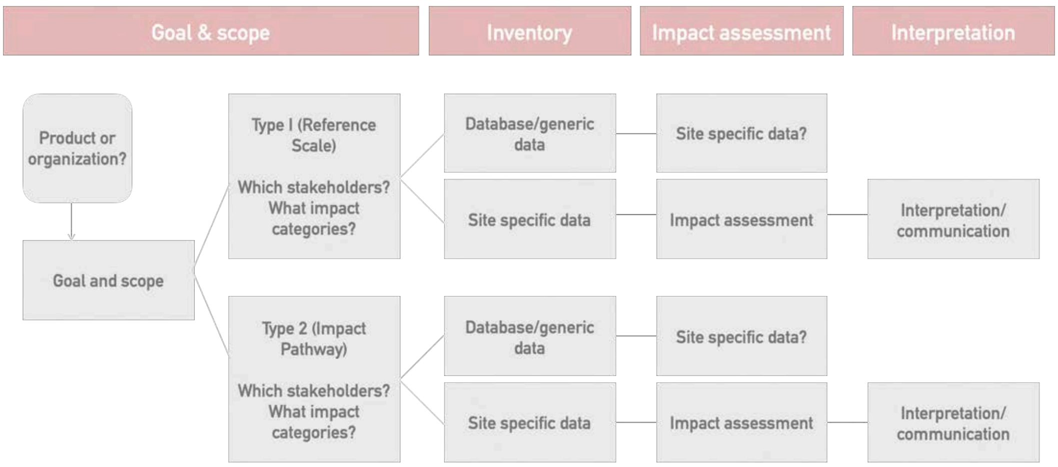


Figure 3.4 S-LCA decision tree. Adapted from UNEP et al. (2020)

We applied the S-LCA methodology in **Chapter 8**.

3.4 Social participation

In this thesis, different methods were employed for engaging residents in the decision-making processes of the implementation of the Roof Mosaic. A myriad of methods can be applied in this field known as social participation, public participation, citizen participation or Citizen Science (Strasser et al., 2019).

In the same context of social science, different type of research can be applied. Table 3.3 illustrates the differences between qualitative and quantitative data in social methods. The basic differences are that qualitative research is more founded on gaining understanding deeply of the topic in a small group of stakeholders, and it cannot be analyzed statistically, while the quantitative research is based on a large group of participants and is aiming to have a general idea of the topic and can be analyzed statistically (Bryman, 2012).

Table 3.3 Qualitative research vs quantitative research. Adapted from Bryman (2012)

	Qualitative research	Quantitative research
Objective/purpose	To gain an understanding of underlying reasons and motivations. To uncover prevalent trends in thought and opinion	To quantify data and generalize results from a sample to the population of interest
Sample	Usually a small number of non-representative cases	Usually a large number of cases representing the population of interest
Data analysis	Non-statistical	Statistical data is usually in the form of tabulations Findings are conclusive and usually descriptive in nature.
Example	Focus groups, individual depth interviews, group discussions	Survey, structured interview, structured observations, content analysis

We used both qualitative and quantitative research and mainly two types of methods: surveys and participatory processes. Table 3.1 illustrates the chapters where these methods were applied. The two methods are described below:

3.4.1 Surveys

A survey is a specific technique for gathering data. These data are collected mainly by questionnaires or by structured interviews on usually many different cases at a single point of time, asking for a range of variables and analyzing them seeking for patterns of association. The differences among surveys are the form of data and the method analysis (De Vaus and de Vaus, 2013).

Figure 3.5 depicts the different steps in conducting a survey. From the research topic, to decide what type of survey carry out, the sample that will be used, the statistical analysis and the final discussion of the outcomes.

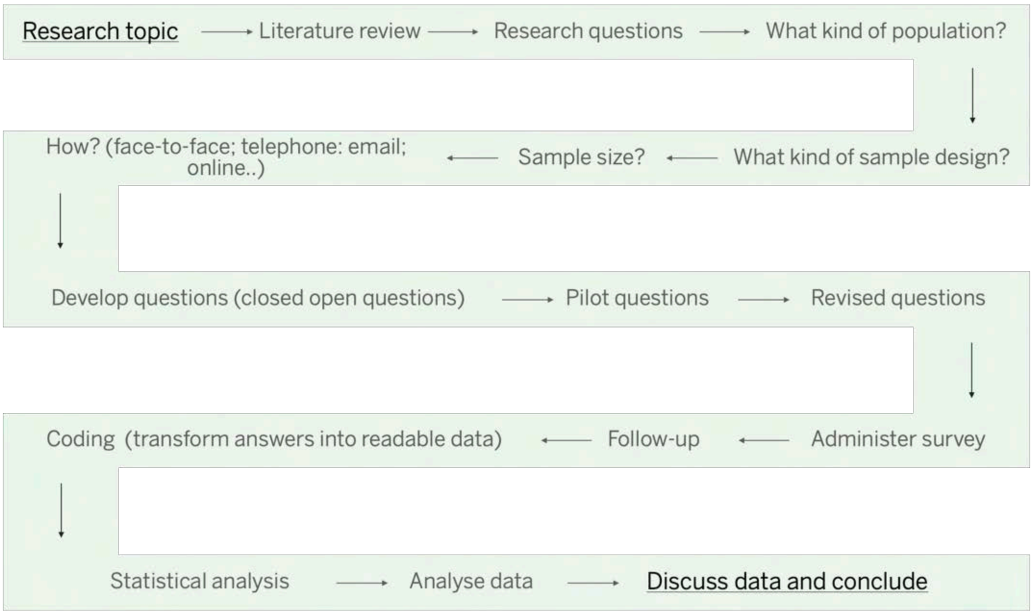


Figure 3.5 Steps in conduction a survey. Adapted from Bryman (2012)

We used surveys in **Chapter 5, 6, 7 and 8** to obtain different information from stakeholders, ranging from consumption patterns in vegetables to social information from suppliers of growing media, among others.

3.4.2 Participatory processes

Two different participatory processes were applied in this thesis. The participatory processes are specific techniques to engage stakeholders actively in decision-making processes. They are used for consulting, involving and empowering citizens in relevant decisions, policies or activities (Rowe and Frewer, 2004). Participation can aid to understand the current issues and tailor the best solutions for all the relevant stakeholders.

Under the umbrella of participatory processes, exists many different forms of participation: from voting in a specific process to involve in the entire design of new infrastructure, policy, etc. The IAP2 proposed the different degrees of participation, from “inform” to “engage” (see Table 1.4) (International Association of Public Participation, 2020).

Chapter 5 and 6 used the World Café methodology (Brown, 2005) - a kind of focus group (see description in chapters)- to codesign future scenarios and select relevant indicators for citizens.

In the same line, in **Chapter 6** an exhibit of future scenarios was carried out along with a brief questionnaire to know the preferences of residents of the municipality.

3.4.3 Ethics

Participatory processes and surveys were evaluated and approved by the Ethics Committee on Animal and Human Experimentation (CEEAH) of the Universitat Autònoma de Barcelona, member of the network of Ethics Committees in Universities and Public Research Centers in Spain (RCE). To ensure rigor, honesty and responsibility in research and in compliance with current regulations on data protection, such as the Spanish Organic Law 15/1999, on the protection of personal data, and the ethical standards established by international codes, all the participatory processes and surveys carried out were approved by this committee. This committee evaluates all the steps to comply with the current regulations, such as preserving the anonymity of the participants, informed consent, the freedom to participate or not, the type of questions asked and how to protect the resulting data. For this thesis, three different documentations were needed and approved: CEEAH 4639, 4520, and 5539 (see supporting information).

3.5 Urban metabolism: MuSIASEM

Urban metabolism was analyzed using the multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM). This methodology was coined by Giampietro et al. (2013) for the assessment of metabolic patterns of complex systems, such as cities, countries, islands, etc. The MuSIASEM is a tool that helps to effectively analyze the FEW nexus. It can be used for the diagnosis of the metabolic patterns of the current city configuration and also to simulate the impacts of future scenarios and it considers a wide range of dimensions and analytical levels. It results in the construction of a multi-dimensional and multi-scale representation of the metabolic pattern of a complex system (Giampietro et al., 2012).

Using input data such as type of workforce and population, as well as available land (the fund elements) and the flows of food, energy, water and money (the flow elements). The MuSIASEM can provide different types of information:

- The extensive variables such as the total requirement, losses, degree of self-sufficiency and also exports and imports.
- The rates of flow/fund (intensive variables) per hour of human activity or density, i.e., hectares of land, across the different levels and sectors proposed in the system under study (Giampietro et al., 2014).

The application of the MuSIASEM implies a set of different steps and data to construct a metabolic profile (Figure 3.6). **The first stage** is to define what the system is, which means to determine the fund elements of the system under study. These fund elements can be the human activity, which denotes the amount of time (hours) by a given population, or power capacity or manage land (hectares). Subsequently, **the flows** to study have to be specified, for instance, water, energy, food flows. After defining fund and flows, **the different scales and dimensions** have to be constructed, for instance, in a municipality case study the scales could be the municipality (first level), then the housing sector, industry sector and the transport sector (second level), and then the households (third level). **The last step of MuSIASEM** is to check the viability, feasibility concerning internal constraints and desirability with respect to external constraints of the system.

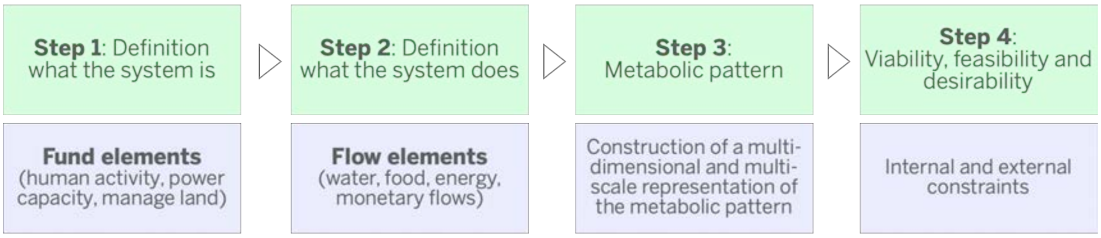


Figure 3.6 Steps for the application of the MuSIASEM

The representation of the metabolism using MuSIASEM is based on environmental impact matrixes that are custom-made for each study. In this dissertation, the end-use matrix and the supply matrix were used. The end-use matrix is focused on the consumption side of the system whereas the supply matrix covers the supply of the different flows.

The MuSIASEM was applied for the accounting of the FEW metabolic patterns of two different municipalities in **Chapters 5, 6 and 7**.

3.6 Sustainability assessment

We applied a sustainability assessment in **Chapters 6 and 7**, using environmental, social and economic indicators (indicators can be checked in the chapter). The sustainability assessment is based on the three-pillar triple bottom line (TBL) model, environmental, social and economic factors which allocate equal relevance on the three pillars in decision-making (Pope et al., 2004). Such sustainability assessments offer a more-forward looking methodology due to considers different criteria and not a single-issue, is multi-disciplinary, multi-dimensional and multi-scale and seeking comprehensive solutions from different perspectives (Finkbeiner et al., 2010). Therefore, such assessment is essential for the successful implementation of novel urban strategies, such as the Roof Mosaic.

3.7 Geographic information system tools

In this dissertation (**Chapters 4, 5, 6 and 7**), aerial imagery and geographic information systems (GIS) were used to retrieve information related to rooftops, such as area, slope, shape, global solar radiation, etc. Different sources were applied such as the light detection and ranging system (LiDAR) which is a remote sensing technology to collect topographic data of the characteristics of the earth's surface, both natural and man-made. Generally, the most precise way to measure landscapes and rooftops of urban areas is made with LiDAR aiming to obtain solar radiation potential (Jakubiec and Reinhart, 2013).

3.8 Cases studies of the dissertation

Three different case studies were selected for this dissertation (Figure 3.10): The Montbau neighborhood (Barcelona) in **Chapter 4**, Badia del Vallès (small city; Metropolitan Area of Barcelona) in **Chapter 5 and 6** and Cerdanyola (medium city; Metropolitan Area of Barcelona) in **Chapter 7**. **Chapter 8** is based on the environmental and social life cycle assessment of one of the components of the farming systems of the Roof Mosaic, i.e., the growing medium; therefore, this chapter is not based in any urban area. We focused the first three chapters on housing estates and **Chapter 7** in three characteristic urban forms: housing estates, originary fabrics and single-family housing areas.

The three different case studies have similar weather because they are located in the same area. The characteristic weather of these urban areas are mild winters (average of 9-12ºC) and hot summers (average of 23-26ºC). The average global radiations is 4.56 kWh/m^2/day (ranging from 1.91 to 7.33 kWh/m^2/day) and an average annual rainfall of 600 mm (AEMET, 2006a).

3.8.1 Montbau neighborhood

Montbau is a neighborhood in Barcelona (Catalonia) (Figure 3.7). It is an emblematic neighborhood where institutions tested an array of urban, constructive and social proposals aimed at the construction of social housing estates (Rieradevall i Pons, 2014a). Montbau is located in the north of Barcelona and was built between 1962-1964 in line with directives established by Modern architecture (Camarero, 2013). It has a population of about 5,070 inhabitants and more than 31% are older than 65 years (Ajuntament de Barcelona, 2017a). Furthermore, the income per capita is low (15,750 € family/year) compared with the rest of the neighborhoods in Barcelona (Ajuntament de Barcelona, 2016a). This neighborhood was chosen as a representative housing estate built between the 1950s and1970s in Europe (Rieradevall i Pons, 2014a).

Figure 3.7 Studied buildings in the Montbau neighborhood

3.8.2 Badia del Vallès municipality

Badia del Vallès is a municipality in the Metropolitan Area of Barcelona (AMB) (Figure 3.8). It was built between 1970 and 1973 aiming to construct 12,000 households, finally, only 5,275 households (13,466 inhabitants) were built with a very dense population in an area of only 0.92 km^2. It is a municipality with low incomes (gross disposable household income: 12,400 €), being usually 75% of the Catalan average (Institut d'Estadística de Catalunya, 2018). This municipality was selected because it is a typical housing estate of mid-rise buildings of 5, 9, 11 and 16 stories, also representative of housing estates in Europe (Serrano Serrat and Vicens, 2016). The constant decrease of the population in the municipality has induced a little reduction in density and also the ageing of the population. Consequently, there is a high rate of inactive population (23%) and unemployed (15%) (Institut d'Estadística de Catalunya, 2018). On the other hand, the municipality has no industry or services for obtaining income; therefore, many of the revenues come from the central government of Catalunya, with the consequence that few renovations have been carried out in this municipality for years. In addition, the municipality suffers from a chronic problem of having in its constructions a very toxic material to health, which is asbestos. In this context, Badia del Vallès faces multiples environmental, social and economic issues that should be resolved in the near future (Serrano Serrat and Vicens, 2016).

Figure 3.8 Different buildings and streets of Badia del Vallès

3.8.3 Cerdanyola del Vallès municipality

Cerdanyola del Vallès is a medium-size city in the AMB, with 57,977 inhabitants where 18.5% are elderly (aged 65 years and over) and 16% are young people (aged 0-15 years) (Ajuntament de Cerdanyola del Vallès, 2019a) (Figure 3.9). Accordingly, it has an ageing population. Cerdanyola has a density of 5,404 inhabitant/km^2, almost three times lower than Badia del Vallès. However, this density is uneven among neighborhoods, where some residential areas have a very low density, such as residential areas of single-family households which can reach 3,276 inhabitant/km^2 and others such as the historic center with 20,610 inhabitant/km^2 (Ajuntament de Cerdanyola del Vallès, 2019a). The gross disposable household income in Cerdanyola (18,500 €) is higher than that in Badia, and the local revenues come from services and industry. The municipality is next to the Collserola Natural Park, the largest park in Barcelona region, which offers the city an extensive green space to enjoy.

Figure 3.9 Panoramic picture of Cerdanyola del Vallès

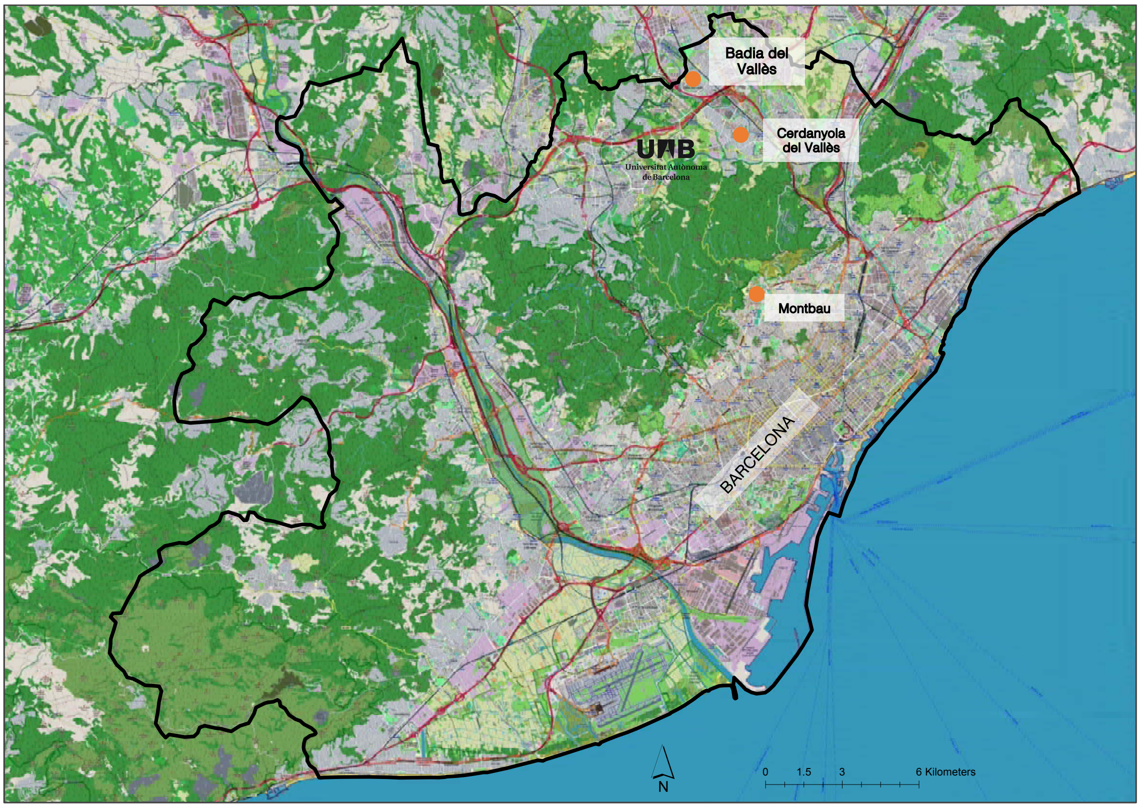


Figure 3.10 Metropolitan Area of Barcelona (AMB) map with the location of the three case studies.

3.9 Open data, open access and gender perspective

With the aim to provide outcomes not only for the scientific community but also for all stakeholders related to this topic, we adopted an open access policy in all the outcomes we have generated during this thesis. Therefore, all papers in this thesis are open access, and all data generated are open access. We used the repository of the Universitat Autònoma de Barcelona: https://ddd.uab.cat/?ln=ca to store all these outcomes. Links to this repository for each paper can be found in the corresponding chapter.

On the other hand, due to the nature of this dissertation and its socially relevant part, we tried to capture all perspectives of public participation. Thus, we tried to have a balance between the participation of women and men in all the participatory processes and surveys. Furthermore, our results are also presented from a gender perspective to assess the similarities and differences among genders (see results in the corresponding chapters).

The Roof Mosaic strategy: a guideline for its implementation

2

Chapter 4

Towards Productive Cities: Environmental Assessment of the Food-Energy-Water Nexus of the Urban Roof Mosaic

4 Towards Productive Cities: Environmental Assessment of the Food-Energy-Water Nexus of the Urban Roof Mosaic

This chapter is the journal paper:

Toboso-Chavero, S., Nadal, A., Petit-Boix, A., Pons, O., Villalba, G., Gabarrell, X., Josa, A. & Rieradevall, J. (2019). Towards productive cities: environmental assessment of the food-energy-Water Nexus of the urban Roof Mosaic. Journal of industrial ecology, 23(4), 767-780. doi: https://doi.org/10.1111/jiec.12829

Abstract

Cities are rapidly growing and need to look for ways to optimize resource consumption. Metropolises are especially vulnerable in three main systems, often referred to as the FEW (i.e., food, energy, and water) nexus. In this context, urban rooftops are underutilized areas that might be used for the production of these resources. We developed the Roof Mosaic approach, which combines life cycle assessment with two rooftop guidelines, to analyze the technical feasibility and environmental implications of producing food and energy and harvesting rainwater on rooftops through different combinations at different scales. To illustrate, we apply the Roof Mosaic approach to a densely populated neighborhood in a Mediterranean city. The building-scale results show that integrating rainwater harvesting and food production would avoid relatively insignificant emissions (13.9–18.6 kg CO_2 eq/inhabitant/year) in the use stage, but their construction would have low environmental impacts. In contrast, the application of energy systems (photovoltaic or solar thermal systems) combined with rainwater harvesting could potentially avoid higher CO_2 eq emissions (177–196 kg CO_2 eq/inhabitant/year) but generate higher environmental burdens in the construction phase. When applied at the neighborhood scale, the approach can be optimized to meet between 7% and 50% of FEW demands and avoid up to 157 tons CO_2 eq/year. This approach is a useful guide to optimize the FEW nexus providing a range of options for the exploitation of rooftops at the local scale, which can aid cities in becoming self-sufficient, optimizing resources, and reducing CO_2 eq emissions.

Keywords: industrial ecology; life cycle assessment (LCA); rainwater harvesting; resource self-sufficiency; solar energy; urban agriculture

4.1 Introduction

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

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

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

A potential action plan is to increase the utility of urban rooftops. We introduce a novel framework, which we call the “Roof Mosaic” approach, to analyze the technical feasibility and environmental implications of using suitable rooftops at local scale (i.e., neighborhoods, districts, industrial and retail parks) to provide food, energy, and water, collectively contribute to environmental, social and economic benefits, and promote self-sufficiency. The transformation of rooftops to improve the performance of buildings has been in practice for many decades (see a list of applications in Table 1.1). Nevertheless, the concept of multiple rooftop uses that create collective, neighborhood-scale benefits has not been yet explored. Most urban rooftops are still used solely as a protective layer that houses technical equipment (Kellett, 2011). An extensive amount of literature documents the utility of single systems on rooftops, but none of the research has combined different systems at the neighborhood level. For instance, Orsini et al. (2014) determined the great potential of rooftop food production in a city, and Sanyé-Mengual et al. (2015b) environmentally and economically assessed the implementation of a rooftop greenhouse in a building. Benis et al. (2018) analyzed food production versus photovoltaic (PV) energy generation on rooftops in a mixed-use neighborhood. Armendariz-Lopez et al. (2016) and Cucchiella and Dadamo (2012) estimated the life cycle cost (LCC) and the environmental performance of PV systems in different building roofs, respectively. Carnevale et al. (2014) compared PV and solar thermal (ST) systems at the household scale. The environmental assessment and the LCC of implementing rainwater harvesting (RWH) were analyzed at building and neighborhood scales (Devkota et al., 2015, 2013; Petit-Boix et al., 2018b; Tavakol-Davani et al., 2013).

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

4.2 Materials and methods

4.2.1 A guide for assessing the implementation of the Roof Mosaic approach

The steps proposed for assessing the implementation of the Roof Mosaic approach are described in Figure 4.1. Each step is explained in the following sections.

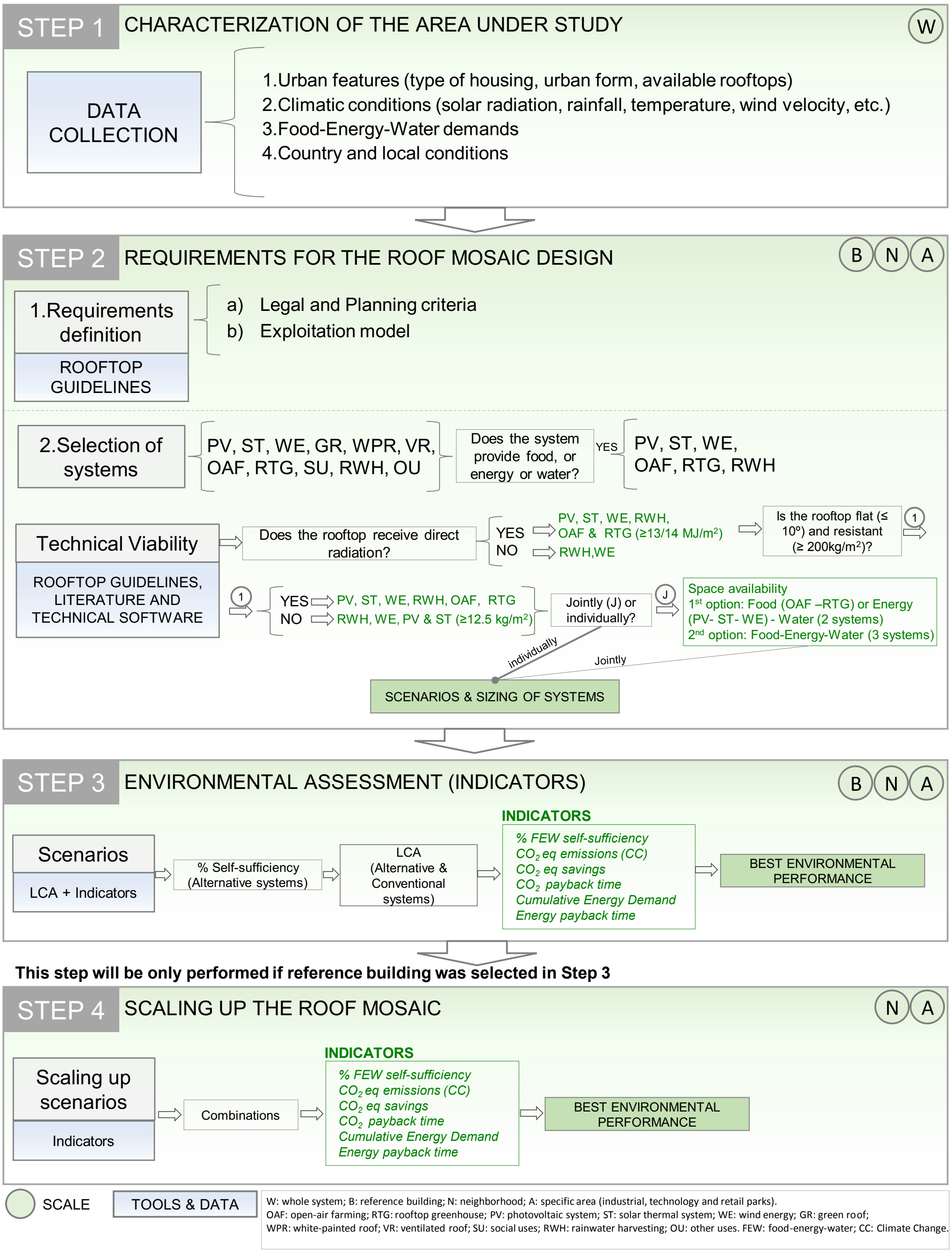


Figure 4.1 Steps proposed for assessing the Roof Mosaic approach

Step 1 Characterization of the area under study

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

1. Urban features (e.g., type of housing, urban form, available rooftops).
2. Climatic variables, i.e., monthly rainfall for sizing the rainwater tank, temperature for choosing suitable crops, solar radiation for sizing the solar panels, and wind velocity and direction for sizing wind energy.
3. Daily demand for produce (kg), energy (kWh or MJ) and water (m^3) to determine the resource quantity required.
4. Country and local social conditions, e.g., income per capita, population pyramid, FEW security, and typical food diet. The typical food diet suggests appropriate vegetables/fruits to be grown on rooftops. The income per capita helps to identify target neighborhoods. The rest of social conditions support the selection of the most suitable system combinations when results yield several possibilities on rooftops**.**

Step 2 Requirements for the Roof Mosaic design

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

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

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

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

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

Step 3 Environmental assessment of the different scenarios and selection of indicators

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

The environmental performance of each scenario can be studied through life cycle assessment (LCA) in compliance with ISO 14040-44 (International Organization for Standardization, 2006). In this case, based on Steinmann et al. (2016), only eight impact categories were analyzed (i.e., climate change (CC, kg CO_2 eq), ozone depletion (OD, kg CFC-11 eq), terrestrial acidification (TA, kg SO_2 eq) freshwater eutrophication (FE, kg P eq), terrestrial ecotoxicity (TET, kg 1,4-DB eq), marine ecotoxicity (MET, kg 1,4-DB eq), agricultural land occupation (ALO, m^2 x year), urban land occupation (ULO, m^2 x year), along with the cumulative energy demand (CED, MJ) (Hischier et al., 2010b). The LCA includes alternative and conventional systems, or only alternative systems if the self-sufficiency is 100%.

To assess both the technical feasibility and environmental implications of the Roof Mosaic, we propose a combination of LCA and field-specific indicators (Lamnatou and Chemisana, 2017; Petit-Boix et al., 2017a). The Roof Mosaic scenario with the best environmental performance will be the one displaying a larger number of outperforming indicators when compared to the other scenarios, always with the same functional unit. The nine indicators considered are CC, CED, avoided kg CO_2 eq/year per inhabitant (CC_A, equation 4.1; Alsema (2000)), CO_2 eq payback time (CPBT, equation 4.1; Alsema and Phylipsen (1995)), energy payback time (EPBT, equation 4.2; Sumper et al. (2011)) and FEW self-sufficiency percentages. The CPBT is the time period required for a system to avoid the production of the same amount of CO_2 generated to produce the system itself, and the EPBT is defined as the period required for the energy system to produce the same amount of energy that was utilized for all these life cycle stages. All indicators are equally weighted.

$$CPBT = \frac{CC_P + CC_T + CC_I}{\frac{CC_A}{year} - \frac{CC_{UM}}{year}} \quad where\ \frac{CC_A}{year} = Yield_f \times \frac{CC_f}{U_f} \qquad (4.1)$$

$$EPBT = \frac{CED_P + CED_T + CED_I}{\frac{E_G}{year} - \frac{CED_{UM}}{year}} \qquad (4.2)$$

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

Step 4 Implementation of the Roof Mosaic approach in neighborhoods when a reference building is selected

This last step will be performed only if a reference building was selected in step 3. Here, we seek to upscale the reference building scenarios proposed in step 3 to create neighborhood designs through the Roof Mosaic approach. To prioritize these upscaled designs, we considered (i) the proportion of each FEW configuration in the building, looking for combinations with a balanced degree of resource self-sufficiency (equation 4.4), and (ii) their environmental performance based on the environmental indicators defined in step 3 (equation 4.3).

$$IN = \frac{\sum_{s=1}^{n} (EI_s \times B_s)}{TB} \qquad (4.3)$$

$$SSN_f = \frac{\sum_{s=1}^{n}(Yield_{f,s} \times B_s)}{D_{f,B} \times B_N} \qquad (4.4)$$

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

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

4.2.2 Application to a case study

Step 1: Characterization of the area under study

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

Step 2: The Roof Mosaic design

The legal and planning criteria vary depending on the system. Food production is not restricted, as long as the harvests are used for self-sufficiency, which is the goal of the Roof Mosaic in this study. Agriculture for commercial purposes is not permitted in Barcelona because the territory is classified as urban land (Metropolitan Area of Barcelona, 1976). RTGs cannot be built on some rooftops of Barcelona because of height/volume restrictions, so allowances are determined on a case-by-case basis by local technicians (Ajuntament de Barcelona, 2018a). No constraints are associated with housing ST, PV and RWH systems on rooftops. In fact, the Spanish Technical Building Code sets mandatory minimums for electricity and sanitary hot water self-sufficiency in new buildings that exceed a built area of 5,000 m^2 (Spanish Government, 2017a) and requires also a separate RWH system (Spanish Government, 2017b).

The roof is a typical vented flat roof (≤10° surface slope) with live loads greater than 200 kg/m^2. The solar radiation is suitable for all systems because it is higher than 13-14 $MJ/(m^2 \cdot day)$ (Nadal et al., 2017b). The features of the rooftop enable the application of any FEW systems. Our design assigned 550 m^2 to energy or food production and the rest of the surface to house the water tank due to the L-shape of the building (see the layout in Figure 4.2 and in the supporting information). Furthermore, the total surface of the rooftop was used to harvest water. Food production included OAF and RTG. In the case of energy, PV and ST were assessed separately to evaluate the supply of electricity and hot water, respectively. WE systems were not assessed because wind turbines can cause rooftop disturbances and additional problems for the residents. As a result, we proposed four pairwise scenarios in the same rooftop complemented with conventional supply to meet the resource demand within the same functional unit. The multifunctional rooftops are:

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

For food systems, we considered only one tomato production cycle per year in spring-summer. We applied hydroponics to limit rooftop loads (80-100 kg/m^2) (Nadal et al., 2017b). We considered a yield of 10 and 15.3 kg/m^2 in OAF and RTG, respectively (Martínez-Blanco et al., 2009; Sanjuan-Delmás et al., 2018). The technologies used for PV and ST systems were the most commonly applied, that is, multi-Si modules (Paiano, 2015) and thermosyphon ST systems (Kalogirou, 2009).The PV and ST outputs were 42,150 kWh/year and 384,102 MJ/year over ten years, respectively. After this period, an efficiency reduction of 0.7% per year is assumed for PV systems (Fthenakis et al., 2011). To size the tank, we used the rainfall series from 1996 to 2015 from the nearest weather station to Montbau. Water demand was calculated using the average demand for laundry in a European household (40 L/(household·day)) (Comission Regulation (EU), 2010) and the average dwelling occupation in Montbau (2.4 inhabitants/household) (Ajuntament de Barcelona, 2017b). RWH also supplied rainwater to the crops, accounting for 2.59 and 2.18 L/(m^2·day) in OAF and RTG (Sanyé-Mengual, 2015; Sanyé-Mengual et al., 2015b). Using the Plugrisost® software (Morales-Pinzón et al., 2015), we obtained a 7-m^3 tank (see technical data in the supporting information).

Step 3: Environmental assessment of implementing the Roof Mosaic approach in the reference building

a) Goal and scope

The functional unit was to meet the annual FEW demands of an average resident of Montbau. This translates into the supply of tomatoes (17.4 kg/year), electricity (1334 kWh/year), sanitary hot water (2398 MJ/year) and water for laundry and irrigation (6.1-6.5 m^3/year) through alternative systems complemented with the supply of conventional systems (i.e., imported food, and energy and water networks). We assumed a lifespan of 30 years. The system boundaries (Figure 4.2) include construction (i.e., production of materials, transport to site and installation) and use/maintenance, whereas the end of life was excluded due to the long lifespan considered and the corresponding uncertainty in relation to the realistic end-of-life scenarios.

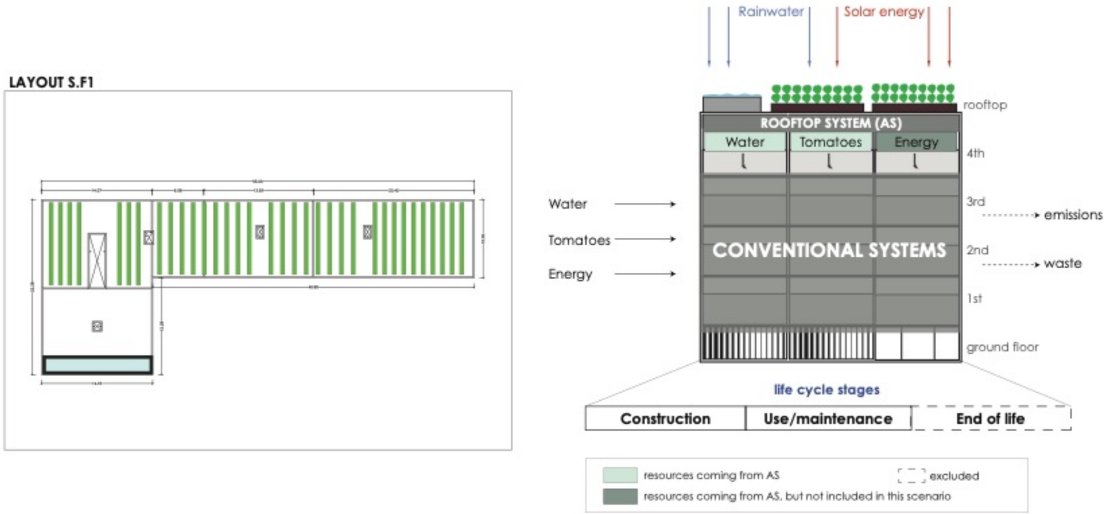


Figure 4.2 layout (left-hand side) and diagram (right-hand side) of the system represented by S.F1 where water and tomatoes come from rooftop system (AS = alternative systems). Energy (electricity and hot water) comes from conventional systems in this scenario. The rest of the scenarios are available in the supporting information

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

b) Life cycle inventory (LCI)

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

c) Life cycle impact assessment (LCIA) and indicators

The LCIA was performed using Simapro 8.1.4 (PRé Consultants, 2017) and the ReCiPe (H) method (Goedkoop et al., 2008). The nine indicators described in step 3 were selected and the remaining LCA indicators are provided in the supporting information.

Step 4: Implementation of the Roof Mosaic approach in Montbau

We assessed eight different combinations (C.1-C.8) of the reference building scenarios S.F1 to S.E2 within the neighborhood following the purpose of the Roof Mosaic, which is to seek a balance in providing FEW to the neighborhood at the minimum environmental cost. Following these premises, the most accurate options were chosen (Table 4.1). Potential additional combinations were rejected due to unbalanced proportions between the three FEW systems.

Table 4.1 The eight different combinations proposed in the neighborhood

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

Combinations (C.) of 3 systems (food, energy, water); S: Scenario; Every column shows the number of rooftops using every scenario. RWH: Rainwater harvesting; OAF: Open-air farming; RTG: Rooftop greenhouse; PV: Photovoltaic; ST: Solar thermal.

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

4.3 Results

4.3.1 Environmental burdens of the FEW at the reference building scale

Environmental impacts and self-sufficiency of the four proposed scenarios

Figure 4.3 compiles the environmental impacts of the building-scale scenarios, including all analyzed life cycle stages of alternative systems complemented with conventional systems. In general, combining food systems with RWH (S.F1 and S.F2) was the most environmentally sound option when compared to energy systems with RWH (S.E1 and S.E2). This trend is true for all midpoints except for ionizing radiation, where S.E1 had the lowest impact. Food systems scored between 10% and 90% better than energy systems. Among farming techniques, OAF seemed to be the best alternative for all impact categories, except for agricultural land occupation, as RTGs had a larger yield.

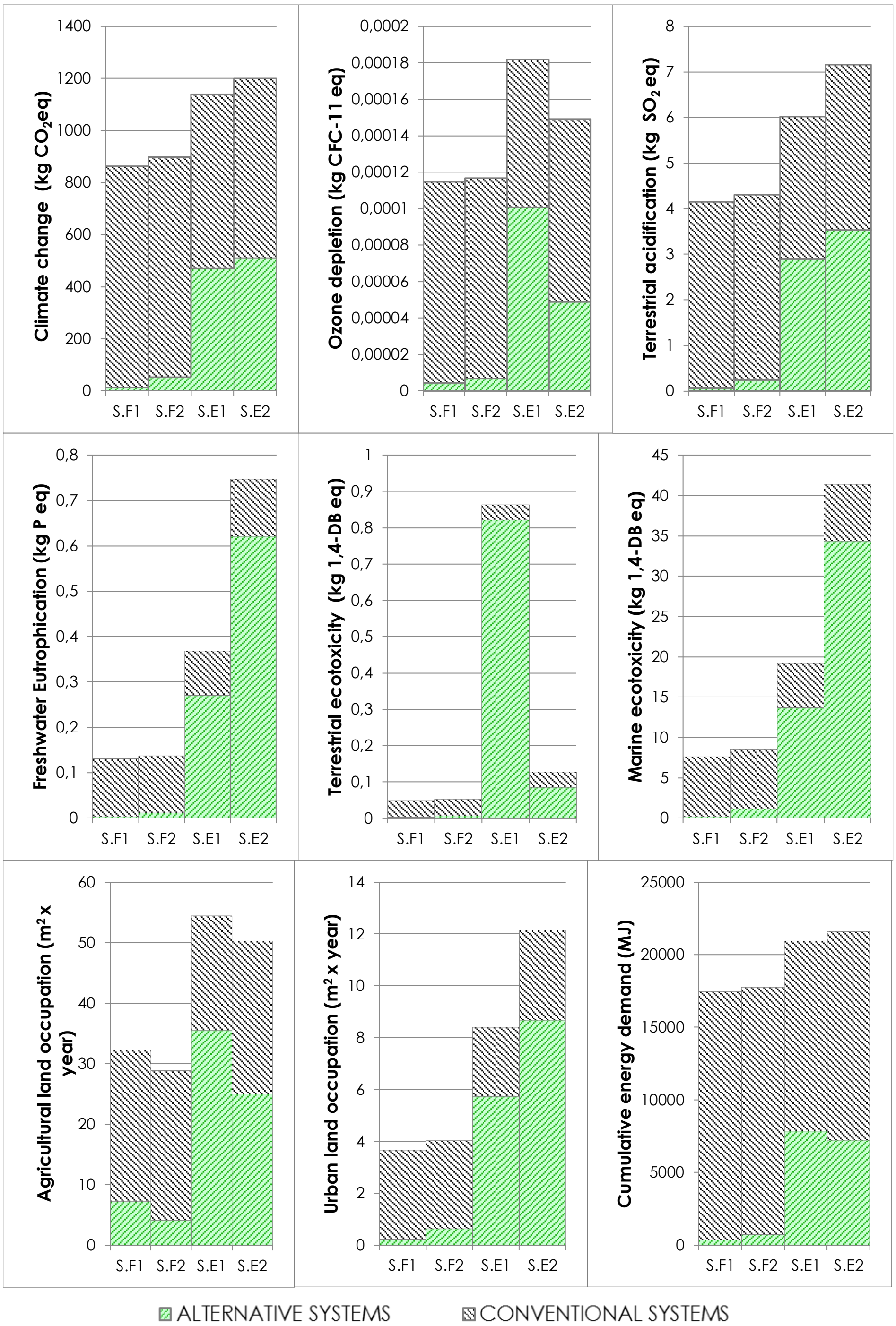


Figure 4.3 Environmental impacts of the four scenarios of alternative production on the rooftop and the required conventional systems to meet the total demand

Nevertheless, these results depend on the degree of self-sufficiency of each scenario (Table 4.2), or in other words, on the contribution of conventional supply systems to the environmental scores of each configuration. Food production reached high self-sufficiency (S.F1 = 52% and S.F2 = 69%), and the impacts of food production were much lower in alternative than in conventional systems in all categories; this is because fewer and more environmentally friendly materials were used. The alternative energy systems in S.E1 had greater impacts (55%-93%) than conventional systems did in 6 of the 9 categories. S.E2 had similar results, except for ozone depletion (OD) and agricultural land occupation (ALO), where the percentage was higher than and equal to that of conventional systems, respectively. However, the difference in self-sufficiency between energy systems was remarkable (S.E1 = 30% and S.E2 = 100%), mainly because of the higher efficiency of ST collectors compared to PV panels. In addition to this difference, alternative energy supply systems require large amounts of impactful materials for their construction (S.E1 = 34.8 kg/m^2 and S.E2 = 29.4 kg/m^2), such as metals, chemical products, and energy, which generate negative effects in these categories.

Table 4.2 Self-sufficiency of each scenario at reference building scale

Flow	Demand	Supply							
		Rooftop systems				Conventional systems			
		S.F1	S.F2	S.E1	S.E2	S.F1	S.F2	S.E1	S.E2
WATER (laundry + irrigation) (m^3/(inhabitant·year))	6.1-6.5*	21%	22%	24%	24%	79%	78%	76%	76%
FOOD (tomatoes) (kg/(inhabitant·year))	17.4	52%	69%	0%	0%	48%	31%	100%	100%
ELECTRICITY (kWh/(inhabitant·year))	1334	0%	0%	30%	0%	100%	100%	70%	100%
NATURAL GAS (sanitary hot water) (MJ/(inhabitant·year))	2398	0%	0%	0%	100%	100%	100%	100%	0%

*Range

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

Avoided CO_2 eq emissions and CO_2 and energy payback times

Table 4.3 illustrates the avoided kg CO_2 eq/year per inhabitant and CPBT and EPBT of alternative systems. Food systems were environmentally better and had slightly higher self-sufficiency than S.E1 but lower than S.E2 (100%), whereas the avoided kg CO_2 eq were much higher in energy systems, which would avoid approximately 10 times more CO_2 eq emissions than food systems. This results from the high quantities of CO_2 eq generated in the conventional electricity and natural gas networks. PV systems save the greatest amount of CO_2 eq emissions (0.49 kg/kWh). However, they are penalized by their lower self-sufficiency (30%) in comparison with ST systems (0.26 kg/kWh).

Table 4.3 Avoided kg CO2 eq/(inhabitant·year), the CPBT and the EPBT using alternative systems

	Avoided kg CO_2 eq/(inh·year) (CC_A)				CPBT (years)				EPBT (years)			
Flow	S.F1	S.F2	S.E1	S.E2	S.F1	S.F2	S.E1	S.E2	S.F1	S.F2	S.E1	S.E2
WATER (laundry + irrigation)	0.44	0.45	0.46	0.46	1.77	1.77	1.77	1.77	N.A.	N.A.	N.A.	N.A.
FOOD (tomatoes)	13.5	18.1	0	0	0.91	3.39	-	-	N.A.	N.A.	N.A.	N.A.
ELECTRICITY	0	0	195.5	0	-	-	2.40	-	-	-	1.80	-
NATURAL GAS (sanitary hot water)	0	0	0	176.1	-	-	-	2.94	-	-	-	0.66

N.A: Not available; inh: inhabitant; - : the flow (food or/and energy) is not in this scenario.

On the other hand, the CPBT results (Table 4.3) were the lowest for food systems in S.F1. On the contrary, S.F2 had the highest payback time, 3.39 years, because of the higher emissions caused by the greenhouse infrastructure. Regarding energy systems, S.E2 obtained the highest CPBT (2.94 years), while S.E1 was slightly lower.

EPBT was only calculated for scenarios with alternative energy supply (Table 4.3). For the production of energy, both the electrical and thermal outputs were converted into primary energy values based on the efficiency of energy conversion at the demand side in Spain (Dones et al., 2007). ST systems had an EPBT of 0.66 years, while PV systems triplicated the payback time. Thus, the high energy consumption of Si-based modules was confirmed (Carnevale et al., 2014), which was the most relevant aspect of their life cycle along with the material consumption. These results could be compared with existing literature. However, this indicator depends on different factors, such as module type, primary energy conversion, or location (solar radiation) (Peng et al., 2013). Hence, different results can be found, from <0.5 to 1.2 years for ST systems and from 1.5 to 4.9 years for PV systems (Ardente et al. 2005; Hang et al. 2012; Alsema 2000); our results are within these ranges.

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

4.3.2 Implementation of the Roof Mosaic approach at the neighborhood scale

This section focuses on the different options proposed at the neighborhood scale, using the same functional unit that was used for the reference building scale. Table 4.4 displays the different combinations and an array of indicators that were obtained using this approach (step 4). At this scale, any hot water surplus (51%) could be distributed among buildings.

Table 4.4 Analysis of the indicators of eight different combinations proposed at the neighborhood scale. The best environmental performance indicator is in bold and the darker the green color, the larger the number of outperforming indicators

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

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

C: combination; W (L+I) water (laundry + irrigation); F (T): food (tomatoes); E: electricity; HW: hot water; CC: climate change; CPBT: CO2 payback time; CED: cumulative energy demand; EPBT: energy payback time; Neighborhood: 981 inhabitants; inh: inhabitant; y: year; RWH: rainwater harvesting; OAF: open-air farming; RTG: rooftop greenhouse; PV: photovoltaics; ST: solar thermal systems.

The results show that three combinations had equally high numbers of outperforming indicators, scoring 4 positive indicators out of 9 (C.1, C.2 and C.5). They obtained the highest avoided CO_2 eq emissions (159-160 kg CO_2 eq/(inhabitant·year)) but also had high values of CO_2 eq emissions (CC) in their construction stage (331-345 kg CO_2 eq/inhabitant) because of the high environmental burden of the energy systems. These combinations showed nearly identical levels of self-sufficiency in all the systems, which is especially relevant to hot water.

C.4, C.6 and C.7 each achieved 3 out of 9 positive indicators. C.4 obtained the lowest EPBT because more ST systems than PV systems were assigned to the rooftops. C.6 was similar to C.5 but obtained slightly lower CO_2 eq savings than C.5 did because it had one additional OAF system. C.7 emitted the least CO_2 eq emissions and displayed the least CED in its construction stage, as it had more rooftops with OAF systems and fewer rooftops with energy systems. C.3 and C.8 were the combinations with the fewest favorable environmental indicators, primarily because of the moderate values achieved for most of the indicators.

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

4.4 Discussion

4.4.1 Demonstrating the Roof Mosaic approach

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

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

4.4.2 The potentiality of the Roof Mosaic approach

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

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

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

4.5 Conclusions

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

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

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

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

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

Assessment of the implementation of the Roof Mosaic in urban areas

3

Chapter 5

More than the sum of the parts: System analysis of the usability of roofs in housing estates

Methodological Innovation

This chapter provides a novel combination of methodologies. We used the MuSIASEM to characterize the integrated food-energy-water metabolic profile of housing estates for the first time. Subsequently, we used the MuSIASEM as input to inform the implementation of the Roof Mosaic in the municipality. Furthermore, a participatory process was added to incorporate the preferences of the residents to proper design future scenarios of rooftop uses in the municipality. These mixed methodologies ensure more open and democratic planning of future sustainable urban strategies to tackle climate change. To our knowledge, this is the first time that the integrated FEW metabolic profiles of housing estates were characterized.

5 More than the sum of the parts: System analysis of the usability of roofs in housing estates

This chapter is the journal paper:

Toboso-Chavero, S., Villalba, G., Gabarrell Durany, X., & Madrid-López, C. (2021). More than the sum of the parts: System analysis of the usability of roofs in housing estates. Journal of Industrial Ecology, doi: https://doi.org/10.1111/jiec.13114

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.

Keywords: industrial ecology; rainwater harvesting; renewable energy; Roof Mosaic; urban agriculture; urban metabolism

5.1 Introduction

Cities have expressed different urban forms since their inception depending not only on their physical but also on their non-physical characteristics, e.g., density, distribution, size, shape, urban layout, building/housing types, etc. (Jenks and Colin A, 2010). One of the most globalized urban forms are housing estates (HEs), i.e., mass social housing (Kabisch and Grossmann, 2013; Monclús and Díez 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 cross 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, 1994b; Rieradevall i Pons, 2014b) 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 (Baldwin 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 (Baldwin 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 (Baldwin 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 and Coelho, 2007; Solecki et al., 2011). Some examples include the general improvement of areas with high economic costs (Helleman and 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 - i.e. 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 for 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 -i.e. 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 (Khadija Benis et al., 2018; 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, i.e., 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, i.e., 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, etcetera. 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 food-energy-water 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), which is a quantitative method proven valuable for studying complex multiscale 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 to effective climate action for at-risk populations of a widespread urban form, i.e., 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 a fourth and fifth section.

5.2 Materials and 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 5.1). 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., 2013, 2012). 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.

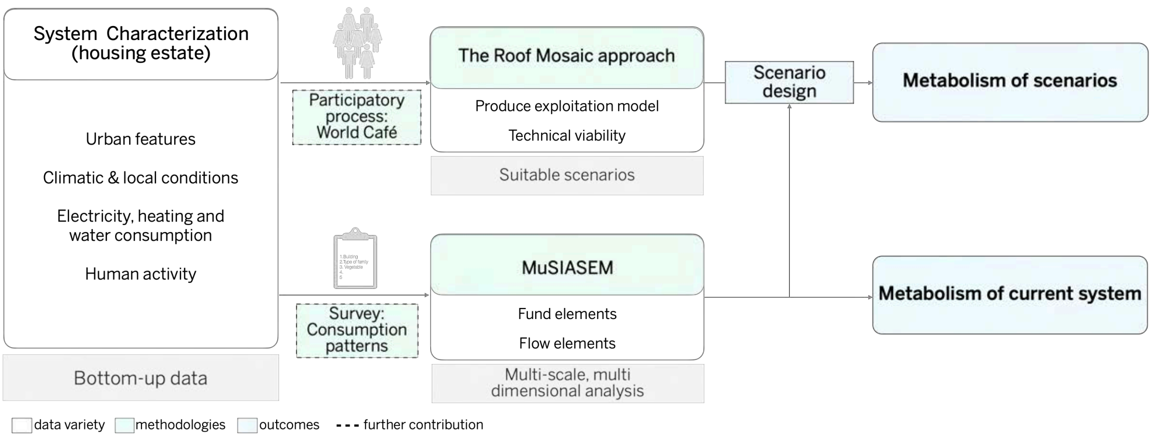


Figure 5.1 Schematic workflow designed for the proposed urban system strategy

5.2.1 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 and 4b. There are 69 identical type A high-rise buildings that are 9 and 11 stories tall and provide 1,402 households; 48 identical type B medium-rise buildings of 5 stories tall that provide 1,440 households; 49 identical type C high-rise buildings that are 9 and 11 stories tall and provide 2,148 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 supporting information for an extended characterization of the municipality and buildings).

The municipality's population is characterized by the contractive pyramid (see supporting information) (Saroha, 2018) typically associated with developed countries with low mortality and fertility and an ageing population. Figure 5.2 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.

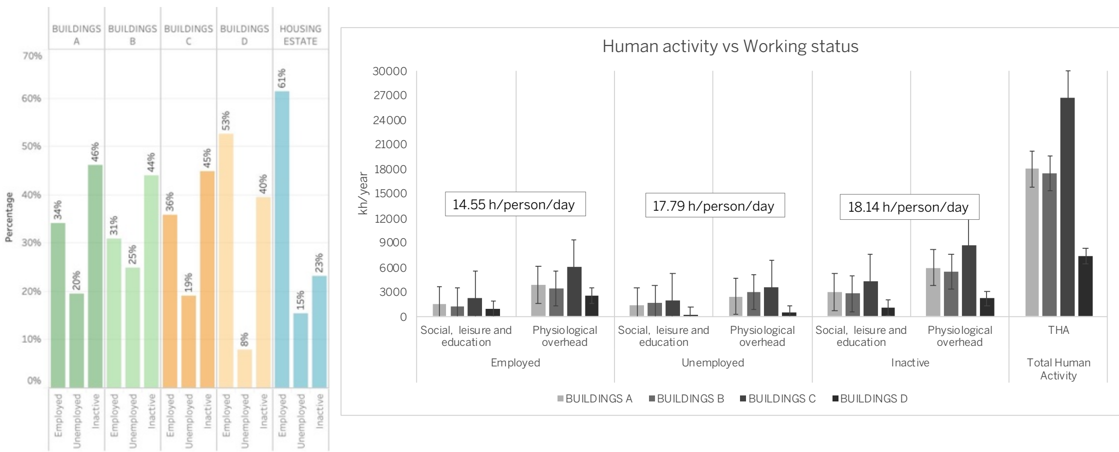


Figure 5.2 Left graph: Percentages of residents' employment status among housing estate and buildings (2018). Right graph: Human activity in social, leisure and education activities and physiological overhead per working status and building type. Boxes illustrate the average human activity (hour/person/day) of all household activities. h: hour; kh: kilohour

By the same token, Figure 5.2 displays human activity (HA) (hours) 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.

We used three different types of data:

a) 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 (see supporting information). 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., 2021a) (see supporting information).
b) 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.
c) A variety of data such as FEW consumption, the population pyramid (Institut d'Estadística de Catalunya, 2018) and human activity (hours (h)) (Figure 5.2) (Generalitat de Catalunya, 2011), which denotes the amount of time (hours) 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 modelling 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 (kg of vegetables) per household. We validated these outcomes with the average values of official statistics (See expanded information in the supporting information).

5.2.2 The Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM)

The MuSIASEM (Giampietro et al., 2013, 2012) 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:

System definition. The definition of analytical levels for an MuSIASEM is based on the spatial scale of the studied municipality (Figure 5.3). 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.

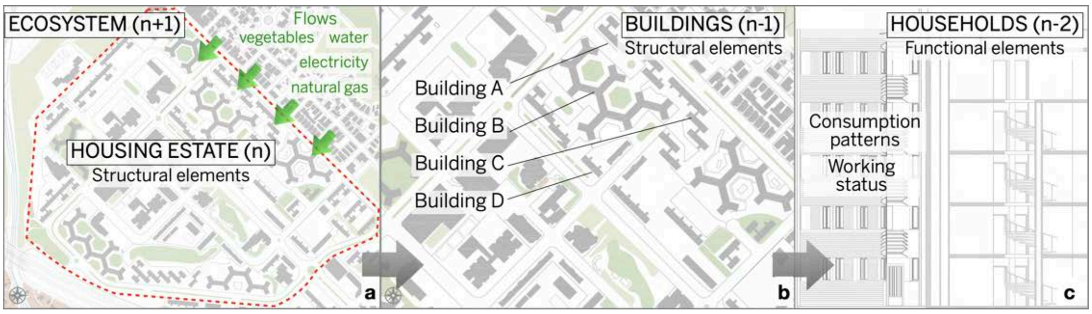


Figure 5.3 Graphical dendrogram (profile of distribution) showing structural and functional elements across the four hierarchical levels (n+1, n, n-1 and n-2) of the case study. Panel a illustrates the housing estate and ecosystem levels, panel b shows the building level and panel c shows the household level

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 5.1.

Table 5.1 Definition of indicators and dataset used for the analysis of metabolic patterns of the HEs and the proposed rooftop scenarios. [1] Ajuntament de Badia del Vallès, (2019); [2] Sorea, (2019); [3] FAO, (2011); [4] Domene and García, (2017). Sources are <u>*underlined*</u> *in the table*

MATRIX	LEVELS (SCALES)	FUND ELEMENTS	INDICATORS (flow elements & 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	<u>city council data</u> [1]
			heating total consumption (HTC)	MJ/year	<u>city council data</u> [1]
			water total consumption (WTC)	m^3/year	<u>company data</u> [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	<u>Food and Agriculture Organisation of the United Nations (FAO)</u> [3]
	n (decentralized scenarios in the municipality) Scenario 1 Scenario 2 Scenario 3 Scenario 4 Scenario 5		electricity losses (EL)	kWh/year	<u>previous study</u> [4]
			water losses (WL)	m^3/year	<u>company data</u> [2]
			vegetable total requirement	kg/year	VTC + VL
			electricity total requirement	kWh/year	ETC + EL
			water total requirement	m^3/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
				m^3/household/year	WTS/HH

VTS: vegetable total supply; ETS: electricity total supply; WTS: water total supply; HH: number of households

Matrix. *The end-use matrix* (see the template in the supporting information) 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 hours/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 – modelled 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 one 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). The total requirement is the resource consumption (end use) adding the losses.

These results are illustrated in Figure 5.4 and Figure 5.5 and in Table 5.2 of the results section.

5.2.3 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 the supporting information.

After this participatory process, the Roof Mosaic (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 firsts are 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). 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 ten 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 ten years in the area (327-919 l/m^2/year). The uncertainty is illustrated in Figure 5.5 with black bars and Table 5.2 with absolute values in brackets. Details of the uncertainty analysis can be found in the supporting information.

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., 2021a) (see supporting information). They have a load capacity of higher than 300 kg/m^2 (Serrano 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.

5.3 Results

5.3.1 Characterization of the current metabolic pattern of housing estates

Figure 5.4 provides a comprehensive account of the metabolism of the municipality and of building types in the form of end use extensive and intensive indicators.

Total end use by building (level n-1). Type C has the highest value of total end uses for FEW (Figure 5.4, 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/hour, respectively).

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.

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 5.4 (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.

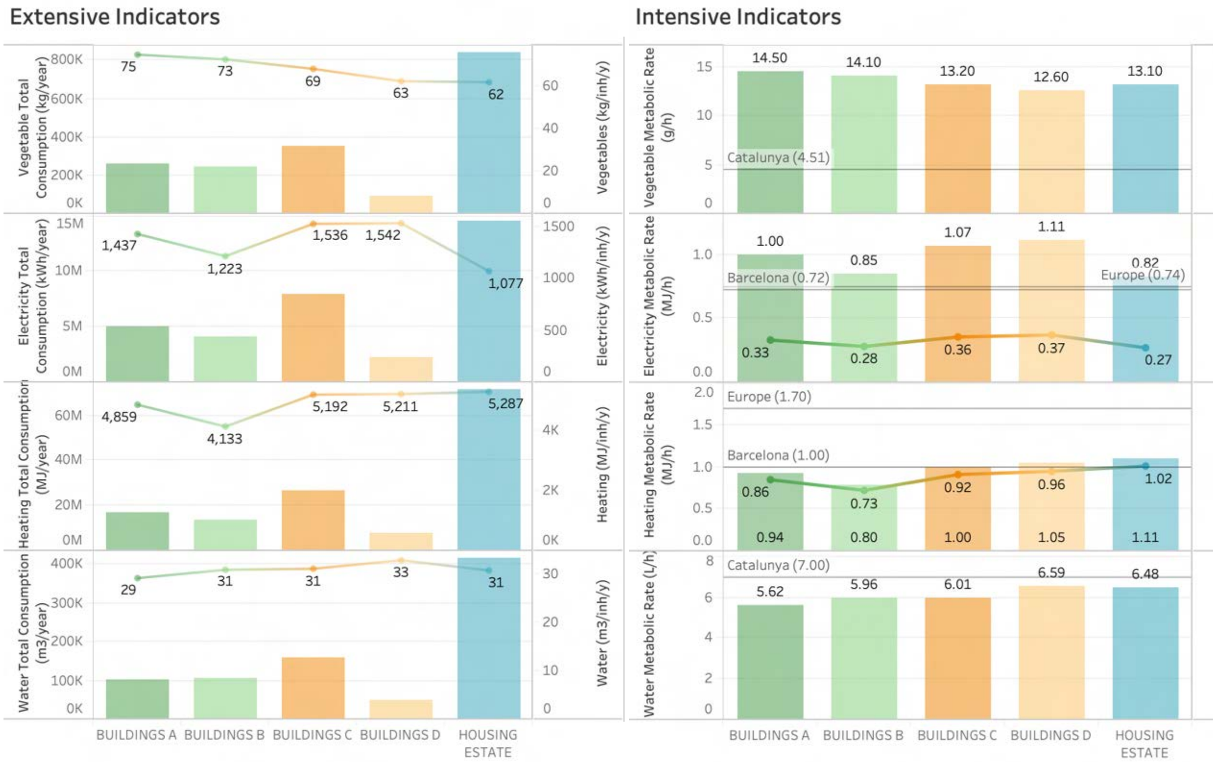


Figure 5.4 End-use matrix indicators (extensive indicators and resource consumption per capita (line chart) are shown on the left and intensive indicators are shown on the right) by building and municipality compared with averages for Barcelona, Catalunya and Europe (horizontal lines) (Madrid and Cabello, 2011; Pérez-Sánchez et al., 2019; 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

5.3.2 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, i.e., food and energy production and rainwater harvesting 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 (see supporting information). The limitations residents perceived are related to the monetary investments of different systems and to the maintenance (time required) of agricultural systems on rooftops, e.g., 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. Rainwater harvesting 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 multifunctionality 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).

5.3.3 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 to 5 is implemented on rooftops (Figure 5.5 and Table 5.2), they could ensure half (between 42-53% (65.5 to 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, 1994) 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/hh/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/hh/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 to 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.

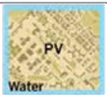
Electricity production is included for PV panels and energy savings are included for green roofs

Figure 5.5 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. S1: scenario 1; S2: scenario 2; S3: scenario 3; S4: scenario 4; S5: scenario 5

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 three 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., 2015b), 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), ergo these self-sufficiency percentages will decline. Nevertheless, this further reinforces the goal of exploiting any form of water in this future context.

Table 5.2 displays savings per household and levels of human activity, i.e., 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 (10890 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 5.2), this only represents 2, 1.2 and 1.6 hours/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 m²/inhabitant) and the type of infrastructure required to implement such systems.

Table 5.2 Part of the supply matrix of the system, including other considerations. For the full results, see supporting information. The values of the uncertainty assessment are in brackets; hh: household; kh: kilohours

		Description	Annual savings/hh	Annual human activity	Annual human activity/hh	Considerations
ROOFTOP SCENARIOS	SCENARIO 1		**electricity** 937 *(670-1300)* kWh **water** 6.4 *(3.6-10.2)* m³	**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)* m³	**electricity** 0.09 kh **water** 10.65 kh	3.5 h	**green spaces:** 2.5 m² /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)* m³	**vegetables** 384 kh **electricity** 0.09 kh **water** 10.65 kh	73.5 h	**green spaces:** 2.5 m² /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)* m³	**vegetables** 223 kh **electricity** 0.09 kh **water** 10.65 kh	43.6 h	**green spaces:** 2.5 m² /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)* m³	**vegetables** 303 kh **electricity** 0.05 kh **water** 10.65 kh	59.2 h	**green spaces:** 3.7 m² /inhabitant Need for rooftop access

5.4 Discussion

5.4.1 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 to 53% lower than those for Europe, respectively, which translates into a significantly lower heating metabolic pattern for HEs (Figure 5.4, right side).

Conversely, for the vegetable metabolic rate, the municipality consumes more than three times than 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 (see supporting information). 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 the supporting information 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 (see supporting information). 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 (Baldwin 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 1660 €/month (see supporting information) 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 five 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 have been related to cold home temperatures (Howden-Chapman et al., 2007). Serrano 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.

5.4.2 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 to 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) calls to halve food losses and waste by 2030. Rooftop food production can help achieve this goal (FAO, 2019).

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 cites this approach as a means to substantially increase the global use of renewable energies (United Nations, 2019).

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., 2017; K. Benis et al., 2018; 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.

5.5 Conclusions

This study assessed the implementation of FEW systems on the rooftops of housing estates. 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 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, i.e., 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 to 14.50 g/h for vegetables, 0.82 to 1.11 MJ/h for electricity, 0.80 to 1.11 MJ/h for heating and 5.62 to 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 to 53% of their vegetable consumption, 9 to 35% of their electricity use, and 38 to 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, e.g., types of families present and their current conditions, time available and time spent on household activities, resource requirements, etc. 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 face social and economic needs, with the aim to play a crucial role in environmental upgrading, guiding metropolises to evolve to more resource self-producing, socially just, and healthy habitats.

Chapter 6

Incorporating user preferences in rooftop food-energy-water production through integrated sustainability assessment

Methodological Innovation

This chapter proposes a new combination of methodologies to design better future scenarios of the implementation of FEW on urban rooftops and breaching the gap between scientific analysis and user preferences. Here, we present an innovative combination of participatory processes and a survey, urban metabolism, through the MuSIASEM methodology, and relevant indicators, applying LCA. The participatory processes and survey were beneficial to incorporate residents' preferences and to choose relevant indicators and the final scenarios to implement in the municipality. The MuSIASEM was useful to assess the FEW consumption pattern of the neighbors and, finally, the LCA aided in calculating the environmental impacts of these system

6 Incorporating user preferences in rooftop food-energy-water production through integrated sustainability assessment

This chapter is the journal paper:

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Abstract

We propose a participatory integrated sustainability assessment for an emergent urban sustainability strategy: the implementation of food-energy-water production on roofs, based on an integration of participatory processes with a high level of resident involvement and a multi-dimensional sustainability assessment (including environmental, social and economic indicators). The proposed framework was applied to a typical housing estate in the Barcelona region made up of 201 buildings and 13,466 inhabitants and characterized by a high-share of low-income families. We assess five future scenarios of joint electricity production (photovoltaic panels), vegetable production (through open-air farming and greenhouses), green roof implementation and rainwater harvesting and rank them following non-participatory and participatory approaches. Most residents preferred scenario 1, which dedicated the rooftops to the production of electricity and the harvest of rainwater, thereby providing 35% of their electricity consumption and 38% of their water needs for flushing. This scenario also scored the best in terms of social indicators, covering 33% and 8% of energy and water poverty, respectively, and had a maintenance investment of only 2 hours/household/year. In general, there was a tendency for residents to choose solutions providing water and energy (scenarios 1 and 2) over the food production potential of rooftops (scenarios 3, 4 and 5). However, the environmental assessment indicated that the most suitable alternatives were those promoting vegetable production, meeting 42 to 56% of the residents' fresh produce demand and reducing environmental impacts by 24-37 kg CO_2eq/m^2/year. Hence, we found that residents were mainly concerned with energy expenses and not so much with food insecurity, social cohesion or the impacts of conventional supply networks. Our assessment supports urban resilience and helps identify and breach the gap between scientific and user preferences in urban environmental proposals by educating and informing residents through an integrated assessment and involving stakeholders for future successful strategies.

Keywords: Urban agriculture, urban resilience, farm to fork, energy and water poverty, public participation, gender dimension, citizen science

6.1 Introduction

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

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

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

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

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

6.2 Materials and methods

The conception of this research is founded on an initial article dedicated to the metabolism of the area under study, the municipality of Badia del Vallès (13,466 inhabitants; density: 14,387 inhabitants/km^2), a typical housing estate in the Metropolitan Area of Barcelona (AMB) that faces common environmental, economic and social issues such as energy and water poverty and urban and social degradation (Toboso-Chavero et al., 2021). The two methodological components that constitute this study are the participatory processes (steps 1, 2 and 6; section 6.2.1) and the sustainability assessment (steps 4 and 5; section 6.2.2). The framework used (Figure 6.1) is based on a combination of quantitative and qualitative methodologies with the aim of proposing a comprehensive and participatory assessment for the deployment of a novel strategy: the Roof Mosaic.

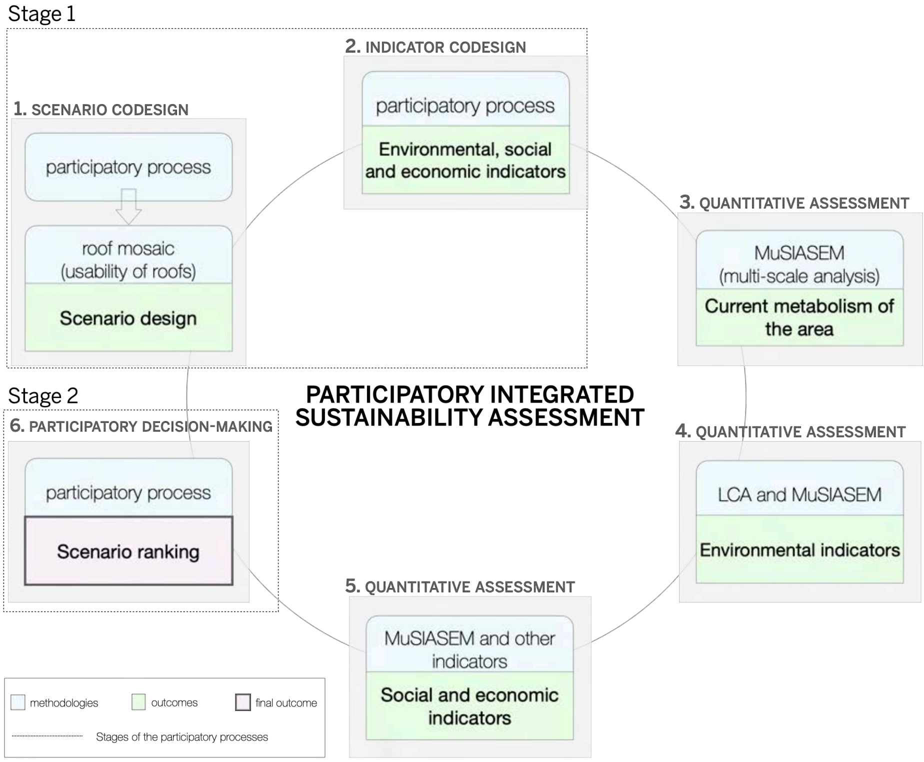


Figure 6.1: Framework for participatory integrated sustainability assessment

6.2.1 Participatory processes stages

The participatory processes are split into two stages.

Stage 1: Codesign of scenarios and of assessment indicators. The first participatory process was carried out with residents of the municipality who were over 18 years of age. Participants were invited in December 2018. A workshop of fourteen neighbors (29% women, 71% men) was conducted with no preselection of participants based on the World Café methodology (Brown, 2005). This methodology is characterized by a relaxed environment of small groups (4/5 people maximum), with a facilitator that gives agency to the participants, and takes notes of all the conversations on the topic proposed. The workshop aimed to scrutinize the concerns and preferences of neighbors related to their municipality, the application of FEW systems on their roofs and the relevant indicators for them. According to the IAP2, this participatory process is at the "collaborative" level, the second highest position within the spectrum of public participation. The design protocol for the participatory process is available in the supporting information.

We examined the data based on grounded theory methods (Corbin and Strauss, 1990), coded the data, and extracted the key concepts from the answers. Subsequently, we applied content analysis by counting the concept frequencies. They were scored from 1 to 5 depending on the number of responses related to each concept (Table 6.1).

Table 6.1 Matrix to establish the scores of the different answers related to the concepts retrieved from the participatory process

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

Stage 2: Participatory decision-making. This process was carried out in September 2020 and aided in identifying neighbors' preferences and comparing the most suitable scenarios obtained from the sustainability assessment. We designed six different posters with this information. One poster displayed the current situation in the municipality as retrieved from a consumption pattern survey carried out by the authors (Toboso-Chavero et al., 2020), and five posters (see posters in the supporting information) with the five scenarios proposed and with all the indicators (section 6.2.2). An exhibit of these posters and a short questionnaire were conducted in the municipality. This questionnaire could be answered online at https://docs.google.com/forms/d/e/1FAIpQLSepoPptehmltBNNHRToShSGGCetksv31ssXcE2ub5AciqIkUQ/viewform or in hard copy. The questionnaire asked for gender, age, and type of stakeholder and then asked for the most suitable scenario for the municipality and also a ranking from the first position to the last position of the five scenarios. The possibility of not using rooftops for anything was also included. The exhibit lasted for twelve days, and residents were able to vote for their choices within this time. After that, all the responses were gathered, analyzed, and compared with those retrieved from the sustainability assessment (see the following protocol in the supporting information).

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

6.2.2 Integrated sustainability assessment

This component includes an array of environmental, social and economic indicators selected in harmony with previous studies (Toboso-Chavero et al., 2021, 2019) and the residents' concerns resulting from the participatory process (section 6.2.1). Table 6.2 summarizes the different indicators, including the degree of interest that was assessed, including the same scores as in section 6.2.1. The indicators used for the sustainability assessment were as follows:

Sustainability indicators

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

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

Environmental indicators

The LCA methodology was used for three of the environmental indicators: Global Warming (GW; kg CO_2eq/m^2/year), Global Warming of the conventional networks for CO_2 savings (kg CO_2eq/m^2/year), and Cumulative Energy Demand (CED; MJ/m^2/year) (Hischier et al., 2010b). These indicators were evaluated in compliance with ISO 14040-44 (International Organization for Standardization, 2006) using Simapro 9.0 software with the ReCiPe method at the midpoint level (hierarchical perspective) and the Ecoinvent Database 3.5 (Swiss Centre For Life Cycle Inventories, 2018). The functional unit is 1 m^2 that supplies different resources, this translates into the supply of electricity (76 kWh/m^2/year), vegetables—tomatoes, lettuces, green beans and peppers—(10.3 kg/m^2/year for OAF) (Boneta et al., 2019) and 14.16 kg/m^2/year for RTGs (Rufí-Salís et al., 2020)), a 1 m^2/year GR system and 1 m^3/year of RWH. The system boundaries include the extraction of raw materials, production, transport and use, and the end-of-life is excluded due to the long life span of the systems, which was assumed to be 30 years. All the inventories of PV panels, GR, OAF, RTG, RWH and conventional networks are available in open access at: http://doi.org/10.5565/ddd.uab.cat/237969. They came from experimental data from the Barcelona region and were adapted to this study. Other derived indicators for the LCA were CO_2 payback time (CPBT; years) (Phylipsen and Alsema, 1995) and energy payback time (EPBT; years) (Sumper et al., 2011a).

Social indicators

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

Economic indicators

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

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

Table 6.2 List of indicators for assessing the different proposed scenarios

Indicator	Description	Unit	Calculation	Reference	Degree of interest
		Sustainability Indicators			
Self-sufficiency	Quantifies the percentage of the self-production on rooftops of the different resources	% (percentage)	(TS/TC)*100	MuSIASEM	4
Increase in green spaces	Considers the total green area (GR, OAF, RTG) in relation to the total population	m²/inhabitant	TGS/Tin	Taylor et al., 2011; Van Herzele and Wiedemann, 2003; Kabisch and Haase, 2013	1
Production of vegetables	Quantifies the quantity of vegetables produced per m² of rooftop and year	kg/m²/year	TS/TR	MuSIASEM	4
Production of electricity	Quantifies the quantity of electricity produced per m² of rooftop and year	kWh/m²/year	TS/TR	MuSIASEM	5
Production of water	Quantifies the quantity of water harvested per m² of rooftop and year	L/m²/year	TS/TR	MuSIASEM	4
		Environmental Indicators			
CO_2 savings	Quantifies the annual avoided GHG emissions (Global Warming impact category) related to FEW conventional networks per m² of rooftops if the decentralised systems are implemented	kg CO_2 eq /m²/year	$\sum_{S=1}^{n} GWc$	LCA- Recipe method (H), Goedkoop et al. 2013	4
Global Warming	Quantifies the total GHG emissions of the construction phase of FEW systems (OAF, RTG, GR, PV panels and RWH)	kg CO_2 eq /m²/year	$\sum_{S=1}^{n} GWp$	LCA- Recipe method (H), Goedkoop et al. 2013	3
CO_2 payback time (CPBT)	It is the time period required for a system to avoid the production of the same amount of CO_2 generated to produce the system itself	years	GWp/GWc	LCA- Alsema and Phylipsen et al., 1995	1
Cumulative Energy Demand (CED)	Represents the direct and indirect energy use throughout the life cycle of the FEW systems (OAF, RTG, GR, PV panels and RWH)	MJ/m²/year	$\sum_{S=1}^{n} CED$	LCA- Hischier et al., 2010	1
Energy payback time (EPBT)	Considers the time need to compensate the energy produced by the construction of the FEW systems	years	CED/Eg	LCA- Sumper et al., 2011	1
		Social Indicators			
Energy poverty coverage	Quantifies de number of households coverage of electricity from decentralised systems	(%; number of households)	TS/Th	The Green/EFA group of the European Parliament, 2016	3
Water poverty coverage	Quantifies de number of households coverage of water from decentralised systems	(%; number of households)	TS/Th	Lawrence et al., 2002	3
Human activity budget (THB)	It is the human time of a given population dedicated to each system (FEW)	total hours/year	-	MuSIASEM- Giampietro et al., 2012 Project data & Distribution companies	4
Maintenance investment	Hours of dedication for each system (OAF, RTG, GR, PV panels and RWH) per household and year	hour/ household/year	THB/Th	MuSIASEM- Project data & Distribution companies	4
		Economic Indicators			
Monetary savings (MS)	Quantifies the amount of annual money savings for using decentralised systems per household and year	€/household/year	-	Public prices	5
Investment (TI)	The money invest to implement the decentralised systems (OAF, RTG, GR, PV panels and RWH) per m²	€/m²	-	Distribution companies	5
Maintenance cost	Considers the annual maintenance cost of the implementation of decentralised systems per m² and year	€/m²/year	-	Distribution companies	5
Payback period	It is the time, expressed in years, required to generate sufficient savings to recover the initial capital outlay of the project	years	TI/MS	Watson, 2004	1

TS=Total annual supply; TC= Total annual consumption; TR= Total m² of rooftops; TGS=total green spaces; Tin=Total inhabitants; GWc= Global Warming of conventional networks; GWp= Global Warming production phase; CED= Cumulative Energy Demand ; Eg= Energy generated; Th=Total households; THB=Total human budget; TI= Total Investment; TMS= Total monetary savings

6.3 Results

6.3.1 Codesign of scenarios and assessment indicators

A set of scenarios and indicators were proposed based on the preferences of participants at our workshop. The concerns of the municipality's residents (Table 6.3) are mainly related to aging, many senior citizens living alone, lack of social cohesion and lack of economic resources. They are also worried about the lack of residents' commitment and limited political involvement in the issues of the municipality.

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

Table 6.3 Outcomes of the first participatory process. Main social perceptions of the residents regarding their municipality and the use of roofs. Score = 1 to 5

TOPICS	MAIN CONCERNS		PREFERENCES ON ROOFS		BARRIERS OF USING ROOFS		OPPORTUNITIES OF USING ROOFS		PREFERENCES ON INDICATORS	
		score		score		score		score		score
TYPE OF CONCEPTS	Urban Degradation	1	Social use	0	Significant investment	4	Money savings	5	Energy & water poverty	3
	Financial resources	2	Rainwater harvesting	1	Maintenance	4	Resource savings	5	Monetary savings	5
	Little involvement of the neighbours	4	Energy production	4	Little involvement of the neighbours	4	Self-sufficiency	4	Investment cost	5
	Social Degradation	5	Food production	1	Difficult access	1	Sustainability	2	Maintenance cost	5
					Legal issues	1	Product quality	1	Maintenance investment (time spent)	4
							None	3	Environmental aspects	4
							Anticapitalism	1	Production of resources	4

best score … worst score

The participatory process (Figure 6.2) was fundamental for the proposal of scenarios because many scenarios could be implemented, yet only a limited number are in line with the residents' priorities. Accordingly, five different scenarios were presented (scenario 1 (S1; 100% photovoltaic (PV) panels and rainwater harvesting (RWH), i.e., all the rooftops become equipped with PV panels and set up for RWH), scenario 2 (S2; 50% PV + 50% green roofs (GR), half of the rooftops become equipped with PV and the other half with GR, and RWH is conducted on all the rooftops), scenario 3 (S3; 50% PV + 50% open-air farming (OAF) and RWH), scenario 4 (S4; 50% PV + 50% rooftop greenhouses (RTG) and RWH) and scenario 5 (S5; 25% PV + 25% GR + 25% OAF + 25% RTG + RWH)).

Figure 6.2 Pictures of the participatory process carried out with the residents of the municipality.

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

6.3.2 Characterizing environmental, social and economic dimensions to support decision-making processes regarding scenario sustainability

We evaluated the different scenarios through environmental, social and economic dimensions (Figure 6.3). According to these analyses, scenario 1 obtained the most favorable indicators, attaining the majority of its highest values in the social indicators and the others in electricity self-sufficiency (35%), monetary savings (742 €/household/year) and CO_2 savings (47 kg CO_2eq/m^2/year). Nevertheless, it also has the most unfavorable indicators because its performance is mainly based on one resource, i.e., electricity. Scenario 4 is the scenario with the second-most positive indicators, particularly in vegetable self-sufficiency (56%; 14.16 kg/m^2/year) and having enough rainwater to irrigate all crops. However, its performance is worse in the social and economic categories than that of scenario 1. Scenarios 2, 3 and 5 have fewer beneficial indicators, especially scenario 2, which obtained a substantial number of indicators with poor performance, such as the EPBT (6.7 years) and CPBT (2.5 years).

If we compare the different scenarios according to each indicator's average, we can assert that scenarios 3 and 4 perform considerably better than the other scenarios. These two scenarios provide vegetables—through open-air farming and greenhouses—on half of the roofs, electricity on the other half and enough water to irrigate almost all crops. However, in principle, in the first participatory process, residents indicated that they mainly preferred electricity (section 6.3.1), and scenario 1 offered more electricity than either of these two scenarios (S3 & S4). Nevertheless, scenario 1 has the second highest investment cost and does not provide vegetables.

Conversely, scenario 2 has the fewest indicators that are above each indicator's average. It is only the best in water self-sufficiency because less irrigation is required for extensive green roofs of sedum and in the initial investment of the systems because fewer materials are necessary. Likewise, scenario 5 has the second fewest favorable indicators. This is because in this scenario, all the systems (PV, GR, OAF, RTG and RWH) are deployed on the municipality's roofs, resulting in lower values for most of the indicators. However, in the environmental categories, this scenario performs excellently, particularly in the increase in green spaces (3.7 m^2/inhabitant), decrease in Global Warming (35 kg CO_2eq/m^2), short CPBT (1.4 years) and low Cumulative Energy Demand (582 MJ/m^2), which implies that this option is the least environmentally demanding.

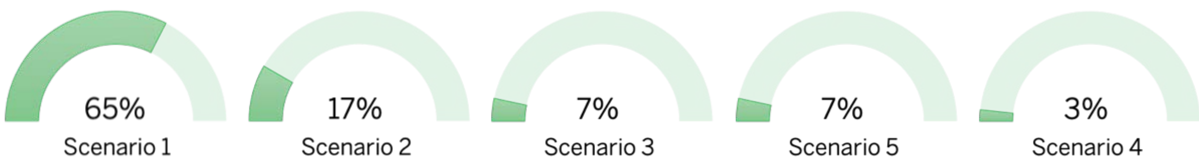
Figure 6.3 Sustainability assessment of the five proposed scenarios. S1: scenario 1 (PV + RWH); S2: scenario 2 (PV + GR + RWH); S3: scenario 3 (PV + OAF + RWH); S4: scenario 4 (PV + RTG + RWH); S5: scenario 5 (PV + GR + OAF + RTG + RWH); h: hour; hh: household; inh: inhabitant; CPBT: CO_2 payback time; CED: cumulative energy demand; EPBT: energy payback time. See all the outcomes at: http://doi.org/10.5565/ddd.uab.cat/237969.

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

6.3.3 Characterization of residents' preferences

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

The exhibit was opened under COVID-19 restrictions. Therefore, it was complicated to gather the opinions of the residents over 65 years old since these residents are not familiar with online questionnaires. Consequently, only 8% of the total respondents were older than 65 years. The most representative age groups were 19 to 44 (58%) and 45 to 65 (32%). Similarly, women are under-represented relative to men, with only 35% of the total participants being female (See the table in Figure 6.4).



Total number of responses	Gender			Age Group				Type of stakeholder		
	Female	Male	Other	<18	19-44	45-65	> 65	Resident	Expert	Public institution
60	35%	63%	2%	2%	58%	32%	8%	95%	15%	8%

Ranking

Figure 6.4 Outcomes of the exhibit. The half-pie charts are the preferred scenarios of the residents. The table represents the type of resident who voted, split by gender, age group and type of stakeholder. The graphs in the bottom section illustrate the share of residents from each building typology (same colors as in Figure 2) that voted for each scenario as first to fifth option. Type of stakeholder: percentage is higher than 100% because some participants selected two characteristics, e.g., resident and expert. See all the outcomes at: http://doi.org/10.5565/ddd.uab.cat/237969

The outcomes display a clear preference for scenario 1; 6 out of 10 residents chose to use their rooftops for producing electricity and collecting rainwater for flushing toilets. This ratio coincides with the first participatory process, where residents agreed as a first option to implement PV panels on their roofs. The second most supported option was scenario 2, but only by 17% of the residents. Furthermore, when a ranking was requested, this scenario also appeared in the second position; nevertheless, only 38% preferred this option, followed by scenarios 3 (23%) and 4 (20%). The third most-preferred alternative was a tie between scenarios 3 and 5. However, in the ranking, the third most-preferred scenario was scenario 3. The least preferred option was scenario 4, with barely 3% of the respondents selecting this option; however, in the ranking, the least-preferred option was scenario 5 (53%). Either way, scenarios 4 and 5 are the alternatives with the least support among residents.

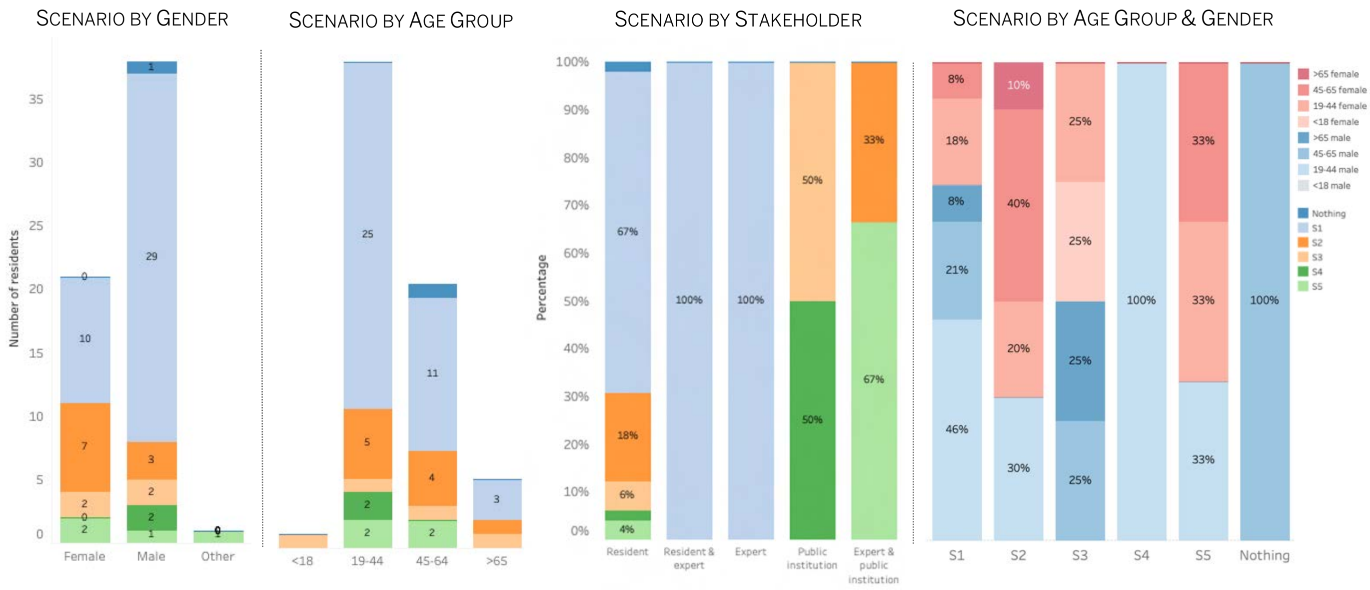


Figure 6.5 Outcomes classified by gender, age group and stakeholder. S1: scenario 1 (PV + RWH); S2: scenario 2 (PV + GR + RWH); S3: scenario 3 (PV + OAF + RWH); S4: scenario 4 (PV + RTG + RWH); S5: scenario 5 (PV + GR + OAF + RTG + RWH)

Considering the scenarios preferred by those with different characteristics, differences by gender can be seen, where women had a more diverse opinion, voting primarily for scenarios 1 and 2 with no votes for scenario 4 (see Figure 6.5, left-hand bar chart). For men, the best option was certainly scenario 1 (76%). In regard to age groups, the residents aged 19-44 years, the best represented group, mainly preferred scenario 1; 7 out of 10 would like to implement the production of electricity on their roofs, which is in accordance with the general results. On the other hand, the 45-65 and over 65 years old groups preferred the same option, scenario 1, but to a lesser extent. Furthermore, combining age group and gender indicates that scenario 1 was mainly selected by men, in particular men aged 19-44; in contrast, scenario 2 was mainly chosen by women (70%) and especially women aged 45-65 and more than 65 years old, accounting for 50% of the votes for this scenario.

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

6.4 Discussion

6.4.1 Comparison between residents' preferences and the sustainability assessment outcomes

We identified some discrepancies between the residents' preferences and the outcomes of the sustainability assessment. Such discrepancies are mostly present for scenarios 2 and 4. Scenario 1 was selected as the first choice of the residents and was also the alternative with the most favorable indicators in the sustainability assessment. Scenario 4 was the second option in the sustainability assessment, but it was ranked last by the residents because the construction of a greenhouse on their buildings was still difficult for them to envision. The fact that the upfront investment is high together with the lack of examples of rooftop greenhouses in Spain were some of the reasons presented. In contrast, scenario 2 received the second most votes from residents but performed the worst in the sustainability assessment. The rest of the rankings are listed in Table 6.4 below.

Table 6.4 Ranking from the sustainability assessment compared to that from the participatory voting

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

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

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

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

6.4.2 Applicability, limitations and policy suggestions

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

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

Nevertheless, the complexity of the trade-offs among the environmental, social and economic parameters challenges one-sided decision-making processes. By incorporating the stakeholder's values in the decision process, complexity is embraced and managed. To provide proper guidance, this participation should go beyond mere consultation and reach at least the level of collaboration[2] as described by the IAP2 Federation (International Association of Public Participation, 2020). Collaboration ensures selection of the scenarios that are better suited to the

[2] "To collaborate" is defined as "to partner with the public in each aspect of a decision."

goal of the study, increasing the probability of a successful implementation. A number of examples of urban development projects that failed due to the opposition of citizens can be found in the literature; see the case of the superblock program's pilot project in Barcelona, a large-scale intervention to address climate change challenges (Zografos et al., 2020), or the failed wind farm projects in some communities (Bell et al., 2005; Hindmarsh, 2010).

This case study was based on a housing estate owned by the local government and built in 1976, where few renovations have been made to the building stock. The façades and roofs of this housing estate need to be refurbished. Furthermore, this situation is similar to that in many housing estates in Europe (Blos, 1999; Scalon and Whitehead, 2008) and in the Barcelona region, namely, the Montbau and Ciutat Meridiana neighborhoods and the Bellvitge municipality (Blos, 1999; Monclús et al., 2017). Consequently, the most plausible path for their renovation would be a public investment to upgrade these areas due to the economic and social issues faced by the residents, who are not able to bear these costs. This is an opportunity for public institutions to manage not only the rehabilitation of these areas but also to provide basic resources (FEW) produced on rooftops in order to ameliorate the energy and water poverty and food insecurity that some households have to cope with. Examples of new public initiatives in Barcelona for boosting rooftop use are the green roof competition[3] or the installation of PV or solar thermal panels on roofs[4], for which the city council subsidizes 75% and 50% of the initial cost. Another type of initiative is the proliferation of energy companies that commercialize only renewable energies, which guide citizens and help them install PV panels on their roofs through shared investments (energy cooperatives).

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

By applying the proposed framework, policymakers can foster agreements and social cohesion among stakeholders by working together to find the best future scenario for the municipality. Having environmental, social and economic indicators for these Roof Mosaic scenarios provides a framework for selecting the best alternative from all plausible perspectives and readapting the current urban regulations and policies for easy implementation of FEW production on roofs. Some examples of these policies can be found in the city of Paris with the reform of the local urban plan (PLU) (Mairie de Paris, 2016), which among other things, obliges the vegetalization of roofs larger than 200 m^2 in new construction, does not consider rooftop greenhouses to be a new story to the building and promotes new green spaces, of which 30 hectares must be for

[3] https://ajuntament.barcelona.cat/ecologiaurbana/en/green-roof-competition
[4] https://energia.barcelona/ca/ajuts-i-subvencions-convocatoria

urban agriculture. Another example is Barcelona, which has an urban agriculture strategy for the city that promotes roofs as key spaces for increasing green spaces and vegetable production in the city in order to attain 1 m^2 more per person of green infrastructure by 2030 (Ajuntament de Barcelona, 2019). The city council also established a strategy for promoting solar energy generation that aims to increase self-consumption, self-production and renewable and local generation and is focused on public and private roofs with public or private investments (Ajuntament de Barcelona, 2017c).

6.5 Conclusions

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

The first participatory process proposed five future Roof Mosaic scenarios and provided a guide for the selection of assessment indicators, such as the production of resources and investment and maintenance costs. The sustainability assessment appraised the Roof Mosaic scenarios environmentally, socially and economically, indicating that scenarios 1 (the implementation of PV panels and rainwater harvesting) and 4 (deploying greenhouses, PV panels and rainwater harvesting) were the best options and scenario 2 (PV panels, green roofs and rainwater harvesting) was the least advisable. Subsequently, carrying out a second participatory process with the residents in which the five scenarios with all the indicators' outcomes were presented, we identified some discrepancies between the sustainability assessment and the residents' preferences, which agreed with scenario 1 (65%), voted for mainly by men (75%), as the best option, but which did not agree with the rankings of the rest of the options. Scenario 2 was the second-most preferred option among the residents (17%) and was mainly selected by women (70%) but was in the last position in the sustainability assessment. Conversely, scenario 4 was the second-best option in the sustainability assessment but the last choice among the residents (3%).

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

Chapter 7

Consumption pattern profiles versus the potential of the local food-energy-water production on urban rooftops in three characteristic urban forms

Methodological Innovation

This chapter provides a novel combination of GIS, MuSIASEM, LCA and participatory processes to propose the best future scenarios in the implementation of the Roof Mosaic. Furthermore, for the first time, it is provided the FEW metabolic profiles of three characteristic urban forms: housing estates, originary fabrics and single-family housing areas.

7 Consumption pattern profiles versus the potential of the local food-energy-water production on urban rooftops in three characteristic urban forms

Summary

Urban areas mainly rely on external markets to meet their resource demand, which leads to a variety of environmental and socio-economic issues. Likewise, urban areas are very heterogonous in many aspects; however, it is possible to find similar physical characteristics in certain areas of the territory, based on their urban morphology, targeting to find more appropriate solutions to overcome these issues. Consequently, we propose to combine urban morphology and the resource (food, energy and water) demand profiles from a socio-economic perspective by implementing a sustainable urban strategy: the Roof Mosaic, i.e., the production of food, energy and water on urban roofs. We combined spatial analysis, multi-scale integrated analysis of societal and ecosystem metabolism, and a survey to characterize geospatially and socio-economically the municipality of Cerdanyola del Vallès (57,977 inhabitants; density: 5,404 inhabitant/km^2,) and three characteristic urban forms, originary fabrics, housing estates and single-family housing areas to create feasible Roof Mosaic scenarios. We found that the municipality can provide 31 m^2 of rooftop per dwelling to implement urban agriculture, photovoltaic panels or harvesting rainwater. By urban form, single-family housing areas obtained the highest share, 22.6 m^2/household, housing estates the lowest 11.5 m^2/household and the originary fabrics are in the middle (17.8 m^2/household). In terms of consumption pattern profile of these residents, the single-family housing displayed the highest values in vegetable (11.4 g/h), electricity (0.85 MJ/h) and water metabolic rates (5.9 l/h) and the lowest were found in housing estates (10.5 g/h; 0.75 MJ/h; 5.0 l/h). Four different policies were proposed, based on the survey outcomes, which depicted significant shares of self-sufficiency in vegetables (16-115%), electricity (13-71%) and the required flushing and irrigation water (13-433%) for the municipality and the different urban forms. These mixed-methods can aid urban planners and institutions to propose feasible future sustainable urban strategies adapted to urban forms and types of residents, meeting their needs while addressing environmental and socio-economic issues.

Keywords: self-sufficiency, urban agriculture, Roof Mosaic, industrial ecology, green cities, circular economy

7.1 Introduction

Cities require high amounts of resources to function, because of a high concentration of population and not enough local resources to meet the demand. Thus, urban areas are highly reliant on external resources (Agudelo-Vera et al., 2012; Bai, 2007). Europe has a high rate of urbanization, more than 7 out of 10 people live in urban centers (UN-Habitat, 2020). Thereby European urban areas are where most people live. Unfortunately, the concentration of population in urban areas triggers a myriad of environmental, social and economic issues. Specially, the European urban population is exposed to concentrations of air pollutants (e.g., PM_{10}, $PM_{2.5}$, O_3, NO_2) above the stringent recommendation of the World Health Organization (WHO), which affects the quality of life of these city-dwellers (European Environment Agency (EEA), 2020). In the same line, European citizens have, on average, 18 m^2 of publicly accessible green infrastructure, which is the double WHO recommends, but unevenly distributed across countries, where southern and eastern countries have the lowest values of urban green spaces access (Maes et al., 2019). Basic resource-wise, European dwellers require the highest share of energy use (26%) in household activities, and energy supply is the second economic activity with the highest share (21%); therefore, both activities account for almost 50% of the total energy consumption (Eurostat, 2018). Regarding water, the largest consumer is agriculture (40%), especially in southern European countries where more and more agricultural lands demand irrigation. Then energy production, followed by mining and manufacturing, and household use (12% - 144 l/person/day) (EEA, 2018). Likewise, European-dwellers have risen the kcal intake by 14% the last years (European Union, 2011), spending 13% in food and beverage of the total annual household expenditure, being the second-largest expenditure after housing, water, electricity and gas (23.5%) (Eurostat, 2019).

In the same context, Europe has the advantage to tackle climate change efficiently thanks to the organization of their urban areas (Timothy Beatley, 2000). Historically, European cities have been fundamentally compact and dense urban forms, walkable and with prominent public transport (Timothy Beatley, 2000). Besides, within these cities, different urban tissues can be encountered. The physical dimensions of urban fabrics affect the type of doable urban strategies to apply because a set of features such as size, shape, distribution of open spaces and type of roofs must be considered (Jenks and Colin A, 2010). Different urban forms can be identified, where the most usual are housing estates, originary fabrics (historic center and suburban extension districts) and single-family housing areas (Oliveira, 2016). Housing estates are widespread in most of the European countries (Spain, France, United Kingdom, etc). They can be defined as *"distinct and discrete geographic housing areas which are dominated by residential blocks of five stories or more"* (Turkington et al., 2004). They are characterized by being massive projects of high-rise blocks with high population density with collective spaces for communal use (Turkington et al., 2004). They often have a range of common issues, such as structural problems, social issues related to social cohesion, insecurity and financial problems (Murie et al., 2003; Van Kempen et al., 2005). On the other hand, the originary fabrics are featured by an irregular layout and a mixture of different buildings and houses with different heights and shapes with no specific pattern, as is the case in housing estates. Streets are often characterized by being narrow and irregular in their layout and widths due to the fact that they come from old villages (Braulio-Gonzalo et al., 2020). Subsequently, residential areas of single-family dwellings have a very different urban morphology from the prior urban forms. They are sprawl spaces with low housing density dominated by detached and semi-detached housing with access to green spaces. They are usually safe and secure sites but with poor access to facilities (Jenks and Colin A, 2010).

It exits an increasing awareness of the crucial role urban morphology – i.e., the discipline of urban planning that studies the physical dimension of the built environment, and among other utilities, it can identify urban fabrics (Oliveira, 2016)- can play in the better coordination and deployment of sustainable urban initiatives (Fang et al., 2015). Cities can be split into smaller systems such as urban forms to find similar urban solutions for their better environmental and social performance. Due to the complexity and heterogeneity of metropolises, smaller parts as urban fabrics, which are a physical expression reflecting specific features, can help to characterize the type of residents that live in these urban forms, finding common environmental and social issues in sites with similar structural conditions (Braulio-Gonzalo et al., 2020). Urban morphology can be an effective classification to compare and aggregate data and find similar climate change solutions (Lamb et al., 2019). Several studies have proposed urban morphology as a key factor to assess different sustainable urban strategies. Braulio-Gonzalo and colleagues 2020 developed a methodology for breaking down cities into small pieces aiming to apply in 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 this sense. Energy aspects and urban morphology have been widely studied, namely matching energy systems for renewable energy and urban archetypes (Perera et al., 2019), or to understand the energy demand and promote energy renovation scenarios (Middel et al., 2014; Rode et al., 2014). Furthermore, for the design of sustainable transport, urban forms have a vital role (Babalik-Sutcliffe, 2013; Feng et al., 2008).

To our knowledge, there is a research gap in combining urban morphology and the resource demand profiles from a socio-economic perspective in sustainable urban strategies. Accordingly, we assess the implementation of a sustainable urban strategy in a medium city, i.e., the production of food, energy and rainwater harvesting on urban rooftops to reduce the consumption and exploitation of external resources; thus, rising their self-sufficiency and security of these three resources. The goal of this research is to present the most suitable scenarios of production of resources in a municipality made up of three different urban forms. To do so, we assess geospatially the potential rooftops of the municipality to implement the production of food, energy and water. Subsequently, we compare consumption (demand) and the potential production of resources (the Roof Mosaic) in different urban fabrics. Crossing the physical part of the municipality (rooftops, buildings, urban tissues) and the social part (consumption pattern profiles and preferences of the residents), we propose future scenarios and policies to apply in this municipality. The combination of spatial and urban metabolism analysis provides an accurate and consistent design for the implementation of sustainable urban strategies, offering the potential production and matching where the demand is the highest, and prioritizing in most needed urban areas.

7.2 Materials and methods

7.2.1 Study area

The case study is based on developing a comprehensive framework for the proposal of suitable rooftops to produce resources (FEW) and match them with the residents' profile and type of urban tissue. Cerdanyola del Vallès in the Metropolitan Area of Barcelona (AMB; 36 municipalities and of 5.4 million inhabitants) (Catalonia; Spain), a medium city of 57,977 inhabitants (IDESCAT, 2020), was selected. The municipality has a Mediterranean climate with mild winters and hot and dry summers. It has an annual average rainfall of 610 l/m^2 and an average global solar radiation of 4.56 kWh/m^2/day (AEMET, 2006a). This municipality was selected because is characterized by five typical urban tissues: a dense historic center, suburban extension, different areas of housing estates, disperse single-family housing areas and isolated industrial parks (PDU, 2017).

This study was divided into two distinct steps (Figure 7.1). First, a geospatial model was developed to characterize rooftops and urban forms, i.e., the morphological characterization (section 7.2.2). The spatial extent of the study area is 31 km^2, 3,583 buildings and 23,726 households. Second, the socio-economic characterization of the municipality (section 7.2.3) was built with the aim to create viable future scenarios in cities, which is crucial to evaluate a range of social features these urban areas possess, such as the consumption pattern profile and the residents' preferences.

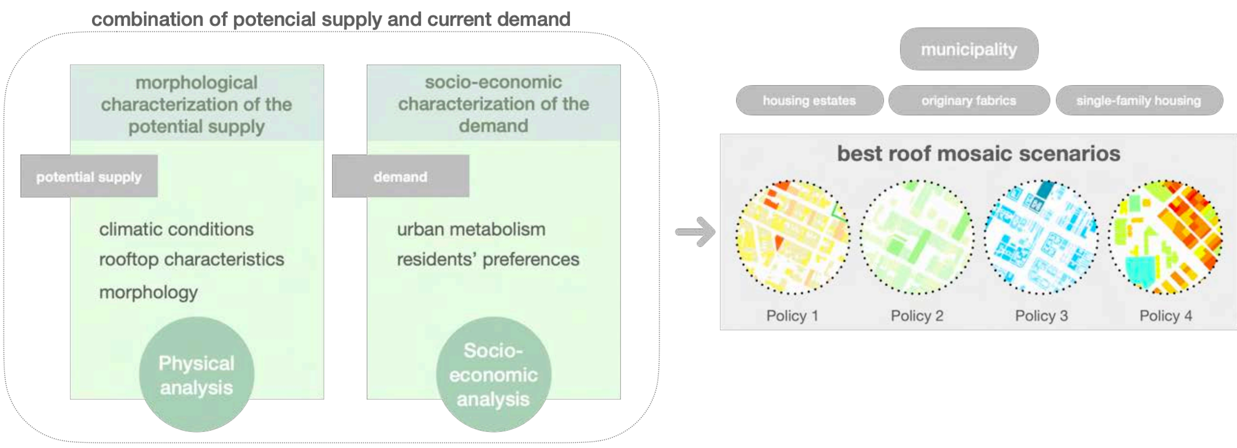


Figure 7.1 Diagram of the main steps of the applied methodology

7.2.2 Morphological characterization of the supply

The identification of suitable rooftops, their characteristics and urban tissues was conducted using different geoprocessing and spatial analyst tools in QGIS and ArcMap software (ESRI Inc.) and different data sources. This methodology is based on Montealegre, S, Guillén-Lambea, Monzón-Chavarrías, & Sierra-Pérez (2021).

7.2.2.1 LiDAR data

The LiDAR data were captured by the National Plan of Aerial Orthophotography (PNOA) on 19 and 28 September 2016 using an airborne Leica ALS50 discrete return sensor with an average density of 0.5 points/m^2. Since point clouds were classified, those points belonging to classes 7 (noise) and 12 (overlap) were excluded from the analysis to avoid errors. A digital surface model (DSM) with a 1-meter cell size was created using the first returns of the LiDAR dataset.

7.2.2.2 Building footprint data

The built areas (i.e., roofs) were provided by the Spanish Cadastre in shapefile format as polygon geometries or footprints. After grouping the building footprints according to cadastral reference and height attributes, a 1-meter inside buffer was applied to the building footprint data (Dirección General del Catastro, 2013).

7.2.2.3 Data Processing

Different characteristics were analyzed: rooftop slope, rooftop azimuth, shading and solar radiation. See supporting information for details.

7.2.2.4 Estimation of the supply potential

A multicriteria decision analysis was applied using the raster layers created previously to select suitable cells for urban agriculture and solar PV panels.

Food: Urban agriculture

The installation of the urban rooftop farming, in general, requires a load capacity higher than 200 kg/m^2 on a flat roof (surface slope $\leq 10^{o}$). Moreover, suitable surfaces should receive insolation equal or more than 3.6 kWh/m^2/day (Nadal et al., 2017c; Sanyé-Mengual et al., 2015a), and at least a roof surface of 13 m^2 to grow vegetables (Zambrano-Prado et al., 2021a).

Energy: Photovoltaic

The annual electricity (Ee obtained in kWh) produced in each rooftop has been calculated using the eq. 7.1:

$$\mathrm{Ee} = \mathrm{IG} \cdot \eta\ \mathrm{PV} \cdot \mathrm{APV} \cdot \mathrm{PR} \quad (7.1)$$

Where

IG is the global annual irradiance in kWh/m^2/y

η PV is the PV panel efficiency

APV is the area of the installed PV panels in m^2

PR is the PV system performance ratio

The global irradiance (IG) received for the panels depends on the PV tilt angle. The panels will be mounted following the rooftop slope if it is ≥38°. For flat rooftops (<38°), the panels will be mounted at the optimal angle for energy production (38°) considering an increasing coefficient of 1.19 for solar irradiance obtained from the PVGIS interactive tool. The module's efficiency (η PV) was 16%, which is a typical value for crystalline silicon modules. See additional details in the supporting information.

Water: rainwater harvesting

There is no limitation on the type of roof or solar radiation to harvest rainwater. The only condition is the location of the tank to store rainwater on the roof. In this sense, the load capacity of the rooftop has to be considered for the placement and dimensions of the water tank (Toboso-Chavero et al., 2019).

7.2.2.5 Level of aggregation

Each of the roofs studied, building by building, are further grouped according to their urban morphology. In the case of the AMB, where our case study is included, the future Metropolitan Plan (PDU) (in process) (PDU, 2017) has analyzed the morphology of the built environment in the following categories among the residential areas. It can be distinguished between single-family and multi-family plots. In depth, residential morphologies are defined based on their growth pattern and the evolution of the urban fabric. Specifically, the morphologies considered were: originary fabrics. Today 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. 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. Another category is 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. Non-residential uses, or other buildings that do not fit the patterns described above, have been considered as 'others'.

7.2.3 Socio-economic characterization of the demand

To characterize the socio-economic part of this municipality several datasets were necessary. The consumption of energy and water were retrieved from records of distribution companies for the years 2018, 2019 and 2020. They were received from each street and number of the building of five or more customers and aggregated by urban fabric and municipality. The consumption of vegetables was obtained from a phone survey. This survey was conducted during April 2021 in the municipality of Cerdanyola del Vallès aiming to know the consumption pattern profile and the social perception of the residents for the use of their rooftops (Table 7.1). The survey used a stratified random sample by type of urban tissue, i.e., housing estates, originary fabrics (including suburban extension) and single-family housing areas. The survey was answered by 1100 residents (see outcomes in open access at the repository https://ddd.uab.cat/). We validated the results with the average values from official statistics.

Table 7.1 Datasets and sources for the current study of the socio-economic profile of residents

DATASETS	consumption of vegetables	consumption of energy	consumption of water	work status	household occupation	human activity	preferences in the rooftop's systems
SOURCES	survey (open access)	distribution company (confidential data)	distribution company (confidential data)	survey (open access)	survey (open access)	official statistics	survey (open access)

We use the supply and use matrices from the multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM) (Giampietro et al., 2009) to characterize the metabolic patterns of each urban morphology and check the viability of the system, using a nexus perspective previously tested in a study for housing estates (Toboso-Chavero et al., 2021). The municipality is considered the whole system and level n and the rest of the levels are given by the different urban tissues: housing estates, originary fabrics, and single-family housing areas (n-1) and the household types (n-2). We assessed vegetables, electricity and water flows. Flow variables are defined as the total end use of each resource per year for each household and building types. The intensive variables were calculated based on human activity (hours (h)) per type of household as a proxy. A detailed list of the variables included is displayed in Table 7.2.

Table 7.2 Definition of end-use and supply matrixes and variables. Resources: vegetables (kilogram (kg); gram (g)), electricity (kWh; MJ), and water (m^3; liter (l))

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

The FEW consumptions were crossed with the potential rooftop production at the municipality and urban forms levels to obtain resource self-sufficiency.

7.2.4 Definition of indicators for future scenarios

Based on the outcomes of the physical - the technical viability to implement these FEW systems- and the socio-economic part - the answers retrieved from the survey about the preferences of the residents (Table 7.1) - different scenarios were proposed. Different indicators were also proposed to measure accurately the benefits and the drawbacks of the different scenarios and the policies to apply to implement these scenarios. We defined performance indicators (PIs) (Table 7.3) based on previous studies, residents' concerns – retrieved from the survey – and the most used on this topic (Toboso-Chavero et al., 2021, 2019).

Table 7.3 Performance indicators (PIs) applied in the case study and the type and source 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

7.3 Results

7.3.1 Rooftop supply potential by urban form (physical analysis)

The municipality depicts a characteristic morphology, as Figure 7.2 illustrates, with a historic center surrounded by suburban extension districts and some housing estates, but also with some housing estates isolated mixed with wide extensions of single-family housing areas. The historic center and suburban extension districts occupy almost the same land as housing estates - around 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 (253 ha) than the other two urban tissues and have only 11% more households. It means that 45% of the gross floor area of the municipality is colonized for single-family housing areas.

The municipality has a total of 72.7 ha of rooftops (Table 7.4) to be exploited for different purposes. All of them can be used for rainwater harvesting, as it is viable to collect rainwater on any typology of roof (Angrill et al., 2016). In terms of urban forms, single-family housing areas have the greatest potential due to more quantity of buildings (13,6 ha; 19%); however, out of these three urban forms, "others" category (which includes public and private facilities and industrial parks) has the highest potential, 31.2 ha, being 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 rooftop surface in relation to land occupied by urban form, the originary fabrics have the highest percentage (19.5%), and the lowest ratio (more than half part) is for single-family housing areas (7.5%). Therefore, more land area is needed in single-family housing, and in contrast there are fewer open spaces in the originary fabrics. Housing estates (12.3%) are in between these two urban forms.

Electricity-wise the municipality only 46% of the rooftops have potential for the implementation of photovoltaic (PV) panels. In the same line, the originary fabrics and the single-family housing areas reduce their potentiality to 45 and 46%, respectively, whereas housing estates a little more, 42%. Related to growing vegetables, the potential surface of rooftops was reduced to 38% in the municipality. Regarding urban forms, the reduction was insignificant for housing estates (-4%), but it was a very relevant decrease of roof surface for the originary fabrics (-49%) and single-family housing (-57%), which means more flat roofs in housing estates and less in the originary fabrics and single-family housing.

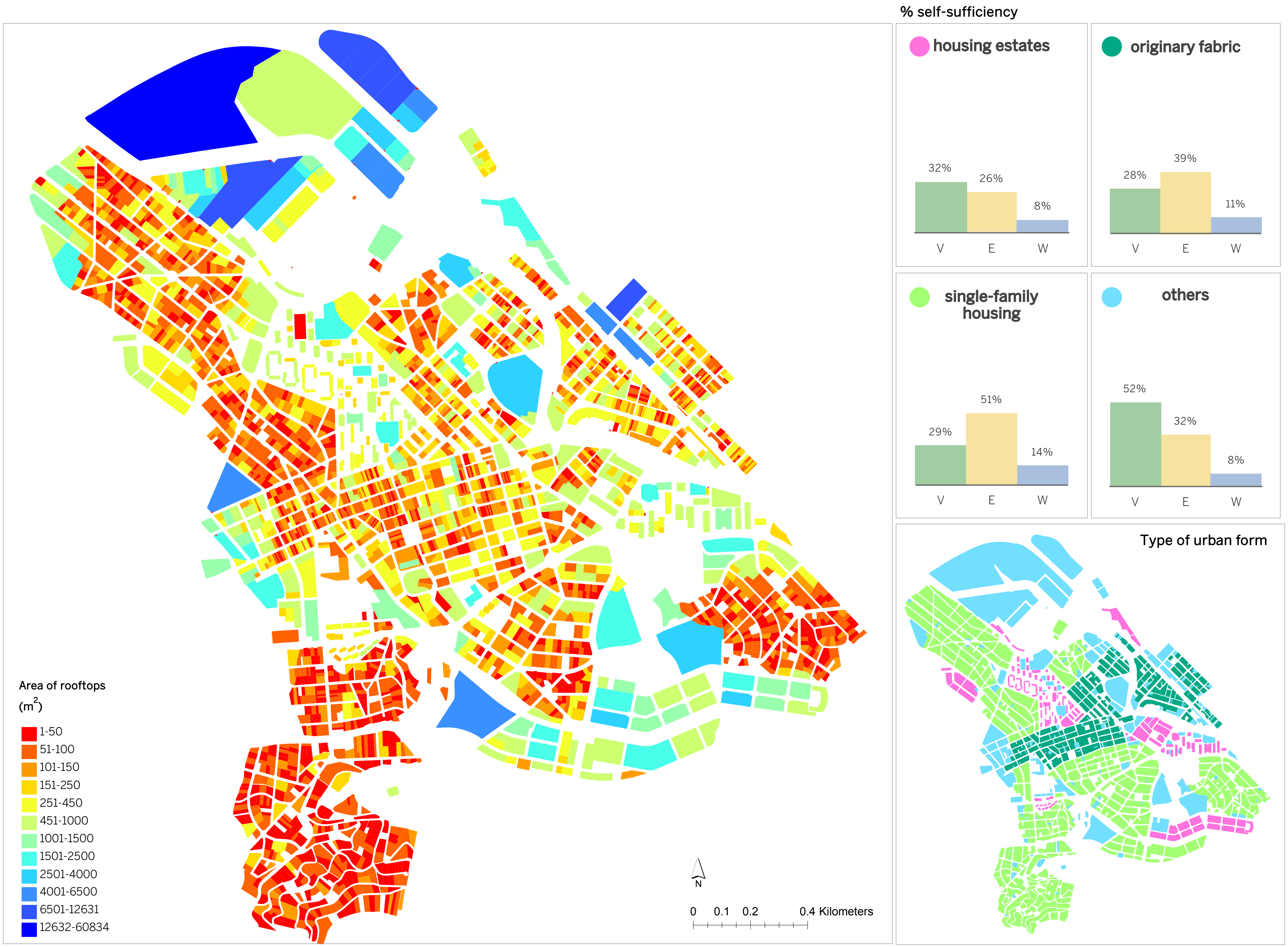

% self-sufficiency
housing estates
32%
26%
8%
V
E
W
originary fabric
28%
39%
11%
V
E
W
single-family housing
29%
51%
14%
V
E
W
others
52%
32%
8%
V
E
W
Type of urban form
Area of rooftops
(m²)
1-50
51-100
101-150
151-250
251-450
451-1000
1001-1500
1501-2500
2501-4000
4001-6500
6501-12631
12632-60834
N
0
0.1
0.2
0.4 Kilometers

Figure 7.2 Map and outcomes of the municipality and the different urban forms. The larger map represents the rooftop areas in m² by range. The bar charts represent the percentage of self-sufficiency of each resources (FEW). The smaller map identifies the three urban forms: housing estates, originary fabrics and single-family housing areas, and others category. HE: housing estates; OF: originary fabrics; SF: single-family housing areas; others: public and private facilities and industrial

Assessing the availability of rooftops with respect to households, 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, about 42% of the total. By urban forms, single-family housing obtained the highest value and the lowest was for housing estates, caused by more density of households in housing estates and, therefore, less availability of roofs; about 11.5 m^2/hh versus 22.6 m^2/hh for single-family housing. For electricity implementation (municipality:14.6 m^2/hh), the tendency was the same, but this availability was reduced by more than half part, 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 implementation of 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).

Table 7.4 Characterization of the rooftops at the municipality and three urban forms. HE: housing estates; OF: originary fabrics; SF: single-family housing areas; others: public and private facilities and industrial parks; hh: household

	municipality	**HE**	**OF**	**SF**	**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)	0.070	0.049	0.046	0.015	0.097
m^2 rooftop/m^2 land (electricity)	0.085	0.052	0.091	0.035	0.085
m^2 rooftop/m^2 land (water)	0.184	0.123	0.195	0.075	0.183
m^2 rooftop/hh (vegetables)	11.6	4.6	4.2	4.5	7.0
m^2 rooftop/hh (electricity)	14.1	4.8	8.3	10.4	6.1
m^2 rooftop/hh (water)	30.7	11.5	17.8	22.6	13.2

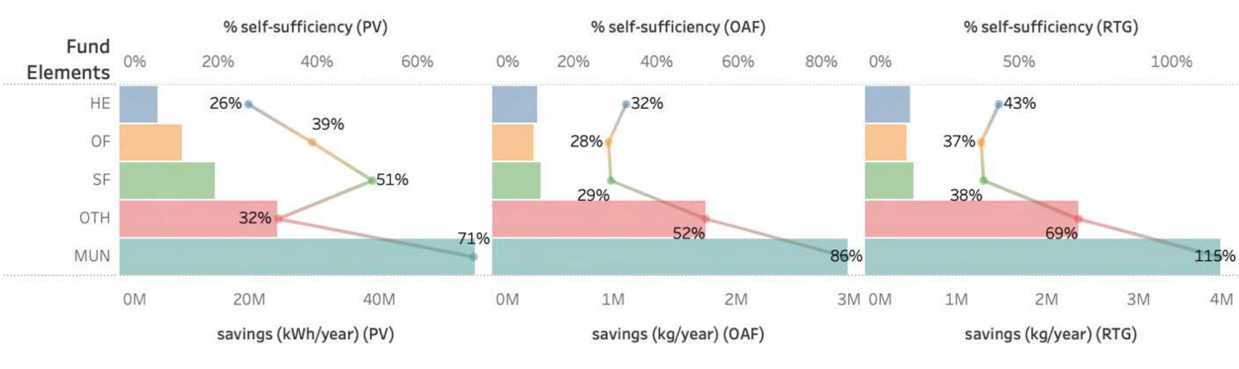
7.3.2 Urban metabolism in the municipality and three characteristic urban forms (social analysis)

7.3.2.1 Production characterization of the municipality and three urban forms

Three possible resources (vegetables, electricity and water) for the potential rooftop production were assessed (Figure 7.3). The combination of energy or vegetable production with water harvesting is possible because no additional space is needed, only a water tank is required, which can be placed on the roof or in other parts of the building or underground (Angrill et al., 2012a).

In terms of vegetable production, the rooftops of the municipality could guarantee between 86% (OAF) to 115% (RTG) of the main vegetables consumed in Cerdanyola, tomatoes, lettuces, peppers, and green beans (59 kg/person/year) (see Figure 7.3). Albeit, by urban form, these percentages decrease considerably, because most available areas appear to be in “others” category, which includes public and private facilities and industrial parks. The highest self-sufficiency is detected in housing estates, both in OAF (32% of self-sufficiency) and RTG (43% of self-sufficiency), due to the lower vegetable consumption, but the highest vegetable total production is identified in single-family housing areas, due to larger amount of m^2.

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



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	3,387,163	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 fabric						0.0017	9,724,183	39%		33	70,318	11%
	single-family areas						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	86%						175	375,699	101%
	housing estates		407	373,661	32%						21	45,287	95%
	originary fabric		368	337,981	28%						33	70,318	163%
	single-family areas		436	400,171	29%						46	98,698	194%
	others		1,908	1,750,961	52%						75	161,395	44%
Decentralized	RTG + RWH (municipality)		1,846	3,889,851	115%						175	375,699	129%
	housing estates		237	499,154	43%						21	45,287	121%
	originary fabric		214	451,492	37%						33	70,318	208%
	single-family areas		254	534,568	38%						46	98,698	246%
	others		1,110	2,339,020	69%						75	161,395	55%
Decentralized	ALL SYSTEMS (municipality)		1,255	1,700,436	50%		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 fabric		146	197,368	16%		0.0009	4,862,092	19%		33	70,318	366%
	single-family areas		172	233,685	17%		0.0012	7,311,713	25%		46	98,698	433%
	others		754	1,022,495	30%		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		4,492,259	NA	SV	SV	207,372,442	NA	SV	SV	2,257,250	NA	SV	SV

Figure 7.3 Supply matrix with the different resources (vegetables, electricity, and water at the municipality (MUN) and three urban tissues (housing estates (HE), originary fabrics (OF) and single-family housing areas (SF) and others (OTH)). 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

The municipality has the potential to collect around 377,699 m^3/year of rainwater. For the potential rainwater harvesting, in the combination 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 higher total surface rooftops in single-family dwellings makes them the ones with the highest potential for harvesting rainwater, and also in terms of self-sufficiency (OAF: 194%; RTG: 246%). Nevertheless, in all urban fabrics, the crops could be irrigated exclusively with rainwater, and there would even be a surplus for others uses.

Apart from the potential production of these resources in the municipality, it is also necessary to account for losses (Figure 7.3, in the table) arising from conventional and centralized systems, i.e., losses from the transformation and distribution of centralized electricity systems, losses from the harvesting, transportation of food centralized and water distribution losses. The highest losses are assigned to the electricity conventional systems by 63% (Domene and García, 2017), then the vegetable losses by 25% (Caldeira et al., 2019) and the lowest ones are for the water centralized systems by 7.4% (retrieved from distribution water company). Consequently, all these losses from centralized systems could be also reduced by applying policies of local production in municipalities.

7.3.2.2 Consumption characterization of the municipality and three urban forms

The total consumption of residents in the different urban forms reveals remarkable differences in the extensive indicators (Figure 7.4). 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 other two urban tissues. 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 than the originary fabrics, which are 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 the resources.

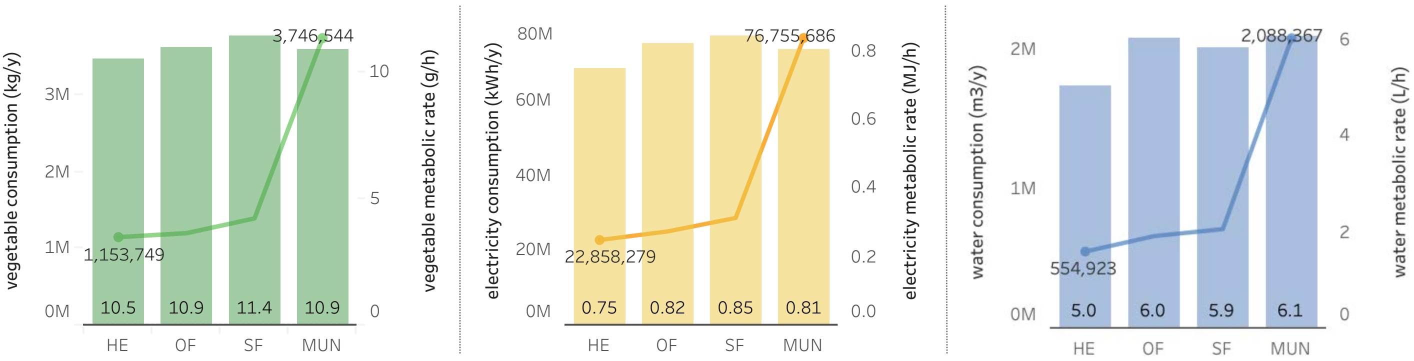


Figure 7.4 Resource consumption (lines) and resource metabolic rate (bars) of the municipality and the different urban tissues. HE: housing estates; OF: originary fabrics; SF: single-family housing areas; MUN: municipality; h: hour; y: year; M: million

Examining the metabolic rates between urban tissues, the highest rates in vegetables and electricity correspond to the single-family housing areas (11.4 g/h and 0.85 MJ/h, respectively) and the lowest to housing estates (10.5 g/h and 0.75 MJ/h, respectively). Single-family housing areas consume about 8.6% more than housing estates in vegetables, 13% in electricity and 20% in water, which translates into a relevant resource consumption in these single-family areas. The originary fabrics exhibit a more heterogeneous behavior. They have lower consumption than single-family dwellings in vegetables and electricity but almost the same water metabolic rate. The originary fabrics are usually an amalgam of different types of buildings, from apartment blocks of few stories to single-family housing; thus, consumption tends to be more variable.

When these outcomes are compared with those of other studies, some differences can be highlighted. The vegetable metabolic rate in this municipality is higher than that of Catalunya, 9.9 gram (g)/hour (h) versus 4.5 g/h 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). Comparing the electricity metabolic rate, the results (municipality: 0.81 MJ/h) are similar to those of Barcelona (0.72 MJ/h) and Europe (0.74 MJ/h) and also to the aforementioned municipality (0.82 MJ/h) (Pérez-Sánchez et al., 2019; Toboso-Chavero et al., 2021; Velasco-Fernández, 2017). Related to the water metabolic rate, in this case, the municipality has a lower rate, 6.1 L/h, than Catalunya and Badia del Vallès, which are 7 L/h and 6.5 L/h, respectively (Madrid and Cabello, 2011; Toboso-Chavero et al., 2021).

7.3.3 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 in the supporting information). Rainwater harvesting was accepted by 43% of the residents to implement on their roofs. The last option was for rooftop farming (OAF and RTG) which was only accepted by 20-21% of the residents. Nonetheless, this proportion increases if the proposal is a combination of all of them (27%), i.e., production of energy, vegetables and rainwater harvesting. Women preferred OAF by 2% more than men. The rest of the systems were preferred more by men than by women by 1 to 5.5%, especially PV panels by 5.5%. Thereby four different scenarios and, consequently, policy suggestions were proposed for this municipality. The four proposed policies were: the combination of electricity production and rainwater harvesting (policy 1), vegetable production and rainwater harvesting (policy 2 with OAF and policy 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 in all roofs (policy 4).

In consonance with the outcomes of the different indicators by policy and urban form (Table 7.5), the highest values in vegetable self-sufficiency appear in policy 3 (RTG + RWH) and in housing estates urban form. Accordingly, the largest area of new green spaces is in policy 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 two urban forms. If the municipality opts for policies 2 and 3, will gain 27 ha of green spaces and almost 14 ha for policy 4. On the other hand, for energy and water self-sufficiency the single-family housing areas obtained the highest share because of more rooftops that are suitable and fewer households in these sites. The originary fabrics have more heterogeneous buildings and roofs; therefore, its values are in the middle.

In terms of environmental indicators, the highest CO_2 savings correspond to policy 1 (PV + RWH) and single-family housing areas, due to a higher number of rooftops. On the contrary, the highest environmental impact related to kg CO_2 eq to build these new facilities pertains to the same policy 1 and the lowest to policy 2 (OAF +RWH) and housing estates, which means that policy 2 is the least environmentally impacting system to construct.

Concerning social indicators, energy poverty will obtain the highest value in policy 1 and single-family housing areas. This policy would cover 71% of the households in the municipality, about 16,906 households could benefit from these systems. Additionally, for water poverty, all policies would have the same potential, and the highest share would be for single-family housing because of more m^2 of rooftops. The implementation of water systems on roofs will cover the water needs of around 4,268 households, i.e., 18% of the total households. Comparing the maintenance investment of hours for families, policy 1 would be the least time consuming while policies 2 and 3 would be the most demanding, due to the care of the crops in these systems.

As for economic indicators, policy 3 is the one that requires the highest investment for the whole municipality; albeit, by urban form, the highest investment corresponds to single-family housing areas in policy 1, due to more m^2 to cover and fewer families to split the cost. Conversely, the lowest investment in all policies, except for policy 3, is allocated to housing estates due to a larger number of households to share the cost. Although, single-family housing would obtain the highest monetary saving in all policies. The highest savings are assigned to policy 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, these private and public facilities and industrial uses tend to have roofs with a very low load capacity and made of metal sheets, fiber cement or other non-resistant materials (Nadal et al., 2017b). Thus, this will be a constraint to implement rooftop farming and it will be more viable to implement PV panels and RWH.

Table 7.5 Municipality and urban form performance per scenario

Indicator group	Area	Indicator	POLICY 1 PV+ RWH	POLICY 2 OAF+ RWH	POLICY 3 RTG+ RWH	POLICY 4 All combined
sustainability indicators	municipality	% vegetables self-sufficiency	0%	86%	115%	50%
	housing estates		0%	32%	43%	19%
	originary fabric		0%	28%	37%	16%
	single-family		0%	29%	38%	17%
	others		0%	52%	69%	30%
	municipality	% energy self-sufficiency	71%	0%	0%	35.6%
	housing estates		25.9%	0%	0%	12.9%
	originary fabric		38.7%	0%	0%	19.3%
	single-family		50.9%	0%	0%	25.4%
	others		31.8%	0%	0%	15.9%
	municipality	%water self-sufficiency	18%	101%	129%	227%
	housing estates		8%	95%	121%	213%
	originary fabric		11%	163%	208%	366%
	single-family		14%	194%	246%	433%
	others		8%	44%	55%	97%
environmental indicators	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 fabric		0	4.2	4.2	2.1
	single-family		0	4.5	4.5	2.2
	others		0	7.0	7.0	3.5
	municipality	kg CO_2 savings /year	33,323,274	5,618,489	7,459,404	19,931,110
	housing estates		3,603,315	719,910	956,140	2,220,670
	originary fabric		5,925,965	661,882	875,555	3,347,341
	single-family		8,909,015	789,306	1,042,297	4,912,408
	others		14,884,979	3,354,927	4,461,894	9,396,694
	municipality	global warming (kg CO_2 eq)	32,718,662	1,336,813	2,704,121	17,604,476
	housing estates		3,616,738	168,452	343,908	1,966,603
	originary fabric		6,175,576	183,401	342,103	3,246,430
	single-family		8,662,822	233,471	421,375	4,527,405
	others		14,263,527	735,639	1,557,819	7,846,383
social indicators	municipality	energy poverty coverage (no. households)	16906	0	0	8453
	housing estates		1970	0	0	985
	originary fabric		2953	0	0	1476
	single-family		4308	0	0	2154
	others		7553	0	0	3776
	municipality	water poverty coverage (no. households)	4268	4268	4268	4268
	housing estates		622	622	622	622
	originary fabric		806	806	806	806
	single-family		1167	1167	1167	1167
	others		1834	1834	1834	1834
	municipality	maintenance investment (hour/household/year)	5	139	83	58
	housing estates		2	55	33	23
	originary fabric		3	51	31	22
	single-family		4	55	34	24
	others		2	83	49	34
economic indicators	municipality	investment (€/household)	5121	3188	6424	4962
	housing estates		1778	1261	2554	1842
	originary fabric		3001	1269	2436	2426
	single-family		3795	1418	2663	2917
	others		2229	1824	3770	2512
	municipality	monetary savings (€/household/year)	1851	335	437	1118
	housing estates		624	133	174	389
	originary fabric		1023	127	164	584
	single-family		1386	139	179	772
	others		826	196	258	527

7.4 Discussion

7.4.1 Potential production on rooftops vs consumption in three characteristics urban forms

The three characteristic urban forms analyzed in this study depict different features for the implementation of the Roof Mosaic. Housing estates areas are distinguished by having more extensive and flatter roofs than the other urban tissues. This was demonstrated by the small difference between roofs available for energy (all type of roofs) and for growing vegetables (flat roofs), reducing their potential by only 4%; however, in the other urban tissues the reduction was around 50%. Likewise, the average of roof surface in housing estates is 420 m^2 – almost three times larger that of the other two urban forms-. They have a remarkable potential for implementing urban 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, flat roofs have more potential for implementing any type of FEW resources, so the promotion of flat roofs in new constructions will help to the more suitable exploitation of these spaces. On the other hand, housing estates have the lowest ratio of m^2 of rooftop per household and has the smallest apartments, averaging 86 m^2, 7% less than the originary fabrics and 17% less than single-family housing areas. Hence, there is an actual need to provide additional common spaces for these families. On the other hand, the originary fabrics manifest more heterogeneous buildings and rooftops than housing estates, because of the combination of different constructions, mixing the old town and new constructions of blocks and houses. This urban tissue evidences the lowest ratio of rooftops and open space, meaning that it is the most compact area, with few intermediate spaces between buildings. The average rooftops are 127 m^2; therefore, some are too small to implement rooftop farming, although the best solution would be to use roofs for green infrastructure aiming to endow these areas of more green spaces. Regarding single-family housing, the rooftops are the most limited, averaging 104 m^2 but having the highest open spaces between buildings and being the largest households (102 m^2) and the most m^2 rooftop per dwelling. They would be more viable to implement PV panels due to the open space they have to use for soil-based agriculture and their characteristic small and sloping roofs. Therefore, urban forms are key to implement the most suitable system on roofs as other climate change adaptation strategies.

Having in mind the physical characteristics of these urban forms would be easier to promote a strategy for self-sufficiency in these areas. However, consumption is another key parameter to consider proposing a suitable strategy. Housing estates have an average consumption of 3,000 kWh/hh/year, the originary fabrics 3290 kWh/hh/year and single-family housing 3,394 kWh/hh/year. They are similar to the Catalan average (3,400 kWh/hh/year) (Generalitat de Catalunya, 2020a) and under Spain average (4046 kWh/hh/year) and European average (Enerdata, 2020). For average water consumption in the municipality (88 m^3/hh/year), the lowest 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). Comparing with the average in Spain (130 m^3/hh/year (2017)) or the European average (111 m^3/hh/year) is a significant difference (The European Federation of National Associations of Water Services, 2017). Comparing the vegetable consumption (59 kg/person/year), it is higher than the Catalan average (32 kg/person/year) (Generalitat de Catalunya, 2020b). Therefore, the self-sufficiency of every urban form is not only dependent on the availability of rooftops but also on the consumption pattern profiles of the residents which can be very different between urban forms and regions.

7.4.2 Future policies for productive urban spaces in municipalities

Four different policies were proposed for this municipality and its different urban forms. At the municipality level, policy 1 (PV+ RWH) obtained the most positive indicators; by urban form, housing estates show better outcomes in policies 3 and 4, both dedicated to vegetable rooftop farming. These urban fabrics have higher self-sufficiency in vegetables and lower monetary investment and environmental impacts. Because these areas have mostly flat roofs, so they are ideal for implementing OAF or RTGs. These types of roofs can be found in most housing estates (Baldwin Hess et al., 2018). In contrast, these areas tend to have households at risk of water and energy poverty (Baldwin Hess et al., 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, in electricity self-sufficiency, which could achieve 51% of electricity self-sufficiency if PV panels are installed on all their roofs. These roofs' areas are usually small and steep, therefore, more feasible to implement PV panels than urban farming, and also because they have large open space of soil to make better use of it for urban 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 space, they are compact, so more necessity of green spaces will be required. Thereby, most of these roofs could be used for urban farming (policy 2 and 3), or the largest ones for urban farming and the smallest for the implementation of electricity, according to policy 4. Likewise, all the rooftops of these urban forms are feasible to harvest rainwater.

At the municipality level, the current local government proposed a general action plan for 2020-2023 (Ajuntament de Cerdanyola del Vallès, 2019b). Among the policies they proposed for the coming years, it can highlight the intention to implement renewable energies in some municipal facilities and to draft a new green infrastructure plan. Consequently, with the new data from this study in hand, both proposals could include more precise planning. In the same line, at AMB scale through the Metropolitan Urban Master Plan (PDU), of which this municipality is part, the future urban territory is being 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 policy 2, 3 or 4- would contribute from 14 to 27 ha to this green network proposed by the AMB. Moreover, following the New Green Deal of the EU, any of these four policies 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.

7.5 Conclusions

The research presented here aims to propose viable future policies of implementing food-energy-water systems for a medium-sized city in the Metropolitan Area of Barcelona and three characteristic urban fabrics, using physical and socio-economic analysis to gain an integrated vision of the residents' needs.

The municipality has three characteristic urban fabrics: housing estates, originary fabrics and single-family housing areas. They have a specific morphology, related to rooftops, buildings, and open space as summarized in Table 7.6.

Table 7.6 Overview of the characteristics of the three urban fabrics

urban fabric	rooftops	buildings	open space
housing estates	most of them flat and large	middle and high-rise blocks	open spaces among constructions
originary fabrics	heterogeneity of roofs	heterogeneity of buildings	compact areas, few open spaces
single-family housing	small and steep	semi-detached and detached housing	the one with the most open spaces

Consequently, every urban form is distinguished by having different features, more or less prone to implement one or another FEW systems. By dividing the city into pieces (in this case, urban forms) the analysis is more specific and precise and aids to foster policies in similar physical areas. This study can serve as a reference for other cities with this type of forms. In Catalonia, most of the cities are composed of these type 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 crossing the demand of these urban forms with the potential production. We can see that the lowest consumptions are in housing estates, and consequently the highest self-sufficiency in vegetable production (19% to 43%). But not in electricity production due to the large number of households and less space on roofs. Conversely, single-family housing obtained the highest metabolic rates in vegetables, electricity and water (together with the originary fabrics), but because only inhabits one family per dwelling, they benefit from more roofs surfaces, and therefore, the highest self-sufficiency in electricity (25% and 51%) and water (14% to 443%). However, not in vegetable self-sufficiency because most of them are steep rooftops on which agriculture systems cannot be placed. On the other hand, the originary fabrics have average values for both demand and potential production due to the diversity of their buildings, type of families and roofs.

The four policies proposed reveal significant shares of self-sufficiency in vegetables (16-115%), electricity (13-71%) and the required irrigation water (13-433%) for the municipality and the different urban forms. It is also relevant the new green spaces that would be created, between 2.3 and 11.6 m^2/hh, with housing estates being the urban form that would benefit the most. In the same direction, these policies would help to reduce energy and water poverty and also their carbon footprint considerably by producing their own FEW resources on-site. Therefore, these policies can facilitate the municipality and Catalonia to adapt to climate change, where predictions are not very optimistic regarding temperature increase and lack of precipitation (Altava-Ortiz and Barrera-Escoda, 2020). Thus, the use of urban forms for assessing the consumption patterns could aid us to suggest 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 methodology will be useful to evaluate if they follow the same pattern. Similar urban climate solutions can be implemented, leading to more knowledge on the physical and socio-economic aspects of these urban fabrics, and how to take advantage of their constructions and the type of resident that lives. Further efforts should be made to find viable urban mitigation and adaptation strategies to climate change according to urban forms, and resident typologies.

Assessment of the components of the implementation of the Roof Mosaic

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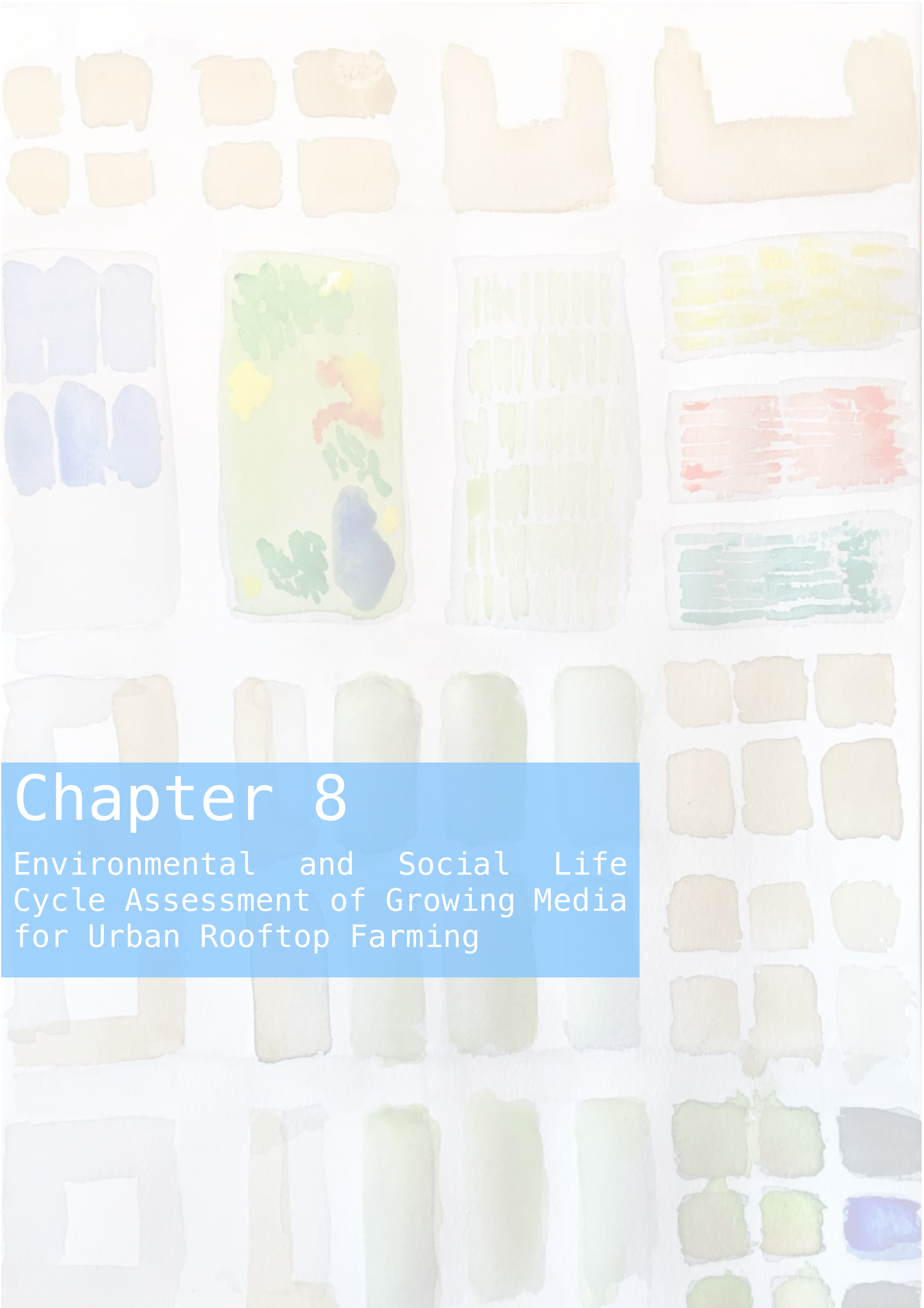

Chapter 8

Environmental and Social Life Cycle Assessment of Growing Media for Urban Rooftop Farming

Innovation in application

This chapter describes and summarizes the application of social life cycle assessment (S-LCA) to various types of growing media to implement urban farming on urban rooftops. It is innovative in the fact that it is the first study to apply such social evaluation methods in the field of urban agriculture. We aim to advance the understanding of environmental and social impacts in the soilless crop production, a vital sector in feeding current and future cities

8 Environmental and social life cycle assessment of growing media for urban rooftop farming

This chapter is the journal paper:

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Abstract

Purpose

New environmental strategies are emerging for cities to become more self-sufficient, such as hydroponic crop production. The implementation of such systems requires materials that usually originate in countries with low labor costs and other legal regulations. To what extent could these strategies be shifting problems across the globe? To answer this question, we performed a comprehensive environmental and social assessment of the various extended soilless systems used to grow vegetables on urban roofs.

Methods

Three different growing media constituents were chosen for this study: perlite, peat and coir, which are produced in three countries, Turkey, Germany and the Philippines, respectively, and are imported to Spain. By using a life cycle assessment, we evaluated the environmental performances of the production and transport of these growing media. Additionally, we performed a social life cycle assessment at different levels. First, we used the Social Hotspots Database to analyze the constituents in aggregated sectors. Second, we performed a social assessment at the country and sector levels, and finally, we evaluated primary company data for the social assessment of the constituents through questionnaires given to businesses.

Results and discussion

The coir-based growing medium exerted the lowest environmental burden in 5 out of 8 impact categories because it is a by-product from coconut trees. In contrast, perlite obtained the highest environmental impacts, with impacts 44 to 99.9% higher than those of peat and coir, except in the land use. Perlite is a material extracted from open-pit mines that requires high energy consumption and a long road trip. Regarding the social assessment, peat demonstrated the best performance on all the social assessment levels. In contrast, coir showed the worst scores in the Social Hotspots Database and for the impact categories of community infrastructure and human rights, whereas perlite displayed the lowest performance in health & safety. Nevertheless, coir and perlite evidenced much better scores than peat in the impact subcategory of the contribution to economic development.

Conclusions

This study contributes to a first comparison of three imported growing media constituents for urban rooftop farming from environmental and social perspectives to choose the most suitable option. Peat appears to be the best alternative from a social perspective. However, from an environmental standpoint, peat represents a growing medium whose availability is aiming to disappear in Germany to preserve peatlands. Therefore, we identify a new market niche for the development of local growing media for future rooftop farming in cities.

Keywords: life cycle assessment, soilless systems, open-air farming, rooftop greenhouses, green cities, urban agriculture

8.1 Introduction

Cities are primordial human settlements of prosperity in our society, generating approximately 80% of the global gross domestic product (GDP) (Floater et al., 2014), and they provide economic and cultural wealth and dynamic territories. Nonetheless, the accumulation of populations, activities and resource demands triggers high pressures regarding pollution, resource use, and land/space competition (Legner and Lilja, 2010). Organizations, governments and academia have focused their attention on cities as high emitters but also because they offer potentials for multi-purpose and easily replicable solutions for sustainability actions (Grimm et al., 2008; Rosenzweig et al., 2010). Many strategies for redressing the ecological problems associated with urban areas have emerged over the years. These initiatives can be grouped into different topics, such as waste management, energy efficiency, water demand, buildings, and renewable energy (Lamb et al., 2019). One initiative has stood out for its remarkable exploitation potential: the use of urban roofs for different purposes, as roofs can comprise up to 32% of the horizontal surface of build-up areas and are mostly underutilized spaces (Frazer, 2005). Roofs can be used for implementing energy production (Bazán et al., 2018; Kyriaki et al., 2017; Madessa, 2015), green roofs (Brudermann and Sangkakool, 2017; El Bachawati et al., 2016; Fioretti et al., 2010), rooftop farming (Montero et al., 2017; Nadal et al., 2018a, 2018b, 2017c), the harvesting of rainwater (Angrill et al., 2016, 2012a; Farreny et al., 2011) or a combination of these applications (Khadija Benis et al., 2018; Corcelli et al., 2019; Toboso-Chavero et al., 2021, 2019).

To deploy these new systems, not only the environmental, social and economic benefits should be analyzed but also the potential drawbacks and externalities[5] of the production of these products to attain a holistic and forward-looking overview of the corresponding strategy (Ramaswami et al., 2016). Materializing these food-energy-water (FEW) systems requires the manufacturing of new materials/products such as photovoltaic panels, rainwater tanks, greenhouses, growing media, etc. Such externalities generated by the production of new materials are usually related to the maelstrom of global trade; thus, the production, and also the supply chain, have become longer and more complex (Pichler et al., 2017). The locations of consumption and production are separated by several miles, and developed countries are mainly favored by cheap products with high environmental and social impacts (Hoekstra and Wiedmann, 2014) while developing countries bear the brunt of these externalities (Riisgaard et al., 2010). The differences in the living and working conditions, the low labor costs or lenient environmental and labor regulations make these developing countries appealing to companies (Hoekstra and Wiedmann, 2014).

[5] An externality is a consequence of an economic activity that affects other parties and is not reflected in the final cost of a product or service.

This globalized delocalization, i.e., the relocation of production activities from developed to developing countries, which mainly occurs because of lower labor costs in the developing countries than in the developed countries (Hammami et al., 2008), is also inherent in obtaining the necessary products for the implementation of FEW systems on rooftops. The main elements are extracted and produced overseas, such as the growing media for agriculture, often coir or perlite, which are manufactured in Asian countries, and Turkey, Greece and different African countries (Bennett, 2018; U.S. Geological Survey, 2019), or the production of photovoltaic panels, mainly dominated by China, which yielded 43% of the global production in 2018 (Solar Power Europe, 2019). This separation between the points of production and consumption causes environmental and social impacts that should be screened and included in any new strategy we propose to enhance the sustainability of cities. Notwithstanding, this global delocalization has also brought prosperity, in some cases, to these countries that have become factories for developed countries (Panagariya, 2019). Some of these positive consequences include job creation, GDP increase, improvement of infrastructure, etc. (World Trade Organization, 2018, 2017).

Intended for calculating environmental impacts of the production of such systems, the life cycle assessment (LCA) (International Organization for Standardization, 2006) is the leading and most extensive methodology (European Commission, 2003). The environmental burdens of some elements of these systems described herein have been extensively assessed, such as the manufacturing of PV panels in countries such as China, Germany and Spain (Fu et al., 2015; Gerbinet et al., 2014; Hong et al., 2016; Lamnatou et al., 2019; Sumper et al., 2011b; Xu et al., 2018; Yue et al., 2014). Nonetheless, few studies have focused their interests only on the growing media used for soilless culture systems (Quantis, 2012; Stucki et al., 2019; Verhagen and Boon, 2008; Vinci and Rapa, 2019; Warwick HRI, 2009) because they are usually not assessed stand-alone and without relating them to plant management practices (e.g. fertigation) (Barrett et al., 2016).

Additionally, little attention has been given to the social impacts, either positive or negative, that these complex supply chains have (Traverso et al., 2012a). Social impacts affect the local communities, workers, and society in general in these centers of production. One of the widespread frameworks used to account for social impacts is the social life cycle assessment (S-LCA) (UNEP/SETAC, 2009), which is also used and recommended by the European Commission (Mancini et al., 2018). The S-LCA has already been applied in the renewable energies sector (Corona et al., 2017; Takeda et al., 2019; Traverso et al., 2012a), but to our knowledge, it has not yet been applied in the growing media sector. This methodology does not have an ISO standard but has a guideline that was updated in December 2020 (UNEP et al., 2020). The S-LCA still has various limitations due to the complexity of social aspects and because of the lack of data and tools used as sector-specific social indicators or general standardized indicators for social performance (Traverso et al., 2012b; UNEP et al., 2020;

Zamagni et al., 2015); only two databases are in operation, the Social Hotspots Database (SHDB) (New Earth, 2019) and the PSILCA (Ciroth and Eisfeldt, 2016). For a general and first screening of aggregated sectors, these databases are suitable; however, for specific products/sectors, in-depth and specific screenings are recommended.

Therefore, to gain insight into this gap in knowledge regarding suitable growing media for implementation on urban roofs, we targeted our study toward the most extensively used growing media constituents in the sector to analyze their environmental and social impacts. We selected the most commonly used growing media worldwide: perlite, peat and coir (Growing Media Europe, 2019). Hence, our research has a twofold goal: to assess the environmental and social impacts, including the positive and negative impacts, of the extraction and production of three constituents to be used in urban rooftop farming (URF), i.e., in open-air farming (OAF) and in rooftop greenhouses (RTG) to grow vegetables. This is the first attempt to dive into the growing media sector suitable for urban rooftops, procuring comprehensive environmental and social life cycle assessment of three different growing media constituents

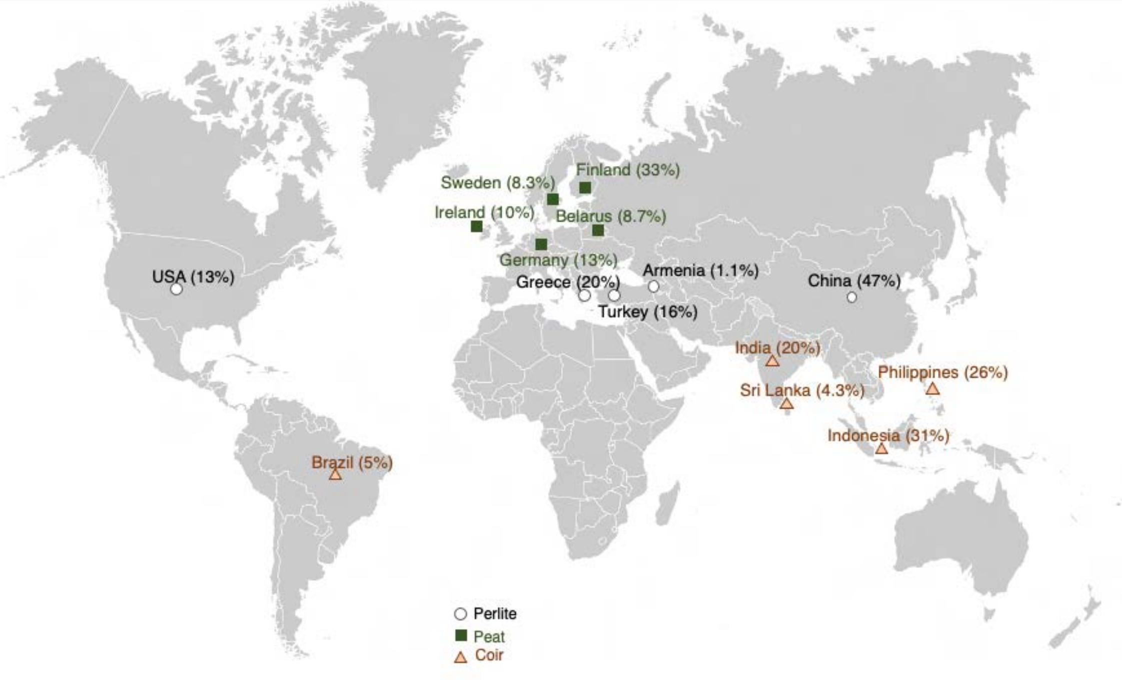
8.1.1 Case study description

Various constituents are used as components of the soilless growing media sector. In this case, three different constituents were chosen. The data used to characterize the growing media were defined based on the literature (Barrett et al., 2016; Maher et al., 2008) and based on their relevancy to this research. Consequently, five different categories were proposed: physical characterization, including the main features; the market price; the world's leading producers; the total production (current & forecasted); and the applications of each growing medium. Data were retrieved from the literature, mainly from scientific papers, books and different reports.

Perlite is an inorganic growing medium sourced from open-pit mining in different countries, whereas peat (extracted from peatlands) and coir are organic growing media, albeit coir is a by-product from coconut trees (Table 8.1). In general, the three constituents do not contain enough nutrients for plants; therefore, they need additional fertilizers. They have similar air-filled porosities and high water retentions. Furthermore, peat and coir have lower bulk densities than perlite. Regarding the market prices, the most economical constituent is peat, then, coir, as it is a by-product obtained from coconut husks, while perlite costs twice as much as the other two constituents. The producers of peat are mainly located in Europe. Therefore, the cost of peat transport and the related environmental impacts are presumably lower than those of the other growing media. Coir is sourced from tropical countries with large crops of coconut trees mainly from Indonesia, the Philippines, India and Sri Lanka. The perlite consumed in Europe usually comes from Greece and Turkey because China, the largest producer of perlite, mainly consumes all its produced perlite internally (U.S. Geological Survey, 2019). The highest projected increase by 2050 is assigned to coir and then perlite, the production of which is expected to increase by approximately 700% of its current production (Growing Media Europe, 2019). Coir, from coir fibers and the coir pith, is the only growing medium that is used exclusively for horticulture, while peat is also used for producing energy and perlite has more diversified uses.

Table 8.1 Characterization of the growing media. kt: kilotons

Leading Producers



CHARACTERISATION	PERLITE		PEAT		COIR	
Physical characterisation [1]	Siliceous volcanic glass (inorganic)		Organic substrate of natural origin - vegetal fossilisation		Waste product of the coconut (cocos nucifera) (organic)	
Nutrient content	No		Very low		High	
Air-filled porosity	High (22-25%)		High (14-22%)		High (12-55%)	
Water retention	Low		High		High	
Bulk density (g/cm^3)	0.1-0.9		0.05-0.29		0.03-0.1	
Market price [2]	55-60 €/m^3		30-36 €/m^3		33-38 €/m^3	
World's leading producers (2019) [3]	China	47% (1,900kt)	Finland	33% (10,000 kt)	Indonesia [b]	31% (18,300 kt)
	Greece	20% (800kt)	Germany	13% (4,000 kt)	Philippines [b]	26% (15,353 kt)
	Turkey	16% (650kt)	Ireland	10% (3,000 kt)	India [b]	20% (11,930 kt)
	USA	13% (520kt)	Belarus	8.7% (2,600 kt)	Brazil [b]	5% (2,890 kt)
	Armenia	1.1% (45kt)	Sweden	8.3% (2,500 kt)	Sri Lanka [b]	4.3% (2,513 kt)
	Total	4,100 kt	Total	30,000 kt	Total	58,352 kt
Production (current & forecasted) [4]	2017	1.5 Mm3/y	2017	40 Mm3/y	2017	5 Mm3/y
	2050	10 Mm^3/y	2050	80 Mm^3/y	2050	35 Mm^3/y
	Increase (%)	667 %	Increase	250 %	Increase	700 %
Applications [5]	Construction	58 %	Energy [a]	58 %	Horticulture	100 %
	Horticulture	18 %	Horticulture [a]	42 %		
	Fillers	15 %				
	Filters	9 %				
	Others	8 %				

[1] (Barrett et al., 2016; Grillas et al., 2001; Maher et al., 2008; Papadopoulos et al., 2008); [2] (Soil and Substrate Preparers Association, 2020); [3,5] (U.S. Geological Survey, 2020); [4] (Growing Media Europe, 2019); [a] only for Europe; [b] Coconut production

8.2 Materials and methods

The system under study involves the growing media used to grow vegetables on rooftops. The growing media are mainly imported from other countries to Spain, which is the top producer of vegetables and fruits in the European Union (EU) (Messe Berlin, 2020). We selected the three most extensively used growing media constituents: perlite, peat and coir (Growing Media Europe, 2019). The methodology consists of two parts: the environmental LCA (E-LCA) (section 8.2.1.1) and the social LCA (S-LCA) (section 8.2.1.2) of these growing media constituents.

8.2.1 Life cycle assessment

The E-LCA was performed following the ISO 14040-44 (International Organization for Standardization, 2006) and the S-LCA was performed using the established guidelines for S-LCA (UNEP/SETAC, 2009). Details are provided for the different sections of the LCA, including the goal and scope, inventory and life cycle impact assessment. The S-LCA was conducted in three steps: (a) a social risk hotspot assessment, (b) country- and sector-specific assessment and (c) a company-specific assessment.

8.2.1.1 Environmental life cycle assessment (E-LCA)

Goal and scope

The goal of this study was to analyze the environmental and social impacts of the extraction, production and transportation of three different growing media constituents imported to Spain that are suitable for URF. The function of these growing media is to serve as the medium with which to grow vegetables, and the functional unit is 1 m^3 of a growing medium for URF, so the reference flow is 1 m^3 of each growing media. The system boundaries include the extraction and production of the constituents (perlite, peat and coir) and their transportation to Spain from Turkey, Germany and the Philippines, respectively (see system boundary diagrams in the supporting information). The use phase is not included because other elements, such as fertilizers, water and auxiliary equipment, would have to be included, and the end-of-life phase is also not included. Consequently, we focused the analysis on the stand-alone constituents.

Life cycle inventory (LCI)

The life cycle inventory can be seen in the supporting information, which includes the constituents and their transportation based on the functional unit. We used Simapro 9.0 software by PRé Consultants, Ecoinvent 3.5 database (Swiss Centre For Life Cycle Inventories, 2018) and GaBi software 9.1.0.53 by Sphera. We used the cut-off system model, therefore, in the case of the coir, as a by-product enters the system burden-free.

Life cycle impact assessment (LCIA)

For the LCIA, we used the ReCiPe 2016 midpoints (hierarchical) V1.03. According to previous literature (Boneta et al., 2019; Rufí-Salís et al., 2020), we selected the following impact categories: global warming (GW; kg CO_2 eq), terrestrial acidification (TA; kg SO_2 eq), freshwater eutrophication (FE; kg P eq), marine eutrophication (ME; kg N eq), ecotoxicity (ET; kg 1,4-DCB) (which sums all three impact categories, including marine, terrestrial and freshwater ecotoxicity), land use (LO; m^2a crop eq), fossil resource scarcity (FRS; kg oil eq) and water consumption (WC; m^3)) (Goedkoop et al., 2013a). We applied the WAVE + factor (Water Accounting and Vulnerability Evaluation Model) (Berger et al., 2018) to the WC impact category at the country level to relate to the potential local impacts of water consumption in the studied countries.

Interpretation

A sensitivity analysis was performed to evaluate the significant parameters and how they influenced the outcomes. Three different parameters related to energy and transport were used for the sensitivity analysis because these growing media constituents are energy intensive. We proposed an improved scenario using more eco-friendly road (euro 5 to euro 6) and ship transports and more decarbonized energy in the production of perlite, which requires a high amount of heat to expand it. The parameters can be seen in the supporting information.

8.2.1.2 Social life cycle assessment (S-LCA)

A first social analysis was performed to obtain a general overview of the growing media and to identify higher social risks using the SHDB. Subsequently, the second and third assessments were conducted to narrow down the social analysis of these growing media in their countries of origin at the sector and company levels.

Goal and scope

The goal of the S-LCA was the same as that in the E-LCA but reduced in scope and focused only on the extraction and production of the three constituents, excluding transportation. We used the same functional unit as that in the E-LCA, i.e., 1 m^3 of growing medium for URF. Three different scales were taken into account to comprehensively analyze constituents' production, i.e., country-specific, sector-specific and company-specific indicators, following the UNEP/SETAC S-LCA guidelines (UNEP/SETAC, 2009). Figure 8.1 illustrates the steps taken to obtain the different social indicators at different scales.

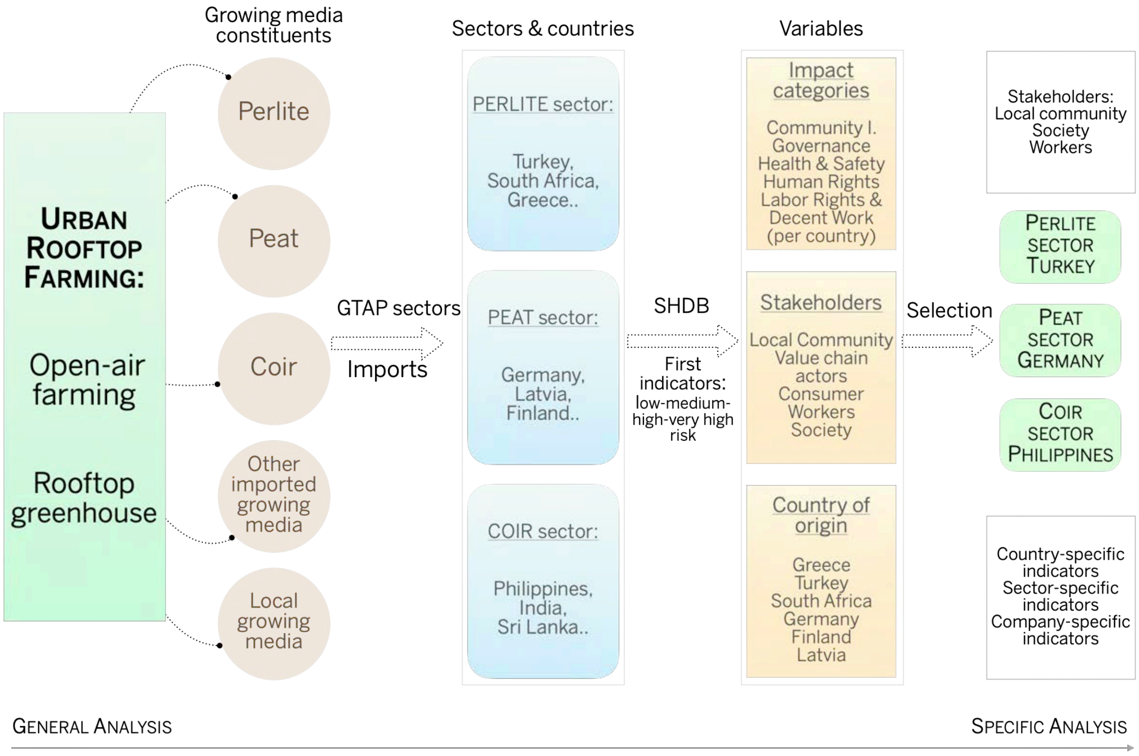


Figure 8.1 Workflow used in this study, from a general analysis to a specific analysis. GTAP: Global Trade Analysis Project; SHDB: Social Hotspots Database

Two systems can be implemented on URF: OAF and RTGs. Such systems require different elements to grow vegetables. Among these components, a growing medium is essential for the proper operation of URF, and it is the component with the most volume used. In this context, an array of growing media can be used for vegetable cultivation. These substances have to share features such as lightness, porosity and water retention capacity (Maher et al., 2008; Papadopoulos et al., 2008). In this case study, three constituents were analyzed: perlite, peat and coir.

Life cycle inventory (LCI)

For this research, we collected two different types of data: general data and site-specific data. General data belong to the potential social risks at the country and sector scales in aggregated sectors applied in the SHDB, and site-specific data relate to social impacts at the country, sector and company scales in the specific sectors of perlite, peat and coir.

Data from the Social Hotspots Database (SHDB)

Social performance was analyzed by means of the SHDB. The SHDB is based on an input-output model, the Global Trade Analysis Project (GTAP), and includes country-specific indicators for 57 aggregated sectors in 140 countries. We used the SHDB 2019 version based on the GTAP global equilibrium model version 9. First, there are five impact categories in the SHDB: community infrastructure, governance, health & safety, human rights, and labor rights & decent work. Second, the stakeholders we chose to examine were local community, value chain actors, consumers, workers and society; third, we determined the country of origin. In our case study, perlite and peat belonged to the aggregated mineral nec (not elsewhere classified) sector, and coir belonged to the plant-based fiber sector of the GTAP model. We retrieved the import data (2018) of these growing media to Spain from official statistics (DataComex) (The Ministry of Industry Trade and Tourism, n.d.). We selected the countries that imported the largest percentage of each growing medium (higher than 3%) (see Figure 8.3). Hence, the first outcomes came from the SHDB performance in the aggregated mineral and plant-based sectors.

Site-specific data for perlite, peat and coir

We performed more specific analyses because the social assessment with the SHDB was performed for aggregated sectors. Consequently, we collected data in two ways:

- country- and sector-specific data retrieved from official statistics, institutions and experts, and
- company-specific data (primary data) obtained through questionnaires

We performed a comprehensive social analysis related to the Sustainable Development Goals (SDGs) and in reasonable time consuming. Therefore, we selected the same impact categories proposed by the SHDB except for governance, and 14 indicators within these impact categories were selected to analyze the social impacts at the country and sector scales considered under the scope of this research (see Table 8.2). The indicators were chosen following the UNEP/SETAC S-LCA guidelines (Benoît-Norris et al., 2013) and for being the most extended and accessible indicators in the growing media sector. The stakeholders relevant to this project were the local community, society, and workers, and the countries selected were Turkey, Germany, and the Philippines, which export the largest amount of each growing medium to Spain. Table 8.2 summarizes the different impact categories, subcategories, indicators, and stakeholders selected in this research; moreover, the last column indicates our own classification of how these social indicators are related to SDGs.

The company-specific data of the growing media constituents were gathered through a questionnaire. The questionnaire was sent via email to 22 companies of the growing media sector, but only three companies answered it. The questionnaire was divided into a first part including basic information about the company/organization, then some general questions related to social reports; the last part dealt with more specific questions about three major themes: health & safety, human rights and labor rights & decent work in the company. The design protocol can be checked in the supporting information.

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Table 8.2 Summary of the impact categories and subcategories, social indicators, and stakeholders and these related to SDGs, proposed for this research. NA: not available

Impact category- Social indicator	Country specific	Sector specific	Stakeholder	Impact subcategory	Sustainable Development Goals
Community Infrastructure					
Drinking water access	x		Local community	Access to material resources	**Goal 6:** 6.a.1 Amount of water- and sanitation-related official development assistance that is part of a government-coordinated spending plan
Children out of school	x		Local community	NA	**Goal 4:** 4.1.1 Proportion of children and young people: (a) in grades 2/3; (b) at the end of primary; and (c) at the end of lower secondary achieving at least a minimum proficiency level in (i) reading and (ii) mathematics, by sex
Hospital beds per 1000 population	x		Local community	NA	**Goal 3:** 3.8.1 Coverage of essential health services (defined as the average coverage of essential services based on tracer interventions that include reproductive, maternal, newborn and child health, infectious diseases, non-communicable diseases and service capacity and access, among the general and the most disadvantaged population)
Employment share (Positive impacts)		x	Society	Contribution to economic development	**Goal 10:** 10.4.1 Labour share of GDP, comprising wages and social protection transfers
GDP contribution (Positive impacts)		x	Society	Contribution to economic development	
National poverty line (% population)	x		Society	Contribution to economic development	**Goal 1:** 1.2.1 Proportion of population living below the national poverty line, by sex and age
Human Rights					
Gender inequality	x	x	Worker/Society	Equal opportunities/ Discrimination	**Goal 5:** 5.5.2 Proportion of women in managerial positions
Health & Safety:					
Fatal injuries		x	Worker	Health & safety	**Goal 8:** 8.8.1 Frequency rates of fatal and non-fatal occupational injuries, by sex and migrant status
Non-fatal injuries		x	Worker	Health & safety	
Labour Rights & Decent Work					
Child labour	x	x	Worker/Society	Child labour	**Goal 8:** 8.7.1 Proportion and number of children aged 5–17 years engaged in child labour, by sex and age
Excessive work hours		x	Worker	Hours of work	**Goal 8:** not specific indicator
Fair salary		x	Worker	Fair salary	**Goal 8:** 8.5.1 Average hourly earnings of female and male employees, by occupation, age and persons with disabilities

Social life cycle impact assessment (LCIA)

This research follows the use of an ordinal scale to analyze the social performance of the three types of growing media by comparing the three options (known as the type I approach). The resulting indicators are scored depending on their relative relevance among the three options (UNEP/SETAC, 2009).

Social Hotspots Database (SHDB)

We used the SHDB to assess generic social hotspots. This method measures the risk hours of the social impact: “risk hours represent the weighted cumulative labor hours where workers in the supply chain may be at risk for each specific social issue” (Takeda et al., 2019). It, therefore, assesses the indicators by assigning a risk level, proposing different classes of risks, from very high to high, medium and low, based on the data distribution, expert judgement and literature.

It is based on labor intensity and divides the GTAP data into wage payments by country and sector by the average country and sector wage; this method offers estimates of worker hours for each sector in each country. The data used for the SHDB come from public institutions, country statistics, NGO reports, trade unions and academic papers. The inventory inputs for the SHDB were the aggregated sector of each growing medium: the mineral nec sector for perlite and peat and the plant-based fiber sector for coir. The countries of perlite production were Turkey, South Africa, Greece, the United Kingdom, Germany, Uganda, Brazil and Mozambique; those for peat were Germany, Latvia, the Netherlands, Estonia, Lithuania, Ireland and Finland; and those for coir were the Philippines, India, Mozambique, Tanzania, Madagascar, Kenia, Ecuador and Colombia.

Site-specific assessment

In the case of each site-specific assessment, we scored the indicators in reference to the direct comparison of the alternatives. The indicators were divided into three different scales: the country scale, sector scale and company scale.

Country scale

The outcomes obtained from the country-specific data were presented numerically on a scale from high (most positive) to medium to low (least positive) performance by a comparison among the alternatives, and a color scale was applied.

Sector scale

For the sector scale, we quantified all the indicators and provided a comparative scale among the options: high, medium or low performance. Additionally, a color scale was applied.

Company scale

The primary data from companies were assessed following the same method as that used for the sector scale. When possible, a score was given to each indicator (high, medium or low performance), and a color scale was applied.

Subsequently, the different outcomes of the different levels were compared (Table 8.4 and Table 8.5), and the overall performances of the three growing media constituents were determined (Figure 8.4).

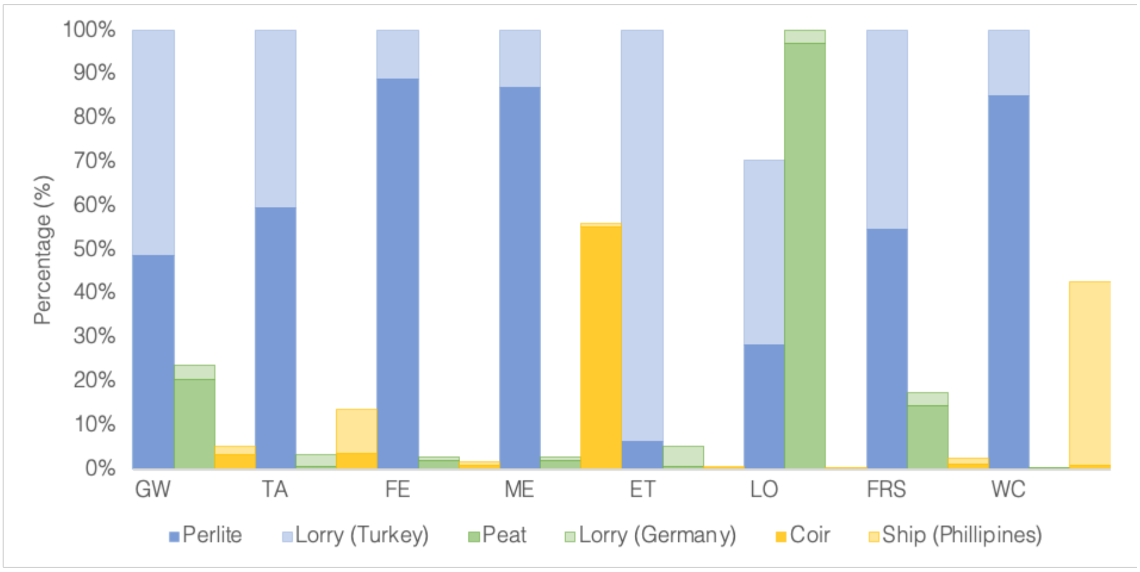
8.3 Results and discussion

This section presents the results of the E-LCA (section 8.3.1) and the S-LCA (section 8.3.2) and a comprehensive assessment of all the outcomes (section 8.3.3).

8.3.1 Environmental life cycle assessment

The environmental assessment is represented by each constituent in its country of origin. The outcomes (Figure 8.2) illustrate that in 7 out of 8 impact categories, perlite, along with its transport from Turkey, had the highest environmental burdens, accounting for 44 to 99.9% higher impacts than those of peat and 65 to 99.7% higher impacts than those of coir. In particular, perlite had higher impacts in freshwater eutrophication (FE) (2.4E-01 kg P eq) and ecotoxicity (ET) (5.9E+03 kg 1,4-DCB eq) compared to the those of other two constituents (peat & coir). There was only one category where the highest environmental impact was attributed to peat; this impact was the land use (LO) impact category (3.1E+01 m^2a crop eq) due to the extraction of peat. On the other hand, coir obtained the highest impact in water consumption before the WAVE+ factor was applied; however, after applying this factor, the water consumption of the perlite growing medium rose considerably due to the scarcity of this resource in its country of origin, Turkey. Coir only obtained significant impacts compared to perlite in marine eutrophication (ME) and water consumption (WC) because of its transport by sea, representing 56 and 42%, respectively, of the impacts of perlite.

The extraction and production of perlite dominated the environmental impacts; perlite had the highest contribution in most of the categories (5 out of 8 midpoints), whereas its transport by road caused the highest environmental burden in ecotoxicity (92%) and land use (60%).



Impact category	GW (kg CO_2 eq)	TA (kg SO_2 eq)	FE (kg P eq)	ME (kg N eq)	ET (kg 1,4-DCB)	LO (m^2a crop eq)	FRS (kg oil eq)	WC (m^3)
Perlite	6.2E+02	2.0E+00	2.4E-01	1.7E-02	5.9E+03	2.2E+01	2.4E+02	3.1E+00
Peat	1.5E+02	6.8E-02	6.7E-03	4.5E-04	3.1E+02	3.1E+01	4.2E+01	3.9E-03
Coir	3.2E+01	2.7E-01	9.4E-03	9.4E-03	3.2E+01	1.0E-01	6.0E+00	1.3E+00

Figure 8.2 Relative impacts of the extraction and production of 1 m^3 of each growing media constituent and its transport. Relative impacts are shown with respect to the highest values in the graph and table with absolute values. The impacts include global warming (GW; kg CO_2 eq), terrestrial acidification (TA; kg SO_2 eq), freshwater eutrophication (FE; kg P eq), ecotoxicity (ET; kg 1,4-DCB), land use (LO; m^2a crop eq), fossil resource scarcity (FRS; kg oil eq) and water consumption (WC; m^3). See all the absolute values in the supporting information

Considering these results, the best performance was observed for coir, despite the long route it must take by ship. Because coir is a by-product that is transformed into a product and almost does not have environmental impacts, most of its impact comes from its transportation by ship. Peat also had low environmental burdens except for those of global warming, land occupation, and fossil resource scarcity. Consequently, perlite is the least favorable option from an environmental perspective since it implies the extraction of a mineral, the use of new resources, the consumption of energy for expanding the perlite, and a long trip by lorry from Turkey.

We have found two studies which are comparable to our study in terms of system boundaries and assumptions, albeit they use different impact assessment methods than the one we applied (ReCiPe). Quantis (2012), performed an LCA of various substrates and applied the Impact 2002+ method, obtaining similar global warming impacts as we found for the three growing media constituents except for perlite, ours is expanded perlite and the global warming impact is much higher (620 kg CO_2 eq/m^3). They ranked from highest to lowest as: black peat (150 kg CO_2 eq/m^3), perlite (100 kg CO_2 eq/m^3), white peat (90 kg CO_2 eq/m^3) and coir (70 kg CO_2 eq/m^3). Another study by Eymann et al. (2015) assessed peat and coir using the IPCC 2013 method for the global warming impact, which gave comparable results of 250 kg CO_2 eq/m^3, and 41-85 kg CO_2 eq/m^3, respectively.

8.3.1.1 Consistency and completeness analysis

We used the most updated datasets for the modelling of the three growing media constituents. For electricity, water and heating, we used specific processes from each country. For transportation, we used a European dataset for Germany, a “rest of the world” (ROW) dataset for Turkey and a global dataset (GLO) for the Philippines. We did not use any allocation in the case of coir by-product as other studies did (Quantis, 2012); therefore, we considered the coir burden-free. Furthermore, as stated in the methods section, we did not model the use phase or end-of-life phase because other materials and processes are necessary in those phases, e.g., fertigation, therefore, we analyzed the stand-alone constituents.

8.3.1.2 Sensitivity analysis

The sensitivity analysis (Table 8.3) further supported the importance of energy (electricity, heating and fuel) in these growing media. We consider transportation, which relies on distance from the country of origin and the weight/volume of the growing media constituents, in the sensitivity analysis due to the relevance of the results depending on these parameters and how the country of origin where the constituents come from can affect the environmental performance.

The analysis indicated that with changes such as the use of an electricity mix that is less reliant on fossil fuels and more recent vehicles (Euro 5 to Euro 6) and ships, most of the outcomes improved considerably. We found reductions in the impacts from 100 to 0.1%. Perlite would reduce its impact on all midpoints by changing the energy that perlite requires for its manufacturing and by changing the mode of transportation from lorry Euro 5 to Euro 6. For peat and coir, only changing the transportation mode would decrease their impacts in most of the categories except marine eutrophication and land use for peat and terrestrial acidification and ecotoxicity for coir.

Table 8.3 Sensitivity analysis based on more environmentally friendly alternatives for the energy source of perlite production and the transport of the three constituents. See the absolute values in the supporting information

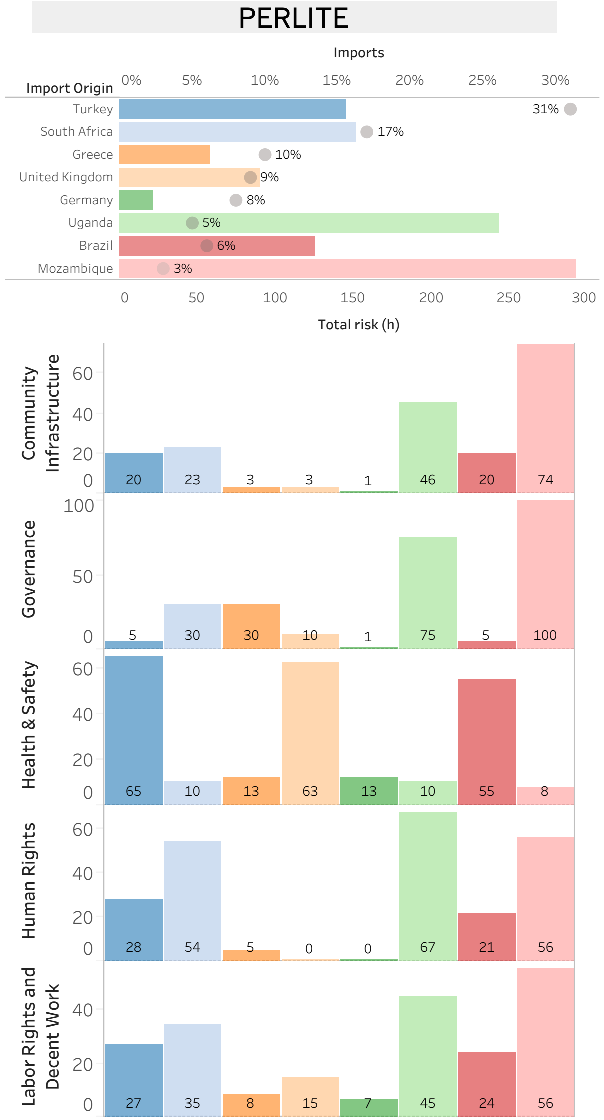
Impact category	GW (kg CO_2 eq)	TA (kg SO_2 eq)	FE (kg P eq)	ME (kg N eq)	ET (kg 1,4-DCB)	LO (m^2a crop eq)	FRS (kg oil eq)	WC (m^3)
Perlite	-23%	-44%	-27%	-24%	-8%	-14%	-23%	-9%
Peat	-2%	-26%	-9%	1%	-0.1%	3%	-3%	-43%
Coir	-13%	3%	-80%	-72%	21%	-27%	-17%	-100%

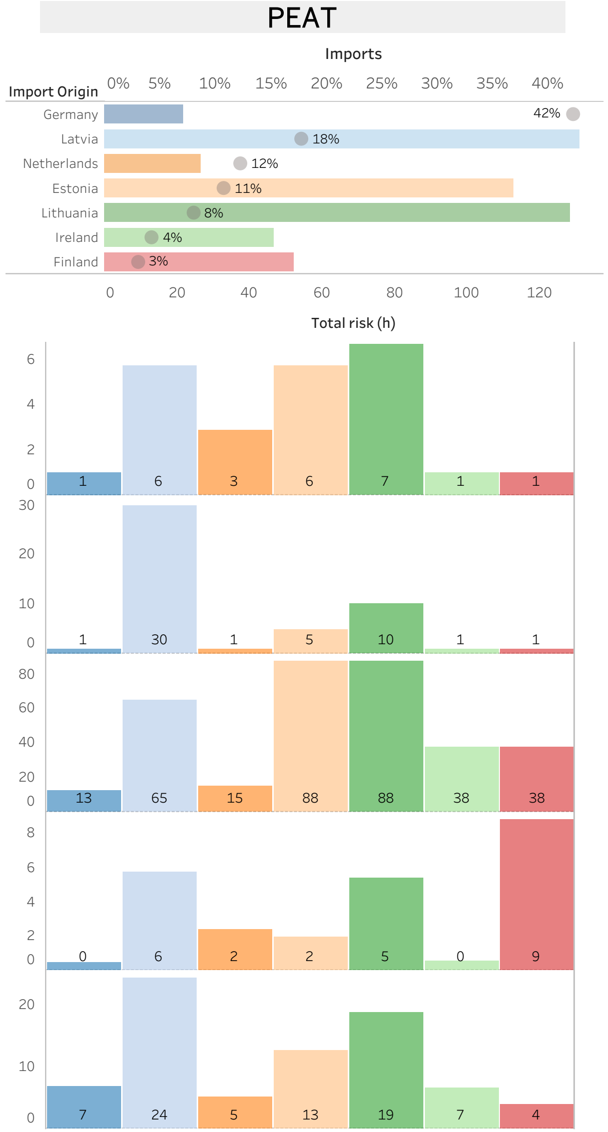
Accordingly, changing the processes that require relevant amounts of energy to other processes based on renewable energies or cleaner technologies can aid in enhancing the environmental performances of these growing media.

8.3.2 Social life cycle assessment

8.3.2.1 Outcomes from the Social Hotspots Database (SHDB)

These outcomes are related to the growing media constituents in the aggregated sector of each country, retrieved from the SHDB. The figures (Figure 8.3) on the top are the total risk hours per country and their imports to Spain in 2018, and the bottom figures are related to the five social impact categories.


PERLITE
Imports
Import Origin
0% 5% 10% 15% 20% 25% 30%
Turkey 31%
South Africa 17%
Greece 10%
United Kingdom 9%
Germany 8%
Uganda 5%
Brazil 6%
Mozambique 3%
0 50 100 150 200 250 300
Total risk (h)
Community Infrastructure
20 23 3 3 1 46 20 74
Governance
5 30 30 10 1 75 5 100
Health & Safety
65 10 13 63 13 10 55 8
Human Rights
28 54 5 0 0 67 21 56
Labor Rights and Decent Work
27 35 8 15 7 45 24 56


PEAT
Imports
Import Origin
0% 5% 10% 15% 20% 25% 30% 35% 40%
Germany 42%
Latvia 18%
Netherlands 12%
Estonia 11%
Lithuania 8%
Ireland 4%
Finland 3%
0 20 40 60 80 100 120
Total risk (h)
1 6 3 6 7 1 1
1 30 1 5 10 1 1
13 65 15 88 88 38 38
0 6 2 2 5 0 9
7 24 5 13 19 7 4

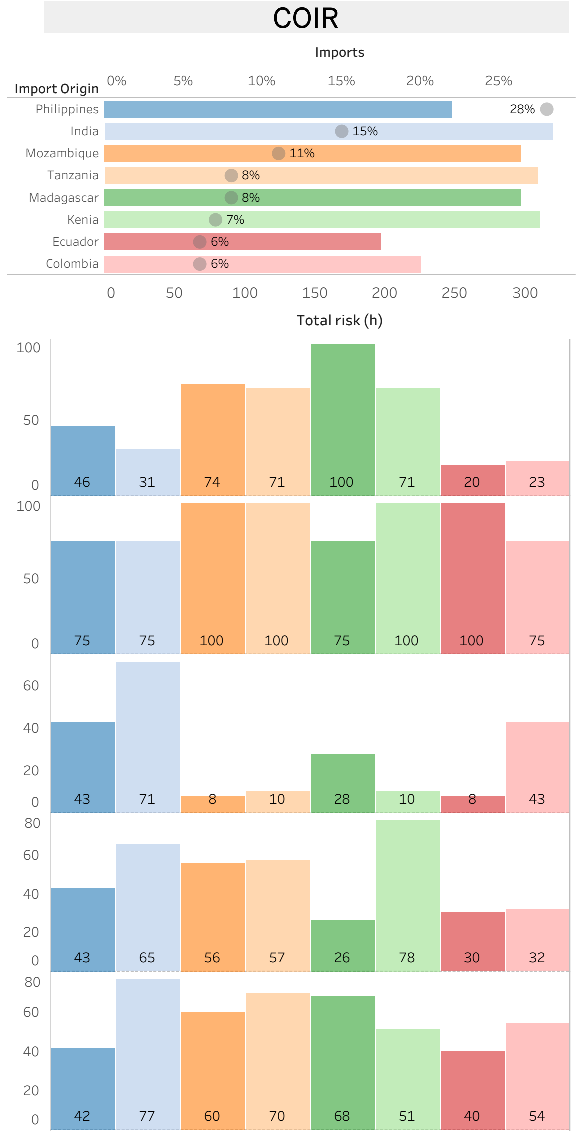

COIR
Imports
Import Origin
0% 5% 10% 15% 20% 25%
Philippines 28%
India 15%
Mozambique 11%
Tanzania 8%
Madagascar 8%
Kenia 7%
Ecuador 6%
Colombia 6%
0 50 100 150 200 250 300
Total risk (h)
46 31 74 71 100 71 20 23
75 75 100 100 75 100 100 75
43 71 8 10 28 10 8 43
43 65 56 57 26 78 30 32
42 77 60 70 68 51 40 54

Figure 8.3 Social risks obtained from the SHDB regarding the aggregated sectors and the imports of the three growing media to Spain. h: hours

The SHDB offers a general overview of the different aggregated sectors. For the mineral aggregated sector to which perlite belongs, the highest-risk hours fall into two African countries: Uganda (243 hours (h)) and Mozambique (294 h), which mainly have risks in community infrastructure and governance, though they represented only 6% and 3% of the total imports to Spain, respectively. The following countries that perform worst are South Africa, Turkey and Brazil. The highest risks among the impact categories in Turkey are health & safety (65 h), human rights (28 h) and labor rights and decent work (27 h), and this country exports the third part of total perlite imported to Spain.

Regarding peat, Latvia, Lithuania and Estonia exhibited the highest risk, particularly in the health & safety category. The rest of the countries performed properly, meaning that the risk hours ranged only from 22 to 53 h. Germany is the country that performed best, with only 22 h, and its highest score was in health & safety. Moreover, the import of peat to Spain was predominantly concentrated in this country (42%).

In general, concerning the coir-based growing media, all of the countries had very high numbers of risk hours, from Ecuador, with 198 risk hours, to the highest, India, with 319 h; in India, governance, human rights and labor rights & decent work had the highest scores. The Philippines is the third best-performing among these countries and exports the most coir to Spain, comprising 28% of the total exports. In general, the Philippines has high risks in all the impact categories.

Taking into consideration these outcomes, the best scores were obtained for peat in Germany, followed by perlite in Turkey, and the highest risk was assigned for coir in the Philippines.

8.3.2.2 Social assessment at the sector and country scales

The following assessment was focused on the specific sectors of perlite, peat and coir from the countries that export the most of each growing medium to Spain (Table 8.4). These outcomes provide specific data about the types of growing media in three different countries that are relevant importers in this sector. Peat from Germany depicts the best performance because 8 out of 14 indicators (57%) performed more positively than the other two options. In contrast, coir obtained the worst performance, with 7 out of 14 indicators (50%) displaying the lowest values, and perlite had most of the intermediate values (50%) among the three options.

Table 8.4 Social assessment of the three constituents at the country and sector levels. The sources of the data can be checked in the supporting information. Gender inequality is sourced from the Classification of Social Institutions and Gender Index (SIGI category (very low, low, medium, high, very high) (OECD, 2020b)

Stakeholder-Impact category (Impact subcategory)- Social indicator	**Perlite (Turkey)**		**Peat (Germany)**		**Coir (Philippines)**	
	country specific	**sector specific**	**country specific**	**sector specific**	**country specific**	**sector specific**
LOCAL COMMUNITY						
Community Infrastructure						
Drinking water access	99%		100%		91%	
Children out of school	5.12%		0.53%		3.25%	
Hospital beds per 1000 population	2.81		8		1	
SOCIETY						
Community Infrastructure (Contribution to Economic Development)						
Employment share (Positive impacts)		6.06%				24.3%
		0.05%		0.0066%		0.53%
GDP contribution (Positive impacts)		1%		0.0021%		0.35%
						8.80%
National poverty line (% population)	13.50%		10.40%		21.60%	
Human Rights						
Gender inequality	25% (low)		18% (low)		53% (very high)	
Child labour	5.90%		4.10%		18.90%	
WORKER						
Health & Safety						
Fatal injuries (number)		33		1		15
Incidence rate:Occupational Injuries per 1,000 Employed Persons		4.41		1.33		0.11
Non-fatal injuries (number)		2806		797		1862
Incidence rate:Occupational Injuries per 1,000 Employed Persons		350		20.2		13
Human Rights						
Gender inequality (woman representation in labor force)		4.60%		NA		14%
Labour Rights & Decent Work						
Child labour		0.002%		0%		2.80%
Excessive work hours		+10%		0%		-22%
Fair salary		331 €/month		2696 €/month		114 €/month
		+16%		-22%		-53%

Scale: low | medium | high

In three out of four impact categories, i.e., community infrastructure, human rights and labor rights & decent work, peat in Germany had the best achievement indicators, followed by perlite in Turkey and coir in the Philippines. These achievements mainly occurred due to the better working conditions and better infrastructure in a highly developed country such as Germany. In contrast, in the subcategory of the contribution to economic development, perlite showed the best behavior, followed by coir and then peat. The reason for this result is that the perlite sector and the coir sector (coconut production) in the studied countries are more prominent, creating more jobs and contributing more to the corresponding GDP than the peat sector, which is a small, family sector with fewer than 20 permanent workers in the companies that is shrinking in recent years due to the Climate Action Plan 2050 proposed by the German government to preserve peatlands (Federal Ministry for Environment Nature Conservation and Nuclear Safety, 2016). By the same token, in the health & safety category, the best performance is observed for coir, then for peat, and the worst performance is observed for perlite. The cause of this result is the high incidence of fatal and non-fatal injuries in mining, which is the mode of production of perlite, an inorganic mineral coming from open-pit mines. Perlite mining is usually associated with a range of respiratory problems (Maxim et al., 2016; Sampatakakis et al., 2013). Nevertheless, in most countries, perlite is classified as a "nuisance dust" (Maxim et al., 2016).

Concerning the analysis of various stakeholders, the rankings for the local community and society follow the general trend, i.e., peat, perlite then coir, due to better conditions in Germany and Turkey than in the Philippines. Nevertheless, for the worker group, the worst performance is assigned to perlite in Turkey because of the worst values of the fatal and non-fatal injuries and excessive working hours indicators, whereas coir exhibits the best scores in general in this group but the worst values for the child labor and fair salary indicators.

8.3.2.3 Social assessment at the company scale

The following assessment at the company level was retrieved from the questionnaire sent to 22 companies. After a long period, we received answers from three companies in each sector and country (Table 8.5). In general, the peat and coir companies shared slightly more information than did the perlite company. Regarding community infrastructure, both companies (peat & coir) have ongoing social or community developments, such as the promotion of nature, research and education or the provision of different projects in schools. In all three companies, most workers are locals (perlite: 100% local; peat: 80% local and 20% migrants; coir: 100% local).

In the same context, the peat and coir companies follow different certifications: the Social Accountability 8000 (SA8000) certification, which involves recognized standards of decent work, and the ISO 9000 production, which is related to quality management systems; however, the perlite company answered positively about the code of conduct in the company but did not mention any specifics. All the companies agreed that they control parameters such as noise, dust and fatal and non-fatal injuries, but none of them provided any data related to these statistics.

Regarding gender inequality, the coir company received the best score because 50% of employees in management positions are women; however, the company was unbalanced in the workforce because 70% of workforce employees are women. In contrast, in the peat company, the majority of employees in management positions are men, and of the total labor force, only

33% are women. Concerning child labor, all of the companies concurred that it is not an issue in this sector. Regarding fair salary and excessive work hours, the companies claimed these were internal information or that they follow national sector-specific rules. However, the perlite company that mentioned that the salary in this sector is higher than in other sectors, which coincides with the fair salary indicator at the sector scale retrieved from official sources ((Table 8.4). However, all of the companies failed to provide any specific figures. With respect to policies related to non-discrimination and freedom to join trade unions, the companies asserted that they follow the standards and laws related to their countries, but no specific data were provided.

These outcomes demonstrate some main issues: a) companies in this sector lack knowledge about the social life cycle assessment, b) it is very complex to obtain social data from companies; 22 companies were contacted, and, after much effort, we obtained 3 responses, and c) companies do not share or do not have sufficient social data, and the data they do share are usually very unspecific.

Table 8.5 Social assessment at company scale of the three constituents. The complete questionnaire and answers can be checked in the supporting information

Stakeholder-Impact category- Social indicator	Perlite (Turkey) company specific	Peat (Germany) company specific	Coir (Philippines) company specific
LOCAL COMMUNITY & SOCIETY			
Community Infrastructure			
Ongoing social or community development infrastructures in local communities	No	Yes. The promotion of nature conservation,restoration and protection. The promotion of science, research and of education	- Provide local jobs - Paint schools and temples - Provide student bursaries
Percentage (%) local workers vs migrants	100% local	20% migrants- 80 % locals	100% local
WORKER			
Health & Safety			
Does your company have a code of conduct that addresses worker rights, health and safety?	Yes	Yes. All the workers' rights of our staff are fulfilled through rigorous compliance of the law and pertinent legal provisions of the countries where our peat extraction centers and substrates manufacturing are located, Strict compliance with the SA-8000 Certification	Yes. Follow ILO Rules: ISO 9000 Production
Measure of noise, dust and hazardous material exposures in the company and their surroundings	Yes, not available	Yes. This is internal information that cannot be provided	No
Statistics in fatal and non-fatal injuries	No	Yes. This is internal information that cannot be provided	Not available
Statisitics in total staff hours worked per week (included overtime)	No	Yes. This is internal information that cannot be provided	40 h/week
Human Rights			
Gender inequality			
% women in the workforce	30 % women	33% women	70% women
% women in managament positions	25% women-75% men	100% men	50 % women- 50% men
Labour Rights & Decent Work			
Child labour	No relevant	No relevant	No relevant
Excessive work hours	9-18h	Our organisation complies with the national legal provisions regarding working hours.	Equal to country sector specific
Fair salary	Legal minimum wage published by government. It is overall higher than other sectors	This is internal information that cannot be provided. In any case it complies the minimum inter-professional wage	Equal to country sector specific wage
Policies regarding non-discrimination and equal opportunity in employment	Yes	Our organisation fulfils the law to guarantee equal treatment and opportunities between women and men in employment and occupation	Yes
Policies regarding freedom for workers to form or join trade unions	Yes	Our organisation complies with the law of freedom association	Yes

Scale			
low	medium	high	

8.3.3 Overall performance for the analyzed growing media constituents. Which growing media are most suitable for urban rooftop farming?

Different outcomes emerged among the different assessments (Figure 8.4). Comparatively, the peat growing medium obtained the highest performance in all the social assessments. This is due to its excellent performance in the SHDB and the impact categories of the local community, human rights and labor rights. Most of its positive performance is related to peat being sourced from a European Union (EU) country, Germany, because of the deployment of human, labor and social security rights and the remarkable work conditions in this country. On the other hand, the peat industry is a small-scale sector that is decreasing in size due to the restrictive peat extraction regulation of the German government that aims to preserve peatlands and cease extraction in the future (Federal Ministry for Environment Nature Conservation and Nuclear Safety, 2016).

Coir obtained the best environmental outcome since it is a by-product resulting from coconut husks transformed into a value-added product, despite the long journey from the Philippines. The coconut sector in tropical countries such as India, Sri Lanka and the Philippines is quite extended, and a variety of products are extracted from coconut trees, such as coconut oil, coconut fibers for example for ropes and mats, beverages, medicines, etc (Maher et al., 2008). Therefore, indicators such as GDP contribution or employment share are very positive in this sector. Conversely, this growing medium has low performance in the SHDB, being the constituent with the highest risk hours in all the impact categories. In the same way, coir has low scores in community infrastructure, in human rights related to gender equality and child labor—approximately 19% in the country and 2.8% in the coconut sector—and in labor rights & decent work.

Perlite is the least environmentally friendly of the three growing media constituents under study, mainly because it is a mineral extracted from mines that requires energy, water and many other processes to be produced and due to its road transportation from Turkey, for example, this could be reduced if perlite comes from Greece, one of the main exporters. Furthermore, the perlite company limited their answers mainly to yes/no and did not provide sufficient details about the social data of the company. Despite these results, this growing medium is affordable, and many conventional greenhouses in Almeria (Spain), where the highest concentration of greenhouses in the world exists, use this growing medium due to its easy management and competitive price (Urrestarazu, 2013). Additionally, Spain is one of the leading global producers of vegetables and fruits, producing 12.9 and 14.4 million tons (2018), respectively (Messe Berlin, 2020). This growing medium showed acceptable performance in the SHDB and in country- and sector-specific assessments, such as community infrastructure and contribution to economic development. Nonetheless, in fatal and non-fatal injuries, perlite scored distinctly worse than the other growing media.

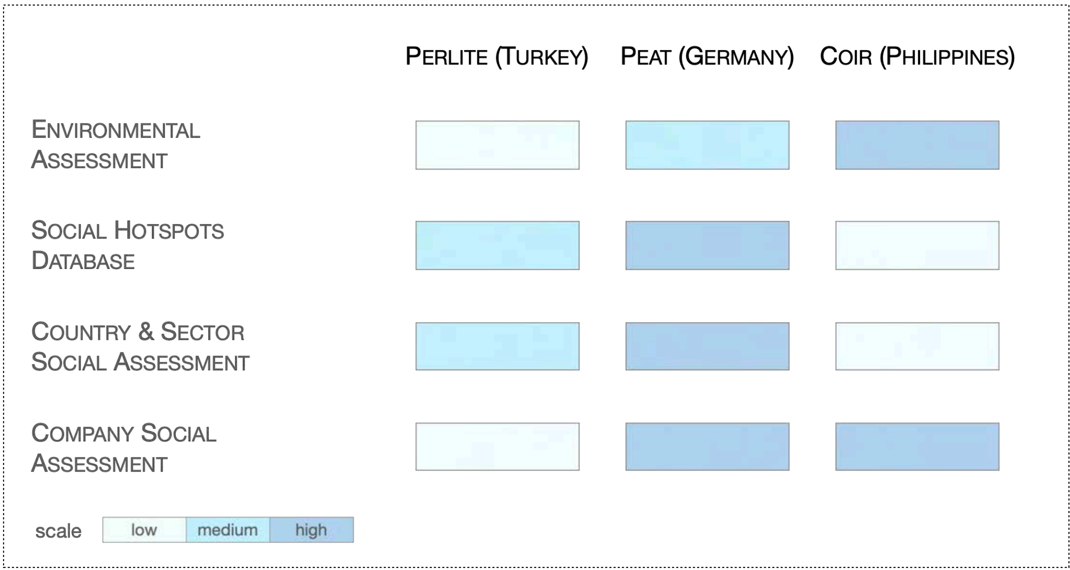


Figure 8.4 Summary of the three growing media constituents and their performances in each assessment type

According to the outcomes, some issues should be highlighted as follows.

- Peat is, according to this study, ideal for use on rooftops in Spain because its social assessment is positive at all scales; however, peat fails in the environmental aspect due to the aim of preserving peatlands and the reduction in their exploitation. A reasonable solution might be the combination of local by-products such as cork granulates or sawdust with peat. In this line, the peat company proposed a combination of peat, coir, perlite and other constituents, and the coir company suggested a terracotta tile waste mixed with coir. Consequently, we identify a plausible new market of local growing media that tailor best in the area where they are applied. The transformation and reuse of waste or by-products could be the solution for future URF (Manríquez-Altamirano et al., 2021, 2020; Parada et al., 2021; Stucki et al., 2019).
- Coir is suitable for local and short-distance countries but not for long-distance countries, such as those in Europe. Coir is a good example of transforming waste into a value-added product. However, all the social impacts of coir related to community infrastructure and human and labor rights should be enhanced for better social performance.
- Perlite has major environmental burdens that should be reduced, but because of it low cost, it is widespread in Spanish greenhouses (Urrestarazu, 2013). Some social indicators of perlite should be improved, such as reducing fatal and non-fatal injuries and controlling noise, dust, etc., for better management of all these aspects. Another solution for this growing medium would be to reutilise it as many times as possible to increase its lifespan,

as some studies advocate that this can decrease its environmental footprint (Acuña et al., 2013; Diara et al., 2012).

Future URF should not repeat the same errors made in conventional food supply chains, such as externalizing the social and environmental costs of delocalized production. Therefore, the growing medium is a key product that must be selected to minimize environmental, social and economic impacts. Proposing local products, and, when possible, growing media from waste/by-products, can improve this selection. As shown in this study, new products, such as perlite, have high environmental and social burdens and long distances from their points of production in countries with lenient labor regulations that rocket these impacts. Accordingly, we display the first attempt to conduct comprehensive assessments of three commercial growing media constituents that will aid in selecting the most feasible growing medium option, in this case for Spain; however, this could be used for other European countries.

8.4 Conclusions

8.4.1 Outcomes from the environmental and social life cycle assessment

We contributed comprehensive assessments of three growing medium constituents used to grow vegetables in future scenarios in cities where land availability is scarce and there will be a need for soilless systems. We analyzed the most extensively used growing media, perlite from Turkey, peat from Germany and coir from the Philippines, to be used in urban roofs to cultivate vegetables by performing an environmental and social life cycle assessment.

The environmental assessment highlighted perlite as the most harmful option compared to peat and coir. Due to the extraction of new material from open-pit mines and the quantity of energy needed for all the manufacturing processes, the highest values in freshwater eutrophication (2.4E-01 kg P eq) and ecotoxicity (5.9E+03 kg 1,4-DCB eq) were obtained for perlite compared with the rest of the growing media. Transport by road from Turkey to Spain also contributed considerably to the environmental impacts of perlite, mainly in ecotoxicity (92%; 5.49E+03 kg 1,4-DCB eq) and land use (60%; 1.29E+01 m^2a crop eq). In contrast, the most environmentally friendly option was coir, despite its long transport route from the Philippines to Spain.

Regarding the social assessment, owing to its origin in an EU country, peat was the most socially friendly growing medium in the three assessments performed due to its more favorable indicators in impact categories such as community infrastructure, human rights and labor rights & decent work compared to the other two alternatives. Subsequently, coir displayed better scores than perlite in general but obtained the worst values of the three alternatives in the SHDB, in the community infrastructure impact category and for social indicators such as gender inequality, child labor and fair salary. Perlite obtained the worst performance in the general assessment; however, it had positive impacts in the GDP contribution and fair salary indicators.

8.4.2 Limitations and methodological challenges

From a methodological standpoint, it was very complex to obtain data for the indicators/impact categories used for the social assessment of not-very-mainstream products, and companies were reluctant to share this information. Therefore, much effort had to be made in this regard. In the same context, social data are not centralized in any institution, and countries sometimes use different indicators with the same purpose; thus, it is necessary to harmonize social indicators and prioritize which social indicators to use. To progress in social assessments and make the assessments more dynamic to perform, we recommend further research aiming to a) prioritize social indicators, as S-LCA presents multiple indicators; we advocate for centralizing efforts in the most common and widespread indicators, such as gender inequality, labor rights, health & safety, etc., or SDGs indicators; b) increase the data availability of disaggregated sectors in databases such as the SHDB and PSILCA targeting to easily perform social assessments; and c) promote among companies the control of social data to generate open-source databases to be used for researchers and organizations. In addition, this research was performed using the first S-LCA guidelines (2009) by the UNEP/SETAC Life Cycle Initiative. Last December (2020), a new guideline was launched, which means that many efforts are already being made; for example, reinforcing and clarifying, with a range of examples, the methodological developments in S-LCAs or linking the S-LCA impact subcategories with SDGs due to the fact that fourteen of the seventeen goals concern social impacts and have many connections with the S-LCA framework.

Obtaining the social data for these growing media in the studied countries was a constraint for this study. On the one hand, few social data, even those related to health & safety and labor rights, are recorded by companies or for specific products, and these data are usually aggregated in general sectors such as agriculture, mining, etc. On the other hand, businesses are reluctant to respond to surveys and share information; hence, new mechanisms must be developed to foster advancements in this field, such as a kind of certification for sharing social data, another type of compensation, or increasing pressure on companies from consumers and institutions to demand transparency in value chains. Ultimately, the social assessment of products is equally relevant as environmental assessment but less developed and harmonized. Consequently, this study aids in progress in this sense in the soilless systems sector, a key industry in feeding cities on an environmentally and socially sustainable path, by identifying a market niche to develop new growing medium mixtures for URF with the objective of seeking growing media from local wastes/by-products that are easy to manage and socially and environmentally sustainable.

Discussion and General Conclusions

5

Chapter 9
Discussion of the main contributions

9 Discussion of the main contributions

This chapter discusses and reflects upon the contribution of this dissertation to the overall aim of sustainable urban strategies and the use of urban roofs as an asset for cities.

Figure 9.1 points out the contribution of this thesis to lead the way for sustainable cities through the implementation of food-energy-water systems on roofs, i.e., the Roof Mosaic. This urban strategy seeks to bring life to all the current empty spaces on roofs. Different urban scales and different types of urban areas were assessed, and different methodologies were applied to deeply understand this strategy and give tools to urban planners, policymakers and local institutions to benefit from their rooftops.

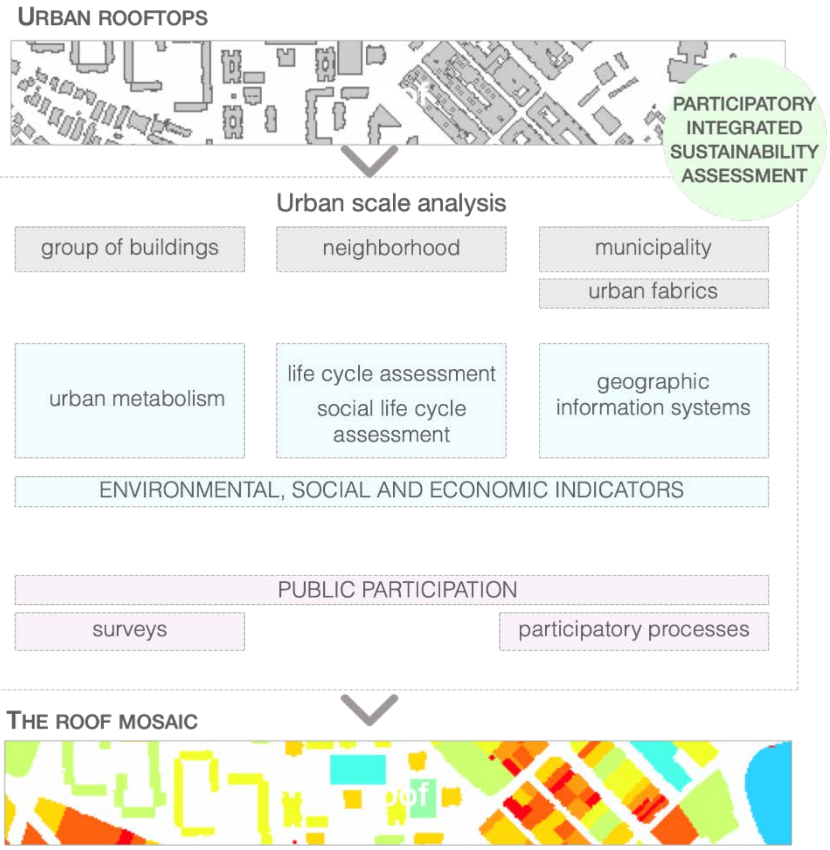


Figure 9.1 Scheme of the contribution of this dissertation in the field of sustainable urban strategies

9.1 Methodological innovation

First, the Roof Mosaic was innovative in this thesis in terms of the way it was structured and proposed. It is not a new concept but in how we posed and organized is a novelty. Second, different methods were applied to evaluate the Roof Mosaic. The dissertation does not propose a new methodology but innovates in the combination of them, in the intersection of different methodologies to obtain outcomes from different perspectives. Consequently, these combinations proposed a new way of analyzing climate change adaptation solutions, such as the Roof Mosaic. In the thesis, we do not limit the assessment to a single methodology or a single perspective, e.g., environmental assessment, but include several methodologies from diverse fields in all chapters, except **Chapter 4** (which only carried out the environmental assessment), combining these methodologies in different manners. The outcomes are more robust and comprehensive having applied this diversity of methods.

The first innovative combination was the application of the multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM) with a participatory perspective for the assessment of the Roof Mosaic **(Chapter 5)**. The participatory process was used to assess the concerns and preferences of the municipality's residents and to propose suitable scenarios. Hence, it was ensured that the chosen indicators and scenarios were relevant for decision-making in the implementation of the Roof Mosaic. Consequently, this combination of methods aids to add the contribution of stakeholders to a method, i.e., MuSIASEM, which is used for the assessment of metabolism in complex systems for a long time.

The second innovative combination, in **Chapter 6**, consisted of a framework for a participatory integrated sustainability assessment. This framework was proposed for the analysis and proper implementation of the Roof Mosaic. It comprises a first stage that includes a participatory process to design the future scenarios for the implementation of the Roof Mosaic and the selection of environmental, social and economic indicators. This was followed by the application of the MuSIASEM for the assessment of the FEW metabolisms and an LCA for the environmental indicators. Then, we also added social and economic indicators. After having all the indicators, we conducted a second participatory process to select together with the residents the most suitable scenarios for their municipality, at that time, with all the environmental, social and economic indicators. Accordingly, the stakeholders were part of the whole process of the design of future scenarios in their municipality. In addition, we used surveys in **Chapters 5, 6 and 7** to include the actual demand of FEW resources. Therefore, the analysis was local and with real data and not averages, considering the current behavior and consumption patterns of citizens.

Finally, **the third innovative combination** comprises using the same methodology of **Chapter 6** but adding the physical characterization of roofs and assessing three different urban fabrics (**Chapter 7**). Thus, the intention was to gradually expand the correct implementation of FEW systems, mixing different methodologies to obtain a multi-scale and multi-dimensional analysis, which offers valuable, far-reaching information for planning rooftop uses. In this way, we bring science, policy and society closer together to enhance decision-making related to urban planning strategies.

In another context, a social life cycle assessment of different growing media was conducted in **Chapter 8**, to our knowledge the first in this field. It can therefore serve as a basis for forthcoming S-LCAs of urban agriculture.

9.2 Application in the context of urban areas at different scales

This thesis is specifically focuses on urban areas; a mix of urban areas and scales were studied to obtain an integrated and robust vision of an array of urban areas. On the one hand, the research was based on housing estates, but in three different urban areas. The first is the neighborhood of Montbau in Barcelona, then a dense municipality, Badia del Vallès and the last case study were different housing estates in a medium city, Cerdanyola del Vallès. The scales studied were at the building, group of buildings, urban fabrics, and municipality scales. Therefore, the different scales aided to identify the synergies about FEW systems and how they work better at large scales, not building by building, and also to propose more specific scenarios depending on the scale. Likewise, focusing only on housing estates gave the opportunity to know in depth these areas in different locations, knowing the metabolic profile of these widespread areas, characterizing their rooftops and their constructions and the type of residents. These areas are very similar and have many advantages to use their rooftops to produce energy, grow vegetables and/or harvest rainwater and replicate the Roof Mosaic smoothly. These studies (**Chapter 5 and 7**) are believed to be the first assessments of the FEW metabolism of housing estates, originary fabrics and single-family housing areas.

On the other hand, in order to advance in the implementation of the Roof Mosaic strategy, **Chapter 7** was devoted to an entire city (Cerdanyola del Vallès) with three different urban fabrics: originary fabrics, housing estates and single-family housing areas. The ambition was to extend the analysis to other urban forms with different constructions and diversity of households. This research addressed the complexity of urban areas and their diversity, displaying those requirements of the FEW implementation can be different, depending on the urban tissue and the metabolic profile of the residents which are highly reliant on the urban fabric. In general, higher consumptions were found in single-family housing and lower consumptions in housing estates.

9.3 An integrated assessment of a new sustainable urban strategy: The Roof Mosaic

9.3.1 The three pillars of the sustainability

Many studies in the field of sustainable urban strategies strive to quantify the environmental impacts of these novel strategies, considering the different inputs and outputs of these systems and comparing them to procure the most environmentally friendly option. However, sustainability is based on a “TBL” (Abraham, 2005) of economic viability, social concerns and environmental issues. Therefore, future policies and strategies for cities should encourage a more integrated assessment. The sustainability assessment is featured by being complex, multi-dimensional and multidisciplinary and solution-oriented, posing different perspectives and resulting in a holistic vision of these proposals. By integrating environmental, social and economic approaches, the research presented here illustrates not only the environmental aspects such as CO_2 emissions, CED but also social aspects such as hours of maintenance by family, coverage of energy poverty, and economic aspects such as monetary investment of FEW systems, monetary savings per family, etc. Thus, a complete picture with the necessary information to choose future Roof Mosaic implementation scenarios. Giving importance not only to one pillar of sustainability but to all of them. A sustainability perspective in the implementation of FEW on roofs has demonstrated a more integrated approach of the strategy, more understandable for stakeholders and more focused on the different residents' concerns. This has been also evidenced in the literature that when applying the analysis of the three pillars creates a more solid, effective and durable success of these projects (Clune and Zehnder, 2020).

By applying the S-LCA in growing media, we also added some insights into the hidden social impacts of the Roof Mosaic components. The S-LCA should be done for all the components of new urban strategies to implement in cities, so that we do not shift the environmental o social impacts to other countries when we enhance our cities. Therefore, the S-LCA helps to identify hotspots in the production of these materials, that tend to be overseas. Growing media are mainly produced in Turkey and Greece (perlite), the coir in India and the Philippines, etc. The PV panels are often manufactured in China and many of the RTGs elements such as steel and plastics are also made in China (Sheng Hong, Yifan Jie, Xiaosong Li, 2019; Wen et al., 2020; Worldsteel Association, 2020).

9.3.2 Urban Metabolism: Metabolic profile of different urban forms

The outcomes of this dissertation constitute an advance on the urban metabolism of three basic resources necessaries in cities: food, energy and water. As shown in Table 9.1 different urban forms were analyzed, two different housing estates in two municipalities, then the originary fabrics and single-family housing areas. These results were also compared with average values in Barcelona, Catalonia and Europe.

Table 9.1 Metabolic profiles of the cases studies and averages of three different locations. NA: not available

Urban fabric	vegetable metabolic rate (g/h)	electricity metabolic rate (MJ/h)	water metabolic rate (l/h)
housing estates (Badia)	13.10	0.82	6.48
housing estates (Cerdanyola)	10.50	0.75	5.00
originary fabrics (Cerdanyola)	10.90	0.82	6.00
single-family housing (Cerdanyola)	11.40	0.85	5.90
Barcelona	NA	0.72	NA
Catalonia	4.51	NA	7.00
Europe	NA	0.74	NA

The housing estates in Cerdanyola displayed the lowest metabolic profile in all the three resources. In contrast, the housing estates in Badia showed higher values in vegetable and water metabolic rates than the other urban forms, hence, higher consumptions in these two resources. Among the urban forms, the highest metabolic rates are assigned to single-family housing areas, being 8% (vegetables), 12% (electricity) and 15% (water) higher than housing estates of the same municipality. Comparing to other locations, only the water metabolic rate is lower in these urban forms. There is a considerable difference in the vegetable consumption between the urban fabrics and Catalonia, this is, in principle, because of different methodologies and scales used. It is therefore advisable to further study multi-scale metabolic profiles to capture scale disparities, i.e., scales of urban form, neighborhoods, municipalities and regions from which very distinct outcomes may emerge. The metabolic rates are based on the available hours residents spend at home and are divided into employed, unemployed and retired. These outcomes are therefore more accurate and consistent than the per capita results because they characterize the type of resident (see Chapter 5 for further details). The study of metabolic patterns is vital for the supply of these basic resources and for the application of the Roof Mosaic where is more indispensable and more sensitive to social and economic issues, such as sites that face entrenched energy and water poverty.

9.3.3 Public participation

In this dissertation, we carried out a range of social methods in almost all the studies. The general goal was to involve stakeholders in more equitable decision-making on relevant issues that affect their daily lives. In topics related to climate change adaptation solutions, it is often complex to include all stakeholders in the decision-making; however, from our view, in cities, it is crucial to rely on the stakeholders' opinion. If these opinions are not considered, residents' groups can emerge against any kind of intervention, as can be seen in many current solar and farm projects (O'Neil, 2021). In this case, the urban strategy to be implemented will colonize the roofs of buildings, most of which are shared, and unused spaces at present, so it is essential to engage citizens in such proposals.

Table 9.2 illustrates the surveys conducted in all four chapters. There are two distinct groups, one aimed at obtaining data to characterize residents and also to find out their preferences for the use of their roofs. The second group is **Chapter 8**; To perform an S-LCA, where information from some sectors is scarce and in an aggregated form, it is indispensable to use surveys to get more information from companies to obtain social indicators. Surveys are at the second level of the spectrum of public participation from IAP2, which is "consult".

The participatory processes were conducted in two different research to involve stakeholders in the decision-making and include their concerns in the decision of future scenarios. These participatory processes empower residents and boost the likelihood of success in implementing new projects in the municipality. Moreover, the involvement of residents aided to analyze the plausible limitations, constraints and also advantages of the use of roofs and to better design these projects. Citizens should be participants of urban sustainable solutions by including them in the whole process. These participatory processes are part of the "collaborative" level, which is one of the highest levels in the spectrum of public participation.

Table 9.2 Social methods used in this dissertation and the obtained information

Research	surveys	participatory processes
Chapter 5	To obtain the residents' characterization such as gender, age group, working status, family unit, type of building where they live, household incomes, monthly energy, water, vegetable expenses, and consumption pattern profile *(consult level)* Sample: 433 people	To know the concerns of the residents and design hand by hand future scenarios *(collaborative level)* Sample: 14 people
Chapter 6	To obtain the residents' characterization such as gender, age group, working status, family unit, type of building where they live, household incomes, monthly energy, water, vegetable expenses, and consumption pattern profile *(consult level)* Sample: 433 people	To know the concerns of the residents, design hand by hand future scenarios, select the relevant indicators and choose the final scenarios to implement in the municipality *(collaborative level)* Sample: 60 people
Chapter 7	To obtain the residents' characterization and preferences to implement on their rooftops *(consult level)* Sample: 1100 people	-
Chapter 8	To obtain data to conduct the S-LCA at company scale *(consult level)* Sample: 3 different companies	-

In essence, we have tried to encompass all possible perspectives, scales and useful methodologies to move forward and present a comprehensive guideline for the use of urban rooftops to produce food, energy and harvest rainwater with the overall goal of advancing into a more just, livable, healthy, green and sustainable society. Additionally, we have shared all these generated outcomes of this dissertation in open access journals and raw data.

Chapter 10

Conclusions

10 Conclusions

This chapter addresses the general conclusions of this dissertation, providing specific answers to the research questions posed in Chapter 2.

> ***Question 1:*** *What are the environmental and socio-economic impacts, and the benefits of the implementation of food production, renewable energy infrastructures and rainwater harvesting, on available rooftops for the purpose of self-sufficient cities?*

The environmental and socio-economic impacts and benefits of implementing the Roof Mosaic on the three case studies are summarized in Table 10.1. The case studies span building, neighborhood and city levels, thereby giving a comprehensive perspective of the viability of the Roof Mosaic.

We identified that the highest environmental impacts occur in the municipalities of Badia and Cerdanyola since the proposed scenarios - which are based on the residents' preferences- have more PV panels. The construction of PV panels and also of RTGs have the highest values in Global Warming, CPBT and CED indicators, because more materials and energy are required than in OAF, GR and RWH systems. PV panels require a range of raw materials such as silicon, glass, aluminium, etc., and high energy consumption (Carnevale et al., 2014; Peng et al., 2013). Furthermore, RTGs need significant quantities of polycarbonate and steel for their construction. The highest monetary investments are also found in Badia and Cerdanyola for the same reason, as more surface with these systems which are more expensive than the implementation of OAF and RWH. On the other hand, the highest hours of maintenance are detected in Cerdanyola, and especially in urban rooftop farming, due to the extensive area of industrial parks in Cerdanyola and the highest hours needed to take care of the crops in these systems. In fact, Cerdanyola displays the highest figures in resource self-sufficiency, increase of green spaces, CO_2 savings and energy and water poverty coverages as it has a large extension of industrial parks that Montbau and Badia do not have. Therefore, more spaces to implement FEW systems.

In general, the increase of green spaces is very substantial in all the case studies, from a minimum of 0.17 ha (Montbau) to a maximum in Cerdanyola of 27.5 ha, which would provide to municipalities a variety of services such as fresh vegetables, enhancement of biodiversity, run-off and heat island effect, among others. The scenarios that implement RTGs on the rooftops, such as Badia and Cerdanyola, have a long payback period of 9 to 15 years due to the high price of this infrastructure in comparison to the low price of vegetables. For the scenarios with PV panels, the investment is also high, however, the high cost of electricity means that the payback period is between 1 and 5 years.

Table 10.1 Indicators of the three case studies

Indicator		MONTBAU	BADIA	CERDANYOLA
sustainability indicators				
Self-sufficiency (%)	vegetables	17-30%	42-56%	50-115%
	electricity	7-10%	9-35%	35-71%
	heating	34-50%	**	**
	water	23%	38% (flushing)// 66-200% (irrigation)	18% (flushing)// 101-227% (irrigation)
Increase in green spaces (m^2/inhabitant)		1.7- 2.8	2.5-3.7	2.4-4.7
Production of vegetables (kg/year)		11,000 - 36,245	352,095 - 470,346	1,700,436 - 2,911,894
Production of energy(kWh/year)		297,649 - 446,473	1,330,515 - 5,032,057	27,346,764 -54,693,528
Production of water (m^3/year)		1,422	27,646 - 34,319	375,698
environmental indicators				
CO_2 savings (kg CO_2 eq/inhabitant/year)		111-160	119- 231	97 - 576
Global Warming (kg CO_2 eq/m^2/year)		46 - 68	35 - 97	4 - 97
CO_2 payback time (CPBT) (years)		1.76-2.17	1.4 - 2.5	1.0 - 4.2
Cumulative Energy Demand (CED) (MJ/m^2/year)		628 - 1,041	582 - 1,570	**
Energy payback time (EPBT) (years)		1.11-1.34	3.0-6.7	**
social indicators				
Energy poverty coverage (%)		**	9-33%	35-71%
Water poverty coverage (%)		**	7-8%	18%
Human activity budget (THB) (hour/year)		**	10,833- 394,390	117,307 -3,289,247
Maintenance investment (hour/hh/year)		**	2.0 - 59.2	4.9-138.6
economic indicators				
Monetary savings (€/hh/year)		**	407-752	335-1801
Investment (€/hh)		**	3155 - 5055	3188 - 6424
Maintenance cost (€/m^2/year)		**	4.01-9.52	4.01-9.52
Payback period (years)		**	5.64 - 9.17	2.77- 14.69

m^2 refers to m^2 of rooftop; ** not estimated

The social impacts of growing media for OAF and RTGs are also assessed and included in **Chapter 8**. In this case, we cannot compare the social impacts of the production of PV panels or other materials from RTGs and RWH due to lack of data for these systems. We would like to point out that this omission might be significant and is worth exploring in the future. For example, the construction of PV panels - which are mainly manufactured in China- could have even higher impacts than the growing media we analyzed. Given the extraction of raw materials, the toxicity of different chemicals such as lead, cadmium, chromium, etc., the energy requirements that entails and the social impacts related to their manufacture (Dubey et al., 2013). In the outcomes for growing media, we found that these social impacts are highly reliant on the country of origin. The best performance was found in peat because it is produced in Germany, although it is a constituent destined to disappear due to the goal of peatland conservation in the country. The other two growing media, perlite (mined in Turkey) and coir (manufactured in the Philippines), displayed higher social impacts, related to community infrastructure, human rights, and health and safety.

Question 2: *To what extent does this new urban-nexus system contribute to a future self-sufficient city?*

The various resources and locations assessed in this dissertation result in different degrees of self-sufficiency, defined as ability to self-produce and self-supply resources. As can be seen in Table 10.1, the general trend is that self-sufficiency in vegetable production is much more attainable than in the production of energy or harvesting rainwater. These values are highly dependent on consumption behavior, such as diet changes to vegan or vegetarian, as well as climatic conditions. In the case studies, the climate is the same, with many hours of sunshine per year and few rainy days (Servei Metereològic de Catalunya, 2020). Therefore, the capacity of growing vegetables and producing energy is high, however, rainwater harvesting is limited due to few rainy days and the fact that rainfall is concentrated in fall and spring. In the three case studies, the capacity of self-sufficient is relevant, being the highest in Cerdanyola with percentages of 50-115% for vegetables, 35-71% for electricity and with the capacity to irrigate all crops without the need to use water from the distribution network. Cerdanyola has a large extension of industrial parks to implement these systems, hence the proportion of self-sufficiency is higher.

Consequently, with the implementation of different FEW systems on urban roofs, 100% self-sufficiency will not be achieved; thus, it is not the only solution to reach more sustainable cities and must be combined with other approaches such as the decrease of the FEW consumption, and the increase of efficiency in these systems. Having said that, it could aid to partially procure self-sufficiency of these resources, giving more food, energy and water sovereignty to cities and their inhabitants and, consequently, providing new spaces for greenery, social cohesion and reducing the impacts generated for conventional and centralized networks.

Question 3: *How can this new urban-nexus system be implemented in different contexts and scales?*

By means of implementing the Roof Mosaic in three different cases, it was possible to capture the differences among different contexts and scales. The first case study, the Montbau neighborhood was effective to see the differences between applying the Roof Mosaic on a single building and a group of buildings. The implementation of these FEW systems on a single building seems to be the worst option due to the loss of surplus resources. Accordingly, when these systems are planned to be shared in a group of buildings these surpluses can be absorbed by the rest of the residents. The Roof Mosaic seeks to find synergies at a macro level to find the maximum harnessing of the resources. Subsequently, in the municipality of Badia, we could observe that housing estates tend to have flat roofs, same observed in Montbau and the municipality of Cerdanyola; therefore, there are no limitations for any of the FEW systems to implement and, because there is no limitation, the residents' preferences are crucial to deciding the type of systems to implement. On the other hand, the case study shed light on the housing estates metabolism, which led to insignificant changes in the consumption pattern profiles of the residents of the buildings in this municipality (12.60–14.50 g/h for vegetables, 0.85–1.11 MJ/h for electricity, and 5.62–6.59 L/h for water). The last case study was the municipality of Cerdanyola, in this research, the main objective was to expand the implementation of the Roof Mosaic in a larger municipality and with different urban forms. Resulting in significant differences among urban forms on the type of roofs and the consumption pattern profiles. Housing estates showed more flat roofs and wider than the other urban forms, i.e., originary fabrics and single-family housing areas, to implement urban rooftop farming. The originary fabrics showed more heterogeneity and single-family housing areas more quantity of roofs per inhabitant, although these roofs are usually smaller and steeper. Therefore, depending on urban forms it will be more feasible to implement one or other systems, but not only because of their characteristic buildings and roofs but also because of the type of inhabitants that usually live in these urban forms. From what we were able to determine in the municipality of Cerdanyola, the highest consumption pattern profiles were identified in single-family housing families, in electricity, vegetables and water (this was the same for the originary fabrics) and the lowest in housing estates.

Question 4*: What is the social perception and acceptance of this new urban-nexus system?*

The social perception and acceptance of the new uses of the rooftops were obtained in two ways: 1) in one municipality (Badia) by two different participatory processes and 2) in the other municipality (Cerdanyola) with a questionnaire (Table 10.2).

Table 10.2 Percentage of the social acceptance of the implementation of different systems on rooftops. NA: not available

Municipality	PV	GR	OAF	RTG	RWH	Combination of all
Badia del Vallès	65%	17%	7%	3%	NA	7%
Cerdanyola del Vallès	77%	25%	21%	20%	43%	27%

The two participatory processes and the survey revealed a clear preference for the installation of PV panels. The majority (65-77%) would be willing to use their rooftops to produce energy. Therefore, citizens have normalized the use of rooftops for this purpose but are not yet accustomed to using them for harvesting rainwater or grow vegetables. For the options of urban rooftop farming, only 7% of the residents in Badia accepted them; however, this proportion increases significantly in Cerdanyola municipality by 20-21% and rises by 27% when the proposal is a combination of all systems (PV+ OAF+ RTG+ RWH), which denotes an interest of a variety of systems on their roofs. Albeit, turning roofs into green and productive spaces could contribute not only to providing one resource (as in the case of the deployment of PV panels and RWH) but also to supporting spaces of cohesion, diversity, liveability and so on. Hence, there is still a long way to go for citizens to envision the implementation of urban rooftop farming on their roofs. Certainly, increasing environmental communication, policies, education and new projects driven by public institutions should be the strategies to follow to raise awareness on how to take advantage of underutilized rooftops and enhance our cities.

Chapter 11
Suggestions for future research

11 Future research

The work developed through this dissertation has made us aware of new lines of research in the overall aim of finding solutions for cities by producing their own food, energy and harvesting rainwater on underutilized spaces, i.e., on rooftops. These potential research lines are identified by chapter in the following table (Table 11.1).

Table 11.1 Possible future research by chapter

PART II	Chapter 4	o **Expand the guidelines.** Not only proposing environmental indicators but also including social and economic indicators. Add more details about the limitations to implement these food-energy-water systems on rooftops such as additional infrastructure. o **Apply another life cycle assessment steps**, such as **sensitivity analysis** to obtain a range of outcomes. o **Apply consequential life cycle assessment.** We only used attributional approach to calculate environmental impacts and avoided burdens of implementing FEW systems. Therefore, it might be useful to test them from a consequential perspective and see the differences in the outcomes.
PART III	Chapter 5	o Apply **uncertainty analysis** in different input data in order to get more reliable data. o **Propose a pilot project** of the implementation of the production of FEW systems in different buildings of this housing estate, designing together with residents and local institutions the scenarios to better meet their needs. This pilot project will allow measuring the actual benefits and limitations of this sustainable urban strategy.
	Chapter 6	o **Incorporate another participatory process** to argue the residents' choices, to have more insights about their preferences after knowing the outcomes of the different indicators and use it for the design of polices for the municipality.
	Chapter 7	o **Apply the same methodology in other urban areas** and the same urban forms (originary fabrics, housing estates and single-family housing) to obtain more reliable data that can be standardized. In addition, more data will be obtained to be able to compare between urban areas and analyze the feasibility of implementing different FEW systems. o **Propose a pilot project** to test in the municipality the implementation of different FEW systems, even in different urban forms. With these data, it will be easier to analyze the actual constraints and benefits of the implementation of these systems. Furthermore, it will be possible to measure the changes in air pollution, biodiversity, etc. o **Create an Urban Lab** *("empower level" of the spectrum of public participation)* in the municipality to have a space for debate between neighbors, institutions and academia on sustainable urban strategies. Co-creation of new and viable projects for the municipality.
PART IV	Chapter 8	o **Add more suppliers of growing media,** and countries to the social analysis. It will be necessary to have prior contacts with these suppliers, as it is quite complex to obtain social data from companies, in general. o **Add local substrates** in the social and environmental life cycle assessment. o **Expand interviews to workers, neighbors, and local institutions.** o Due to **social life cycle assessment** is less standardized and social data is time consuming, we only performed this methodology once. Therefore, we recommend expanding the study to **solar panels, and RTGs components such as steel and polycarbonate** most of which are manufactured in China and there is still a lack of knowledge on the social impacts of these components. However, obtaining social data from China is challenging.

In addition to the specific tasks highlighted in the previous table, we also see the need for:

Inclusion of Citizen Science in sustainable urban strategies

This thesis is based on a sustainable urban strategy, in which quantitative and objective indicators aided to make decisions. However, the use of a new space, in this case, the roofs of shared buildings will change the daily life of the residents. Consequently, proposals for climate change solutions in cities must involve all stakeholders, local and regional institutions and neighbors. Citizen Science is key to progressing in these types of solutions and to their successful implementation. In recent years, numerous wind and solar farms projects have proliferated, thanks to the promotion of green energy by the European Union and governments. However, these projects sometimes encounter strong opposition in some territories, the "not in my backyard" (NIMBY) phenomenon. Thus, Citizen Science offers the tools to co-create these projects more democratically and comprehensively by incorporating all the criteria and preferences of stakeholders.

We believe that progress in sustainable cities should be joint with the residents who are an essential part of these habitats. Proposing new urban strategies having only one perspective, for example environmental, and forcibly applied by governments or companies will not provide the most viable solution for urban areas.

Test different pilot projects in residential buildings and industrial parks

The next logical step of this research would be to implement the Roof Mosaic through different pilot projects. The first projects to implement would be in residential housing. These buildings are inhabited by different families with different preferences and needs; therefore, it is more challenging than any other type of buildings because there is more than one owner; in single-family dwelling it is easier to implement any type of system and there will not be any organizational issues, in principle. But in shared buildings, where a large majority of residents in Europe live, there will be more variety of issues in the pre-construction phase, e.g., the project design, such as what type of FEW to implement, who will take care of the new systems, then the operation phase, to analyze the different problems to overcome, etc. Moreover, additional infrastructure would be necessary, such as access to roofs, or specific equipment, etc. Therefore, starting with pilot projects in this type of construction would give valuable information for later implement the Roof Mosaic at a large scale. Likewise, these pilot projects will also serve to measure different parameters and how they influence cities, such as the air pollution, temperatures, biodiversity, or new ecosystem services they can offer (Langemeyer et al., 2016).

Another option would be to use the rooftops of industrial parks for implementing agriculture, PV panels, or harvesting rainwater. In these areas, it can be found large extensions of underutilized roofs. They are usually grey and unattractive spots. Thus, the implementation of green areas on their roofs could serve as a space to grow vegetables for residents or to produce energy.

However, in industrial parks, if rooftop farming is chosen, some roofs would have to be rehabilitated, as some of them have low load capacity.

These two options will provide local resources by taking advantage of unused spaces, rather than creating new energy/vegetable farms using new land.

Assessment at global scale in different urban areas

This thesis is focused on Catalan municipalities and predominantly on housing estates. Housing estates are spread across Europe and have many advantages in their constructions, such as repetitive buildings and flat roofs for a better implementation of FEW systems. Moreover, the population living in such constructions often faces similar social, economic and environmental problems. Therefore, it would be advisable, firstly, to assess the Roof Mosaic in different housing estates across Europe using the same methodology as in **Chapter 7** and, secondly, in different urban fabrics. The differences in climate, also in consumption pattern profiles of different countries would enrich this strategy and similar or different solutions could be applied in these urban areas. However, it is advisable to foster it above all in urban areas where these resources are most needed, consequently, in vulnerable populations.

Likewise, there are other countries, such as post-communist countries or China, where housing estates are a large majority. So, this urban strategy in these diverse countries would be a valuable research line.

Creation of an open-source tool with all the data from the studies conducted

Different datasets were generated and shared in open access in this dissertation, with the intention to create open-source science and the possibility to be used for local governments, institutions and other scientists. However, due to the limited time of a PhD, it was impossible to gather and share this information in an open-source tool such as instamaps (https://www.instamaps.cat/#/) or OpenStreetMap (https://www.openstreetmap.org/). The generated outcomes could be in an open space to easily consult all the results. In this case, two municipalities and a neighborhood in Barcelona. It would be filled step by step with more information from other urban areas. This information would be easily accessible for municipalities to know the consumption profile of their residents, the availability of roofs and their features. Thereby, this is essential information to apply sustainable policies in cities.

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APPENDIX

Supporting Information

Appendix

Appendix 1- Supporting information for Chapter 4: 219

1. Appendix 1. Supporting information for chapter 4

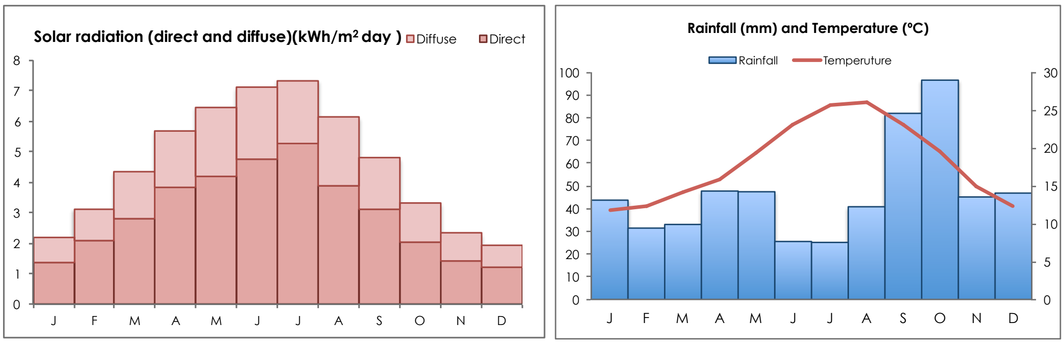
A guide for assessing the implementation of the Roof Mosaic approach

Application to a case study

Step 1: Characterization of the area under study

Solar radiation, rainfall and temperature in Barcelona

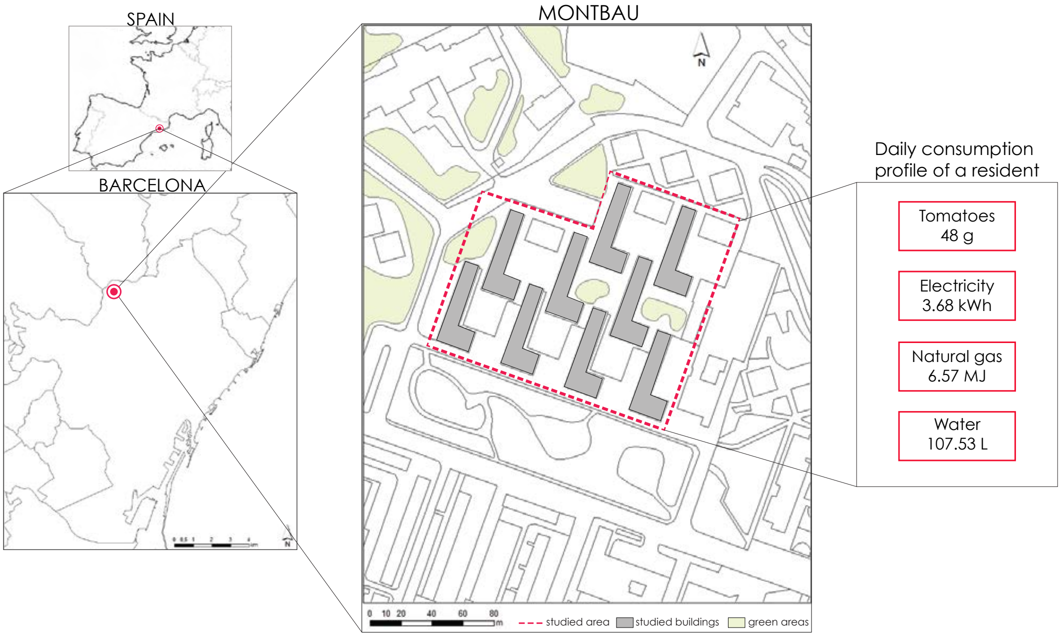
Barcelona is one of the most densely populated cities in Europe (Ajuntament de Barcelona, 2016b). The main climatic features of Barcelona are mild winters (average of 9-12ºC) and hot summers (average of 23-26ºC), annual rainfall of 600 mm (Ajuntament de Barcelona, 2017d), and an average solar radiation of 4.56 kWh/(m^2.day) (AEMET, 2006a) (Appendix 1.1). All these data are useful to design and size the different rooftop scenarios in step 2.



Appendix 1.1 Direct and diffuse solar radiation in Barcelona. Historical series for 1983-2005 (left-hand graph) and mean monthly rainfall and temperature in Barcelona. Historical series for 1987-2010 (right-hand graph)

Neighborhood

The neighborhood (Appendix 1.2) was built between 1962-1964, with a population of approximately 5,070 inhabitants from which more than 31% are older than 65 (Ajuntament de Barcelona, 2017a). Furthermore, the income per capita is low (15,750 €/(family·year)) compared to the rest of Barcelona districts (Ajuntament de Barcelona, 2016a).

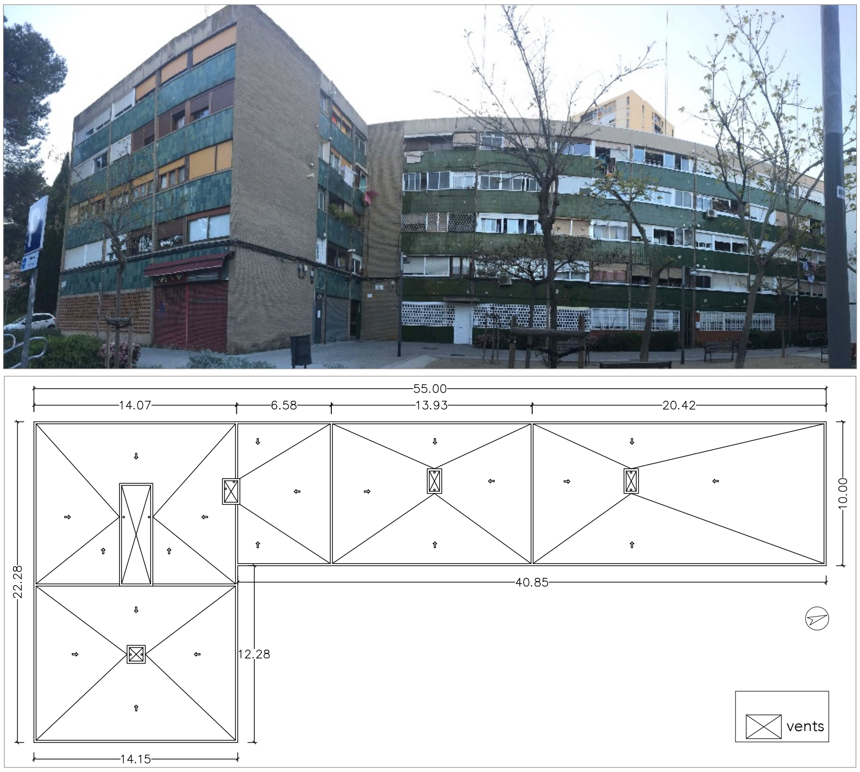


Appendix 1.2 Location of the case study in Barcelona (Catalonia) and the average consumption of a resident based on Generalitat de Catalunya (2015), Ajuntament de Barcelona (2017b), and Metropolitan area of Barcelona (2017)

The main vegetables consumed, based on averages for the population of Barcelona, are potatoes (33 kg/year), tomatoes (17 kg/year), onions (8 kg/year) and lettuce (6 kg/year), which are part of the typical Mediterranean diet (Generalitat de Catalunya, 2015).

Reference building

This is the prototype building of the analyzed neighborhood and the layout of the rooftop (Appendix 1.3), including vents and sill. This roof leans on a structural floor that was designed considering life loads greater than 200 kg/m^2. It is composed of reinforced concrete girder-slabs with ceramic interjoists. The aforementioned parapet and the façades of the building are brick masonry that is 30 cm thick (Camarero, 2013).



Appendix 1.3 Panoramic picture of the analyzed building in Montbau and dimensions, vents and slopes of the rooftop

Step 2: The Roof Mosaic design

Food systems

The hydroponic systems consist of perlite bags (1 x 0.35 m) distributed in rows with a separation of 1.2 m (Montero et al., 2017). We obtained 272 and 238 bags distributed in 34 rows for open-air farming (OAF) and rooftop greenhouse (RTG), respectively, as the RTG structure requires more space.

Rainwater system

Appendix 1.4 Dimensions and components of the rainwater harvesting systems

Rainwater Harvesting systems		
Storage	Tank volume (m^3)	7 (14.15 ×0.495 x 1)
Distribution	Supplying pipe (m)	13.5

Technical data and parameters of ST collectors and PV modules

We used an average solar radiation of 4.56 kWh/(m^2.day) corresponding to Barcelona (AEMET, 2006b). Based on the latitude of Barcelona, the optimized tilt angle of both technologies was 35° (Appendix 1.5).

Appendix 1.5 Technical data of ST and PV panels (Carnevale et al., 2014; Frischknecht et al., 2015a)

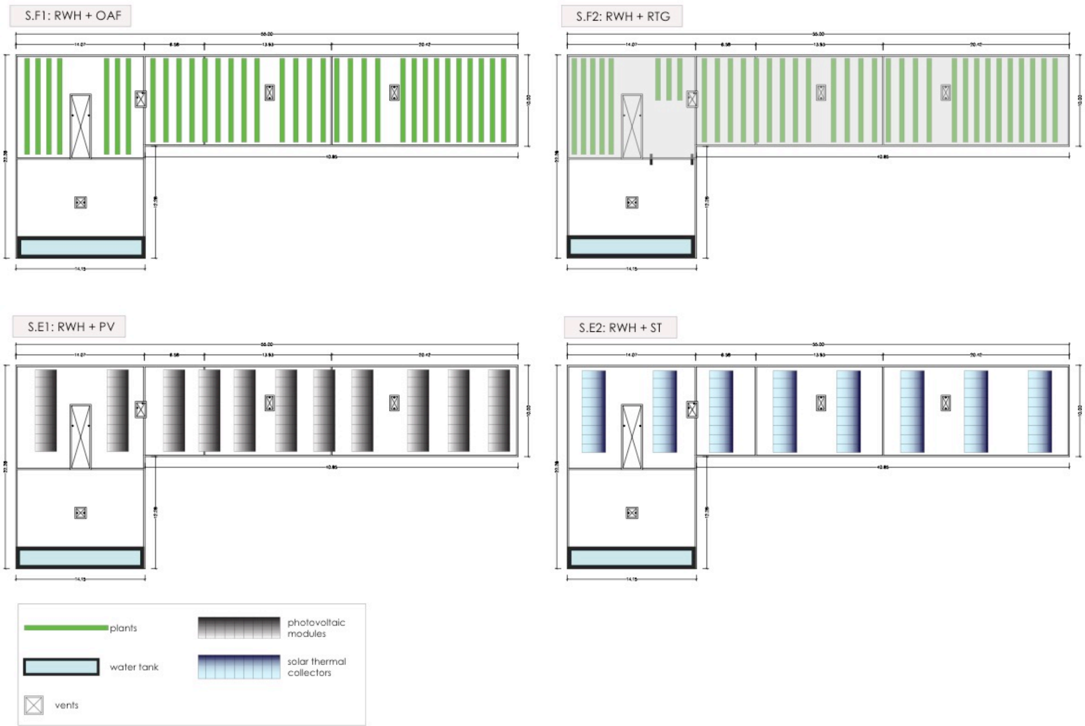
Parameter	Unit	ST	Parameter	Unit	PV- Multi-Si
Collector type (pipes-foil)		Cu-Cu	Module surface area	m^2	1.64E+00
Collector surface area	m^2	2.13E+00	no. cells	no.	60
Collector weight	kg	6.96E+01	Power	Wp	2.45E+02
Collector optical Efficiency $F_r(\tau\alpha)$	–	0.79E+00	Efficiency η	%	14.9
			Module frame		yes
Collector losses $F_r U_L$	W/(m^2·K)	4.80E+00	Module weight	kg	2.53E+01
Water tank capacity	L	1.60E+02	Dimensions	m	1.65 x 0.99 x 0.04
Thermal fluid		water- propylene glycol	BOS efficiency	%	85
Water tank weight	kg	8.62E+01	Mounting structure		flat roof
Mounting structure		Flat roof	Inverter	W	2.50E+02
Dimensions	m	2 x 1.16 x 0.91			

Appendix 1.6 Sizing of PV and ST panels. (Catalan Institute of Energy, 2011, 2009)

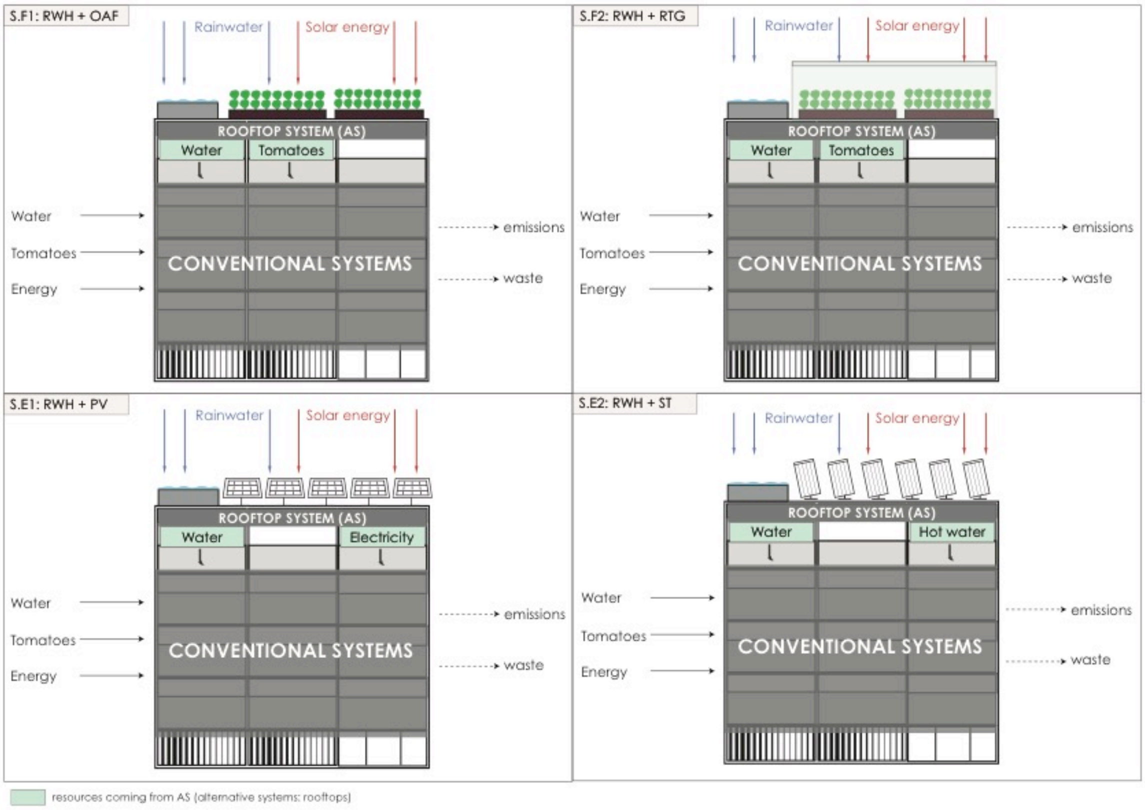
Parameters		Unit	PV systems	ST systems
	SIR= AMR.k	kWh/(m^2·y)	2.01E+03	2.01E+03
Real area (A_P)	A_p = h· cos x^o. w	m^2	1.34E+00	1.91E+00
Total energy per panel (E)	E = SIR · ŋ· A_p	kWh/(panel·y)	4.01E+02	1.46E+03
Distance between modules (Sm)	Sm = k_2 · h· w	m^2	3.91E+00	5.58E+00
Number of panels	Potential surface / (A_p + Sm)		105	73
Total energy	E· number of panels	kWh/y	4.21E+04	1.07E+05
PV panels efficiency (ŋ): 14.9% / ST panels efficiency (ŋ): 38% Tilt angle: 35° (k: 1.208) k_2 : 2.39 / Potential surface: 550 m^2				3.84E+05 MJ/y
SIR: Solar incident radiation, AMR: Annual mean radiation, k: correction factor, h: height, w: width, k_2: correction factor (panel shadows), y: year. PV: photovoltaic. ST: solar thermal.				

Layout and diagram of the different proposed scenarios at the building scale

The four scenarios proposed follow the same pattern (Appendix 1.7). The water tank is placed in the shorter part of the L shape of the building and the rest of systems are distributed along the longest part of the building. Other options can be underground water tank or last floor water tank (Angrill et al., 2016).



Appendix 1.7 Distribution of the different systems on the rooftop of the prototype building in each scenario. RWH: rainwater harvesting; OAF: open-air farming; RTG: greenhouse; PV: photovoltaic; ST: solar thermal



Appendix 1.8 Alternative and conventional systems of each scenario in the reference building. RWH: rainwater harvesting; OAF: open-air farming; RTG: greenhouse; PV: photovoltaic; ST: solar thermal

Step 3: Environmental assessment of implementing the Roof Mosaic approach in the reference building

Life cycle inventory (LCI)

Rainwater Harvesting (RWH)

Appendix 1.9 displays the life cycle inventory of the RWH per 1 m^3 of water, including the structural reinforcement and transportation.

Appendix 1.9 Inventory data of RWH (Angrill et al., 2012b)

Rainwater harvesting system	Life cycle stages		Part	Data (per 1m^3)	
Storage	Construction	Production	Tank	Concrete 20-25MPa (kg)	2.70E+00
				Reinforcing steel frame (kg)	2.00E-02
				Waterproof sheet (kg)	3.00E-02
				Brick wall (kg)	6.80E-02
				Lining mortar (kg)	8.20E-03
			Structural reinforcement	Reinforcing steel frame (kg)	3.30E-03
				Concrete 20-25MPa (kg)	3.50E-01
		Transport	Materials to site	Truck 7.5-16t (tkm); 30 km	9.60E-02
Distribution		Production	Pipe	PP-copolymer (kg)	4.10E-03
		Transport	Materials to site	Van<3.5t (tkm);30 km	1.20E-04

Rooftop greenhouse (RTG)

Appendix 1.10 compiles all the inventory data per 1 m^2 of RTG, including greenhouse structure, auxiliary equipment, transportation and inputs.

Appendix 1.10 Inventory data of RTG (Sanyé-Mengual et al., 2015b)

Life cycle stages		Input	Unit	Per 1m^2
Construction	Production	Greenhouse structure		
		Steel (100% recycled)	kg	8.36E-01
		Concrete 20-25MPa	kg	2.12E-01
		LDPE	kg	7.80E-02
		Polycarbonate	kg	1.60E-01
		Polyester	kg	7.80E-03
		Aluminum	kg	7.80E-03
		Machinery use	kWh	4.00E-04
	Transport	Transoceanic freight ship	tkm	1.61E-01
		Lorry 35-40t EURO5	tkm	1.30E+00
	Production	Auxiliary equipment		
		LDPE	kg	2.30E-02
		Polystyrene	kg	2.60E-02
		HDPE	kg	9.40E-03
		PVC	kg	4.40E-03
		Steel (100% recycled)	kg	5.00E-04
		Expanded perlite	kg	6.20E-01
	Transport	Van, <3.5t	tkm	1.32E-01
Use/maintenance		Inputs consumption		
		Water	m^3	7.97E-01
		Electricity	kWh	1.08E+00
		Fertilizer (N)	g	9.76E+02
		Fertilizer (P_2O_5)	g	6.18E+01
		Fertilizer (K_2O)	g	1.91E+01
		Pesticides	g	4.00E+00

Solar thermal collectors (ST)

Appendix 1.11 shows the inventory data of ST systems for one solar collector, including all the analyzed phases. It was assumed that ST collectors are produced in Spain and road transport was considered.

Appendix 1.11 Inventory data of ST system (Carnevale et al., 2014)

Life cycle stages		Input	Unit	Data (per 1 solar collector)
Construction	Production	Absorbing collector		
		Copper	kg	8.2E+00
		Thermal fluid	kg	9.0E-01
		Epoxy dust	kg	3.0E-01
		Copper	kg	4.6E-01
		HDPE	kg	8.7E-01
		Brass	kg	4.0E-02
		PVC	kg	1.0E-02
		Welding rod	kg	1.0E-01
		Glazing insulation		
		Glass	kg	1.1E+01
		Rigid PUR	kg	4.2E+00
		Flexible PUR	kg	1.0E-01
		Casing		
		Aluminum	kg	4.0E+00
		Stainless steel	kg	6.1E+00
		Galvanized steel	kg	3.4E+01
		Support		
		Galvanized steel	kg	2.7E+01
		Stainless steel	kg	5.0E-01
		Storage water tank		
		Galvanized steel	kg	5.0E+01
		Stainless steel	kg	2.1E+01
		Copper	kg	3.8E+00

		Brass	kg	1.0E-01
		Magnesium	kg	2.0E-01
		Rigid PUR	kg	4.8E+00
		Thermal fluid	kg	5.4E+00
		Epoxy dust	kg	7.0E-01
		Welding rod	kg	2.0E-01
		Energy consumption		
		Absorbing Collector	kWh	1.9E+01
		Support	kWh	2.7E+00
		Water tank	kWh	3.1E+01
	Transport	Lorry	tkm	4.4E+01
Use/maintenance		Energy Consumption For Installation		
		Electricity	kWh	1.5E-01
		Thermal fluid	kg	1.3E+01
		Substitution parts		
		PVC	kg	2.0E-02
		Magnesium	kg	4.0E-01

Open-air farming (OAF)

Appendix 1.12 displays the life cycle inventory of OAF system per m^2 of rooftop, including all the analyzed phases. Auxiliary equipment is locally sourced (< 50 km), except for the substrate, i.e., perlite, which is imported from Almeria (Spain) (800 km). All crops are pesticide-free.

Appendix 1.12 Inventory data of OAF system. (Sanyé-Mengual, 2015)

Life cycle stages		Input	Material	Unit	Data (per 1m^2)	lifespan
Construction	Production	Structure				
		Waterproof	Geotextile	kg	1.20E-02	10
		Growing system				
		Tray	Expanded polystyrene (EPS)	kg	1.45E-01	3
		Perlite	Expanded perlite	kg	2.09E+00	3
		Packaging (perlite)	LDPE	kg	3.10E-02	3
		Packaging (tray)	LDPE	kg	2.00E-03	3
		Fertirrigation				
		Drippers	Polypropylene (PP)	kg	1.00E-03	5
		Tube	Polyethylene (HDPE)	kg	2.80E-02	3
		Tube	HDPE	kg	2.40E-02	3
		Supporting stake	PP	kg	2.00E-03	5
		Microtube	Polyvinylchloride (PVC)	kg	3.00E-03	10
		Tank	PVC	kg	3.60E-03	10
		Tubes, connections	PVC	kg	1.60E-02	10
		Timer, injectors	PP	kg	1.30E-02	10
		Manometer	Steel	kg	2.00E-03	10
		Filters, stoppers	HDPE	kg	2.50E-02	3
	Transport	Transport (kgkm)		kgkm	7.50E+01	
Use/maintenance		Inputs consumption				
		Potassium nitrate		kg	3.03E-02	
		Calcium chloride		kg	1.11E-02	
		Calcium nitrate		kg	3.28E-02	
		Phosphate fertilizer		kg	1.68E-02	
		Potassium chloride		kg	2.61E-02	

Photovoltaic modules (PV)

Appendix 1.13 displays the life cycle inventory of PV system per m^2 of surface, including all the analyzed phases. It was assumed that PV panels are manufactured in Spain and road transport was considered. Maintenance is not needed.

Appendix 1.13 Inventory data of PV system

Life cycle stages		Input	Unit	Data	Source
Construction	Production	Photovoltaic panel	unit	3.13E-01	Ecoinvent database
		Support structure			
		Steel	kg	9.93E-01	UAB installation
		Aluminum	kg	1.12E+00	UAB installation
		Concrete block	kg	1.67E+01	UAB installation
		BOS (Balance-of-system)			UAB installation
		Copper	kg	1.13E-01	UAB installation
		PVC	kg	8.85E-02	UAB installation
		Inverter	unit	1.48E-02	Ecoinvent database
		Installation			
		Electricity	kWh	1.80E-02	UAB installation
	Transport	Transport	tkm	4.99E+00	Distance from company
UAB: Autonomous University of Barcelona					

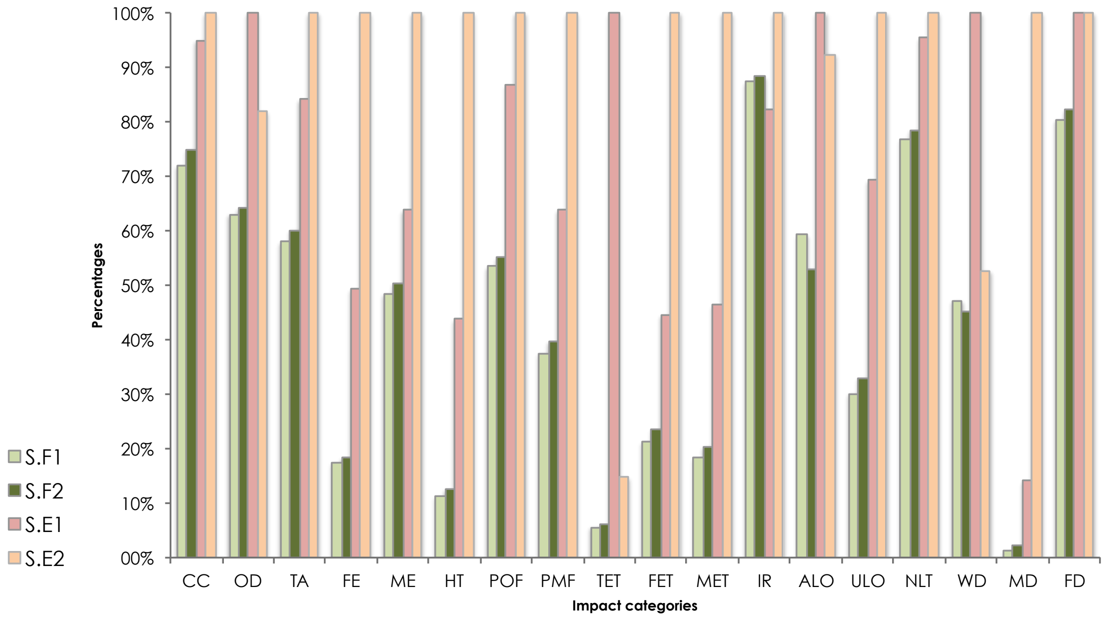
Conventional Systems

All data for conventional systems were retrieved from ecoinvent. Tomatoes refer to global average data, tap water and natural gas to European average data, and electricity corresponds to the Spanish electricity mix.

RESULTS SECTION

Environmental burdens of the FEW at the reference building scale

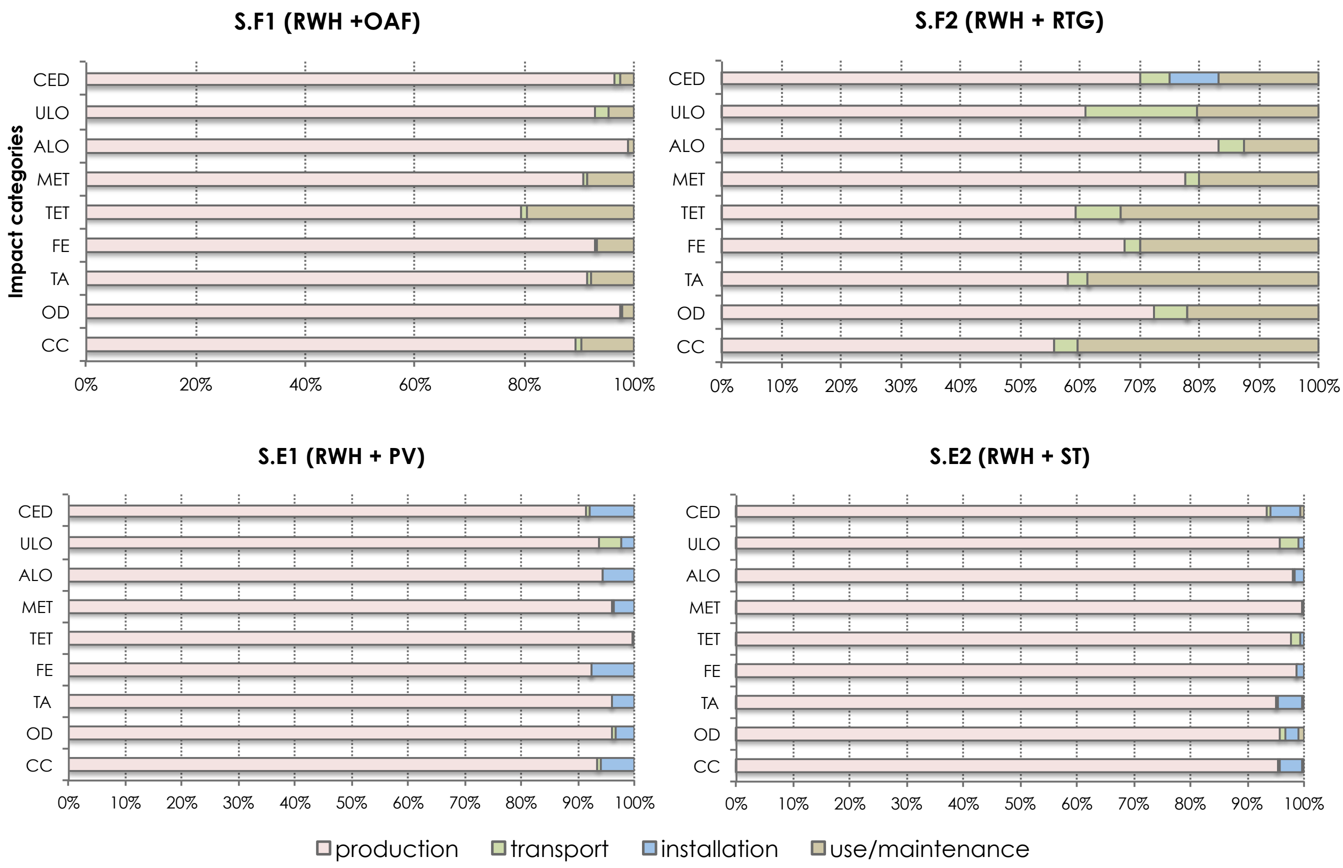
Appendix 1.14 illustrates the environmental impacts of the alternative and conventional systems in each scenario. S.E1 and S.E2 obtained the maximum values, and S.F1 and S.F2 obtained the major number of more favorable indicators, i.e., lowest impact.



Appendix 1.14 Environmental impacts of the four scenarios of the alternative production on the rooftop and conventional systems. Climate change (CC, kg CO_2 eq), ozone depletion (OD, kg CFC-11 eq), terrestrial acidification (TA, kg SO_2 eq), freshwater eutrophication (FE, kg P eq), marine eutrophication (ME, kg N eq), human toxicity (HT, kg 1,4-DB eq), photochemical oxidant formation (POF, kg NMVOC), particulate matter formation (PMF, kg PM10 eq), terrestrial ecotoxicity (TET, kg 1,4-DB eq), freshwater ecotoxicity (FET, kg 1,4-DB eq), marine ecotoxicity (MET, kg 1,4-DB eq), ionizing radiation (IR, kBq U235 eq), agricultural land occupation (ALO, m^2 x year), urban land occupation (ULO, m^2 x year), natural land transformation (NLT, m^2), water depletion (WD, m^3), metal depletion (MD, kg Fe eq), fossil depletion (FD, kg oil eq)

Environmental burdens of the different stages of each scenario in alternative production systems

Appendix 1.15 shows the different impact categories of every life cycle stage in the four proposed scenarios, only for alternative systems. The production of materials phase had the highest impacts in all categories.



Appendix 1.15 Environmental burdens of the different stages, construction (divided into production of materials, transport and installation) and use/maintenance, in every scenario of alternative systems. OAF: open-air farming; RWH: rainwater harvesting; RTG: rooftop greenhouse; PV: photovoltaic; ST: solar thermal.

Climate change (CC, kg CO_2 eq), ozone depletion (OD, kg CFC-11 eq), terrestrial acidification (TA, kg SO_2 eq), freshwater eutrophication (FE, kg P eq), terrestrial ecotoxicity (TET, kg 1,4-DB eq), marine ecotoxicity (MET, kg 1,4-DB eq), agricultural land occupation (ALO, m^2 x year), urban

2. Appendix 2. Supporting information for chapter 5

METHODS SECTION

System characterization

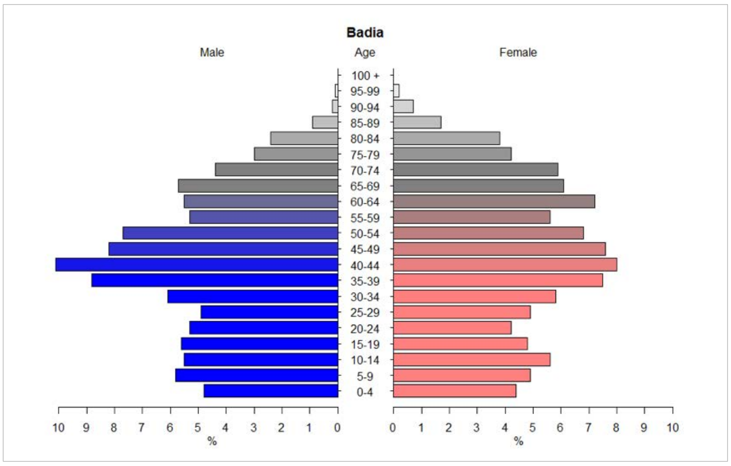
Appendix 2.1 shows the general conditions for the studied housing estate and Appendix 2.2 illustrates the population pyramid of the municipality.

Appendix 2.1 General characteristics of the municipality and roofs, and climatic conditions

General Characteristics[1]	Average municipality consumption	Climatic Conditions[1]	Roofs
Number of families 5,372 (2018)	Vegetables [3] 62.24 kg/inhabitant/year	Average rainfall 574 mm/year	Total m^2 of roofs [4] 66,433
Unemployment rate 17.5% (2018)	Electricity [2] 1127 kWh/inhabitant/year	Average temperature	Inclination [4] <10°
Area 0.92 km^2	Natural gas [2] 5537 MJ/inhabitant/year	Winter 9-12° C	Runoff coefficient [5] 0.9 (concrete) / 0.55 (green roof)
Income per capita 13,800 €/inhabitant/year	Water [2] 48 m^3/inhabitant/year	Summer 23-26 °C	

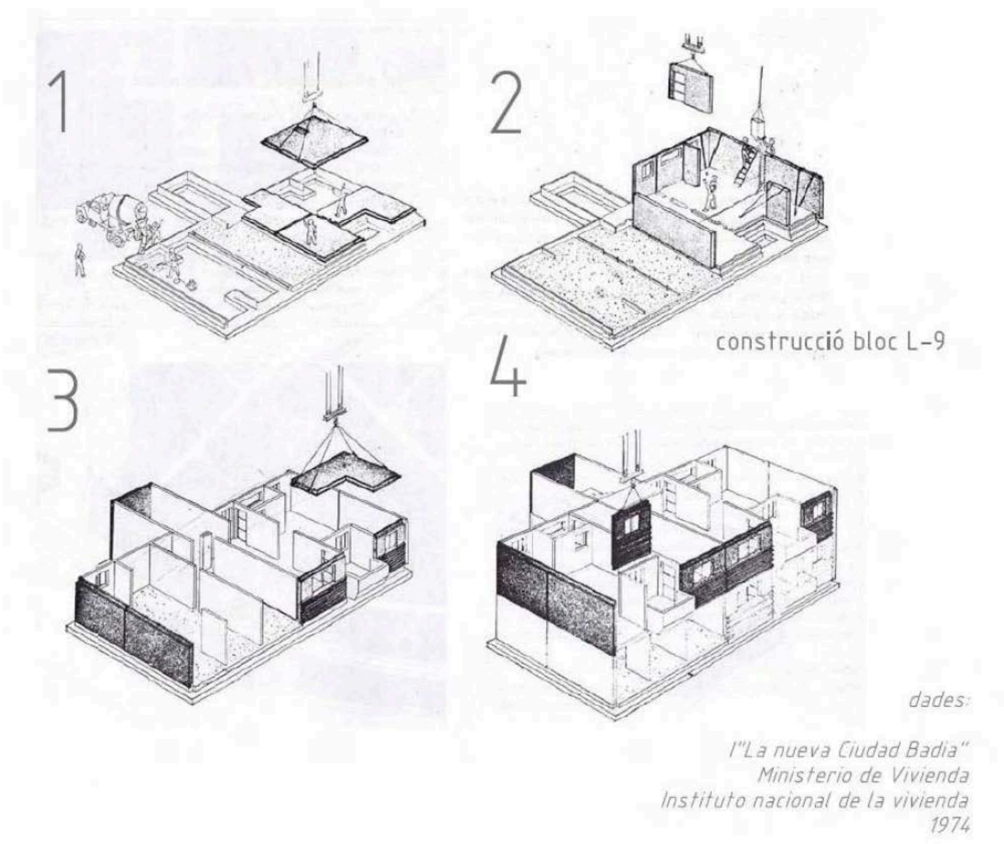
[1] Institut d'Estadística de Catalunya, 2018; [2] Ajuntament de Badia del Vallès, 2019; [3] Consumption pattern survey; [4] airborne LIDAR sensor [5] FLL, 2018

The widest part of the pyramid comprised of the population of 35 to 55 years of age comes from an expansive pyramid of the 1980's related to the baby boomer cohorts. These data stem from general statistics of the municipality.



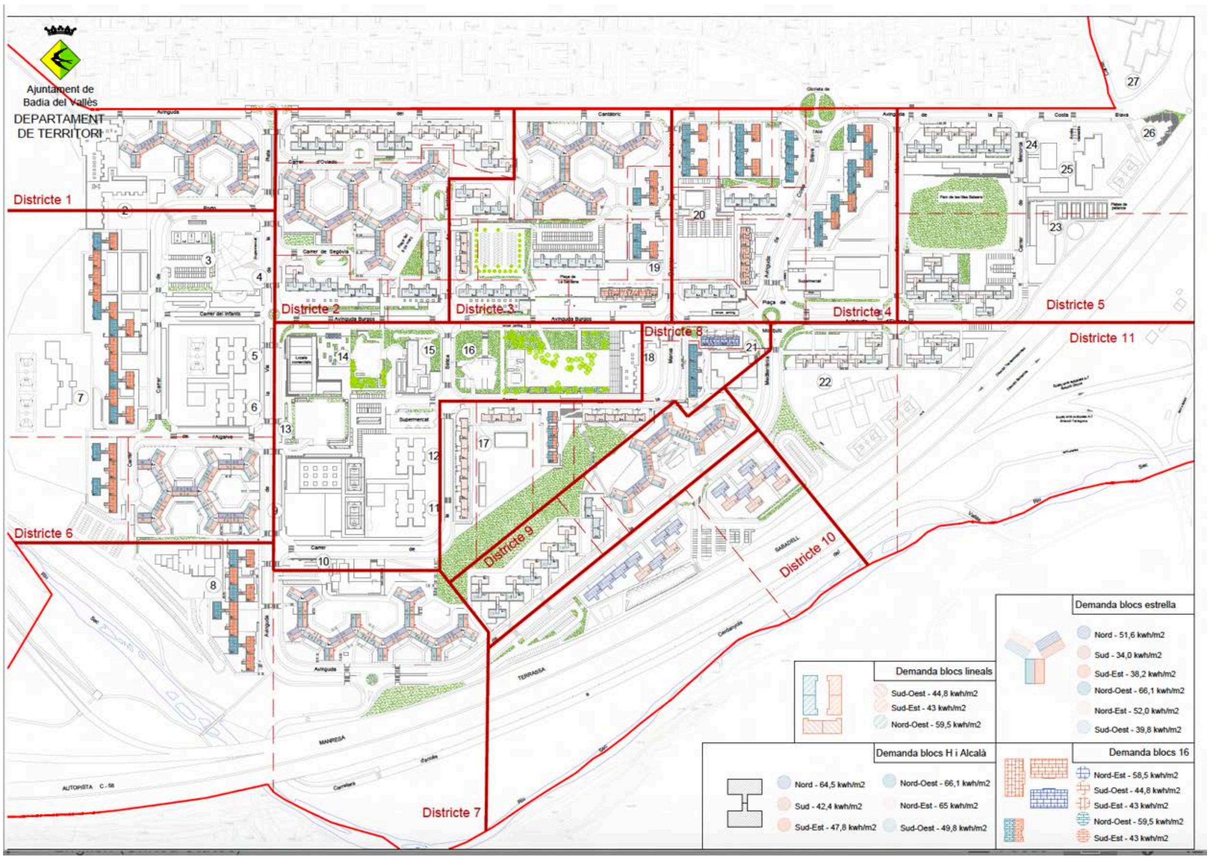
Appendix 2.2 Population pyramid of male and female of the municipality by ages (2018) (Institut d'Estadística de Catalunya, 2018)

Appendix 2.3 shows the construction technique of all the municipality's buildings, named Tracoba. It is a modular construction of prefabricated pieces imported from France.



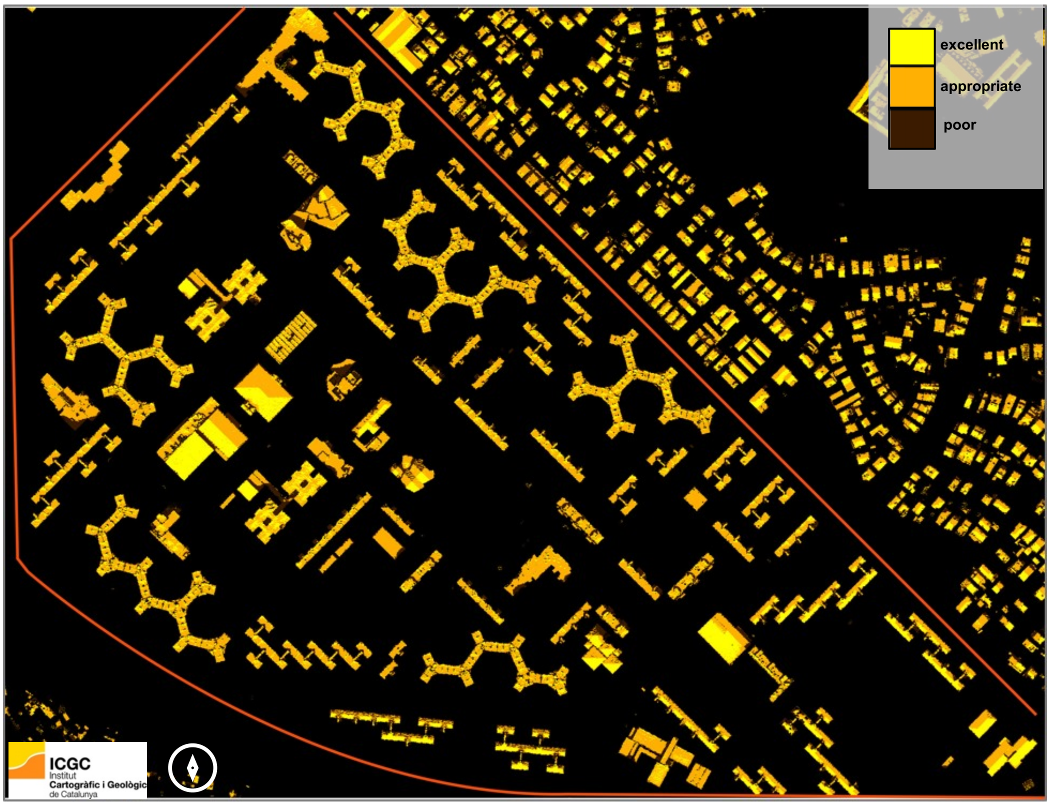
Appendix 2.3 Scheme of the construction technique used in the municipality (1974). Image provided by the city council of the municipality

Appendix 2.4 illustrates the distribution of the municipality and the energy consumption per square meter by type of building. The buildings are in color blue and red, the rest of the buildings with no color are different facilities of the municipality.



Appendix 2.4 Distribution of buildings of the municipality. Alcalà= A buildings; Estrella: B buildings; H= C buildings; Lineal and blocs 16 = D buildings. The layout was provided by the city council of the municipality

Appendix 2.5 illustrates the global solar radiation for the roofs of the municipality. All the roofs show appropriate or excellent conditions for the implementation of agriculture, photovoltaic or solar thermal panels. This was made with an airborne LIDAR sensor, high-density and 0.5 m^2/pixel and roofs' characteristics were validated via Google Earth and in situ in the municipality (Zambrano-Prado et al., 2021a).



Appendix 2.5 Map of the global solar radiation received the roofs of the municipality in one year. Limits: Red color line

Appendix 2.6 illustrates the scales (rows), fund elements (human activity) and the flows (columns) of the area under study, presented as extensive and intensive indicators.

Appendix 2.6 End-use matrix template of the housing estate; kh: kilohour; y: year; g: gram; g: hour; L: liter

END-USE MATRIX		FUND ELEMENTS	EXTENSIVE INDICATORS (FLOW ELEMENTS)				INTENSIVE INDICATORS (FLOW/FUND ELEMENTS)			
		Human Activity (kh/year)	Vegetables (kg/y)	Mechanical (kWh/y)	Thermal (MJ/y)	Water (m3/y)	Vegetables Metabolic Rate (g/h)	Electricity Metabolic Rate (MJ/h)	Heating Metabolic Rate (MJ/h)	Water Metabolic Rate (L/h)
n	HOUSING ESTATE									
n-1	BUILDINGS A									
n-1	BUILDINGS B									
n-1	BUILDINGS C									
n-1	BUILDINGS D									

Consumption pattern survey

The protocol was approved for the Ethics Committee on Animal and Human Experimentation of the Autonomous University of Barcelona (https://www.uab.cat/web/human-research/presentation-1345735629170.html). Code: CEEAH 4639.

The consumption pattern survey aimed to identify the metabolic pattern of the residents. It helped to characterize the residents of the area under study and the actual vegetable necessities of the residents.

It was a face-to-face survey in households using CAPI (Computer Assisted Personal Interview). The computer application was organized for managing the survey. Once the survey was programmed, it was passed on to the technical team, where a verification process was submitted, carrying out a systematic test on fictitious surveys in order to validate the correct functioning of the survey flows. A briefing was carried out with the interviewers who carried out the surveys before starting the study.

Data sheet:

- Universe: population over 18 years old and residents of Badia del Vallès.
- Sample: a sample of 100 buildings was randomly selected.
- Distribution of the sample and selection of individuals: random multi-stage, stratified by 4 types of building.
- Final sample of 433 households. The maximum error per final sample unit (household) was ± 4.54% for the whole sample, for a confidence level of 95.5% (2 sigmas) and under the assumption of maximum indeterminacy (where P = Q = 50%).
- Duration of the survey: 10-15 minutes.
- Supervision, recording, debugging, and validation of the database: Opinometre Institute.

The survey was taken place between May and June 2019. The online survey can be checked at https://docs.google.com/forms/d/e/1FAIpQLSdcyaL5a8VjWBz_Ss43qnXuIS1doInxuqOhgetKZ-JubNNpgw/viewform). This survey asked for the next topics:

- Gender, age group, working status, family unit, household incomes and building where residents live.
- Electricity, natural gas, water and vegetable expenses (€).
- Vegetable consumption (kg of product): Potatoes, tomatoes, onions, cabbage, cucumbers, green beans, peppers, lettuce, eggplants, carrots, zucchini.

Subsequently, the outcomes were analyzed and integrated in the different parts of the study.

Participatory Roof Mosaic scenario design

Design Protocol for the participatory process

The protocol was approved for the Ethics Committee on Animal and Human Experimentation of the Autonomous University of Barcelona (https://www.uab.cat/web/human-research/presentation-1345735629170.html). Code: CEEAH 4520

Objectives of the participatory process:

1. Begin a Trust Building process with participants.

2. Understand local concerns to codesign the future scenarios for the municipality.

3. Make a first approximation.

4. Know the perception of Badia del Vallès residents on the use of their roofs to implement different systems.

Methodology to be used:

The World Café method (Brown, 2005) is designed to create a welcoming and enjoyable environment with the intention of connecting multiple ideas and perspectives on a topic by participating in various small group conversation rounds. This method is particularly useful when you want to make sure you are exploring a topic from different perspectives, to make sure everyone in the room is contributing to the conversation.

What is needed?

A World Café session can last from 90 minutes to 3 hours, depending on the number of rounds of conversation desired. The preparation requirements are:

Appendix 2.7 General description of the requirements of the methodology

DESCRIPTION	
Preparation time of participants	No need previous preparation
Facilitator preparation time	3-4 hours
Facilitator preparation work	Prepare the activity: o Preparation of questions on the topic o Room preparation
Required materials (provided by the UAB)	o Different tables and chairs o 3-4 papers or a large paper (flip chart paper) on each able o Coloured markers, etc.

Step 1: Preparation

- o Develop the questions. The questions are related to the future of the municipality and the implementation of new systems on the roofs of the municipality's buildings.

It began with two general questions:

1. How do you see the future of the municipality? What worries you? (10 minutes) (Contextualization question).

2. How are roofs used in your buildings? Would you like to use it to implement some type of system (agriculture, energy, rainwater harvesting, social use, etc.)? Could it be a solution to the problems you discussed earlier? (15 minutes).

3. What problems / limitations do you see being placed: (20 minutes)

a. Food systems: Open-air farming/Greenhouses

b. Energy systems: Photovoltaic panels for electricity / Solar panels for hot water, others.

c. Rainwater systems: Collect water and/or storage tanks

d. would you use them for anything else?

4. What benefits do you think there will be in the implementation of these systems? (20 minutes)

a. Food systems: Open-air farming /Greenhouses

b. Energy systems: Photovoltaic panels for electricity/Solar panels for hot water, others.

c. Rainwater systems: Collect water and / or storage tanks

5. Would you combine the different systems or not? What combination would you make? (10 minutes)

6. Why would you use food, water and energy for your own consumption? To give to social organizations? To market, although the Metropolitan General Plan-76 of Barcelona does not allow it to? (10 minutes)

7. Who do you think could manage them, yourself, a manager of the city council, social organizations? (10 minutes)

- Invite participants. They were all residents of Badia del Vallès, over the age of 18, a maximum of 20-25 people, were convened through the city council and the association of neighbors of Badia del Vallès. A first meeting was held with them to explain the workshop and we agreed on the one hand, to make some posters to call the municipality of the participants and on the other hand, the workshop was explained in one of the meetings that had the association of neighbors of Badia del Vallès with the residents to be able to recruit the necessary participants.

- Identify and invite selected participants to act as "hosts". Each table must have a host/facilitator that will be on the same table throughout the process. The role of the host/facilitator is to welcome the participants, provide an overview of the question being discussed and summarize the key ideas shared by previous guests at the table. At the end of the exercise, the host is responsible for sharing a summary of the discussion points on their table.

- Prepare the discussion tables and the place where it will take place so that all the participants feel comfortable. With 4/5 people for each table and a projector to display the questions and the time spent on each question.

Step 2: Participatory process

It was held at the public school of Badia del Vallès on 12/12/2018.

1. At the beginning of the workshop, the information of the participants was taken, and they were given a pseudonym, they carried a sticker with their pseudonym during the workshop and the data were taken with these pseudonyms to preserve their anonymity.

2. Introduction (10 minutes)

Explanation of the World Café method and the topic to be discussed.

3. Small discussion groups (4/5 people).

Questions 1,5,6 and 7 were 10 minutes of discussion, question 2 was 15 minutes, and questions 3 and 4 of 20 minutes of discussion.

There was a host for each table, who was in charge of taking note of the discussion. Opinions were saved anonymously. The host took notes in an orderly fashion on large sheets (flip chart sheets), which were the material that was then be used to analyze and save the different discussions.

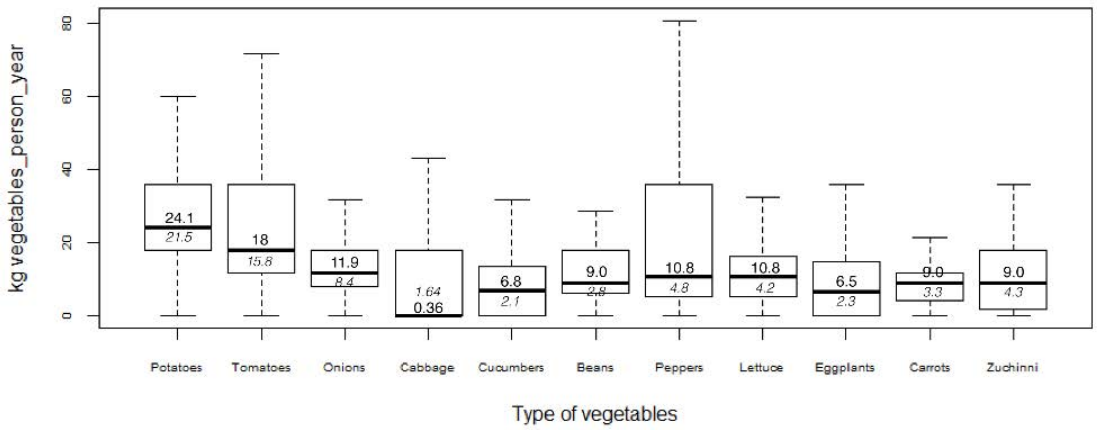
At the end of each round of conversations, all participants are asked except the host to move on to the new tables. The host must remain at their table to share information from the first conversation with the next group.

At the end of the session, there is a summary of the ideas discussed throughout the session.

The answers to each question of each discussion group were saved and then passed to a document to be recorded in order to come up with the key concepts of the discussion.

RESULTS SECTION

Appendix 2.8 depicts the results for the vegetable consumption in the municipality from the performed consumption pattern survey. As can be seen from the boxplot, the general tendency is that the consumption of the vegetables is higher in the studied housing estate than the average in Catalonia (Generalitat de Catalunya, 2018). Similar quantities can be found in both in potatoes, tomatoes and onions. On the contrary, there are substantial variations in the consumption of the rest of the vegetables. Alternatively, food consumption data per capita are given by statistical offices for regions, as is the case of Spain for autonomous communities (MAPAMA, 2020).



Appendix 2.8 Vegetable consumption in the municipality compared to Catalonia average vegetables consumption (italics). In bold the results from the housing estates

Appendix 2.9 illustrates part of the results of the survey carried out in the municipality. The rest of the results are open-access and can be checked in the following link: https://doi.org/10.5565/ddd.uab.cat/226152

Appendix 2.9 *Part of the results of the consumption pattern survey in the housing estate and buildings A, B, C and D.*

Age	A	B	C	D	Municipality
18-34	12.8%	16.2%	7.9%	22.5%	16%
35-54	27.4%	32.3%	28.9%	30.6%	30%
55-64	40.2%	35.3%	47.4%	41.4%	39%
65- +	19.7%	16.2%	15.8%	5.4%	14%
Household incomes	**A**	**B**	**C**	**D**	**Municipality**
No incomes	0.9%	0.0%	4.8%	0.0%	2.1%
Up to 683 €	0.9%	11.7%	4.2%	7.9%	5.5%
684 to 1.029 €	12.0%	43.2%	19.8%	13.2%	23.1%
1.030 to 1.659 €	30.8%	34.2%	25.7%	15.8%	28.4%
1.660 to 2.199 €	12.0%	5.4%	16.2%	23.7%	12.9%
More than 2.200 €	3.4%	3.6%	12.0%	31.6%	9.2%
DK (don't know)	6.8%	0.9%	6.6%	5.3%	5.1%
Not available	33.3%	0.9%	10.8%	2.6%	13.6%
Electricity expenses (monthly)	**A**	**B**	**C**	**D**	**Municipality**
none	3.4%	0.0%	0.0%	0.0%	0.9%
1 to 39 €	13.7%	14.4%	12.0%	5.3%	11.3%
40 to 59 €	26.5%	32.4%	33.5%	31.6%	31.0%
60 to 79€	29.1%	30.6%	24.0%	31.6%	28.8%
80 € and more	16.2%	20.7%	17.4%	26.3%	20.2%
not have	0.9%	0.9%	1.8%	0.0%	0.9%
DK	10.3%	0.9%	11.4%	5.3%	6.9%
Average (€)	61.5	61.9	61.3	66.4	62.8
Water expenses (quarterly)	**A**	**B**	**C**	**D**	**Municipality**
none	3.4%	0.6%	0.0%	0.0%	1.0%
1 to 39 €	5.1%	3.6%	5.3%	6.3%	5.1%
40 to 59 €	25.6%	22.8%	34.2%	36.9%	29.9%
60 to 79€	36.8%	41.3%	50.0%	31.5%	39.9%
80 € and more	16.2%	19.2%	7.9%	21.6%	16.2%
not have	0.9%	0.0%	0.0%	0.0%	0.2%
DK	12.0%	12.6%	2.6%	3.6%	7.7%
Average (€)	62.4	68.0	63.6	64.0	64.5
Vegetables expenses (monthly)	**A**	**B**	**C**	**D**	**Municipality**
up to 20 €	9.4%	6.0%	7.9%	17.1%	10.1%
21 to 40 €	23.1%	22.2%	23.7%	26.1%	23.8%
41 to 60 €	15.4%	21.6%	13.2%	19.8%	17.5%
61 to 80 €	18.8%	24.0%	26.3%	11.7%	20.2%
81 to 150 €	15.4%	16.8%	18.4%	14.4%	16.2%
150 €	12.8%	8.4%	7.9%	10.8%	10.0%
DK	5.1%	1.2%	2.6%	0.0%	2.2%
Average (€)	81.9	77.9	79.6	67.9	76.8

The rest of the raw data can be found in this link:
https://onlinelibrary.wiley.com/action/downloadSupplement?doi=10.1111%2Fjiec.13114&file=jiec13114-sup-0002-SuppMat1.xlsx

3. Appendix 3. Supporting information for chapter 6

METHODS SECTION

Section 6.2 of the manuscript

Stage 1: Codesign of scenarios and indicators

The protocol was approved for the Ethics Committee on Animal and Human Experimentation of the Autonomous University of Barcelona (https://www.uab.cat/web/human-research/presentation-1345735629170.html); Reference number: CEEAH 4520. Same as Chapter 5.

Stage 2: Participatory decision-making

The protocol was approved for the Ethics Committee on Animal and Human Experimentation of the Autonomous University of Barcelona (https://www.uab.cat/web/human-research/presentation-1345735629170.html)

Objectives of the participatory process:

1. Present the results of the survey carried out in the municipality, showing the current situation, including the consumption patterns and the expenses of the households.

Methodology to be used:

What is needed?

Step 1: Preparation

- Collect all the information to show in the posters.
- Draw the different scenarios to have a visual future of the municipality.
- Design the posters to show in the exhibit (Appendix 3.2).
- Print the posters.

After that and online and short questionnaire (https://docs.google.com/forms/d/e/1FAIpQLSepoPptehmltBNNHRToShSGGCetksv31ssXcE2ub5AciqIkUQ/viewform) was design in order to collect the sex of the participant, age group, type of stakeholders and the preferences on future scenarios for their roofs.

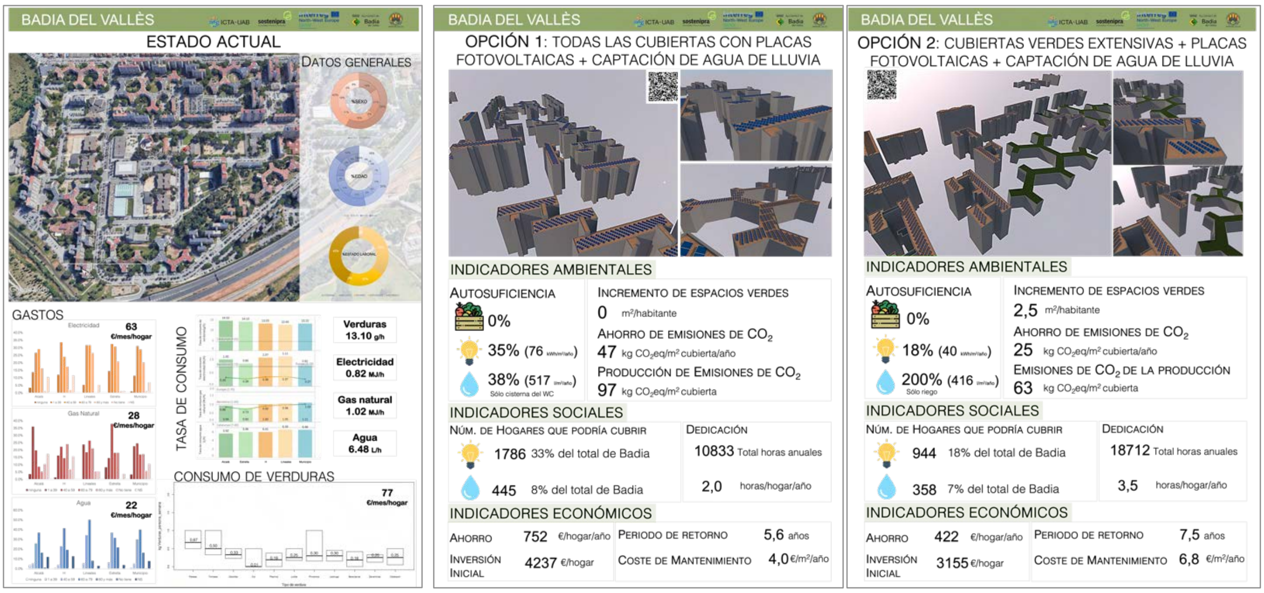
Step 2: Participatory process

It was held at the library of Badia del Vallès on 03/09/2020 (see Appendix 3.1).

Appendix 3.1 Second participatory process with the residents

1. It was a first presentation of the results of the survey and all the data of the municipality and the explanation of every scenario and all the related indicators. The participants could vote online with QR code or in paper (Appendix 3.2).
2. The exhibit lasted for twelve days in the library of the municipality for achieving the maximum of votes possible. They could vote online or in hard-copy.

After this period of time, the data was analysed and presented.



Appendix 3.2 illustrates the posters of the exhibit carried out in the municipality with five different scenarios and the current situation.

4. Appendix 4. Supporting information for chapter 7

METHODS SECTION

Data processing

Rooftop slope

The steepness of the DSM was calculated using the slope tool from Spatial Analyst Toolbox of ArcGIS. The range of slope values in the output raster is 0° for horizontal roofs to 90° for vertical ones.

The rooftop slope determines and limits the photovoltaic (PV) panel tilt angle. The performance of PV panels is strongly affected by the panel position with respect to the sun and the electricity generation is generally highest when the sun incidence angle is perpendicular to the panel. The optimal PV tilt varies depending on the latitude. In this study, simulations were made using the PVGIS interactive tool (European Comission, 2021) designed to obtain the performance of the grid-connected PV. The optimum tilt angle for a PV panel, oriented to the south at Cerdanyola city is 38°.

Rooftop azimuth

The optimal location and orientation of the modules will be the one that allows maximizing energy captured by the system throughout the year. The electrical energy produced by the PV panels depends on the module orientation: the back azimuth (α), the PV tilt (β) and the latitude (ϕ). Azimuth indicates the direction in which the slope faces. The aspect tool of the Spatial Analyst Toolbox was used to obtain aspect values from DSM. It is measured clockwise in degrees from 0° (due north) to 360° (again due north), coming full circle. The resulting aspect layer was converted into "back azimuth" values subtracting 180 degrees to each cell. Thus, 0 ° represents the south position, taking positive values to the west and negative values to the east.

The percentage of energy losses due to module orientation and position have been calculated according to the Basic Document HE5 of the Spanish Technical Building Code, following equations 7.2 and 7.3:

If $15° < \beta < 90°$

$$\text{Losses (\%)} = 100\times[1.2\times10^{-4}\times(\beta-\phi+10)^2+3.5\times10^{-5}\times\alpha^2] \quad \text{(Eq.7.2)}$$

If $\beta \leq 15°$

$$\text{Losses (\%)} = 100\times[1.2\times10^{-4}\times(\beta-\phi+10)^2] \quad \text{(Eq.7.3)}$$

where α is the back azimuth in degrees, β is the tilt in degrees, and φ is the latitude.

Both equations were applied using a conditional map algebra expression with the Raster Calculator tool in ArcGIS. A cell of the rooftop is considered suitable for PV system installation if the energy losses due to the tilt and azimuth are less than 20%. Therefore, the result was reclassified into a binary raster. Those cells with a value greater than 20% were assigned a value of 0 (unsuitable roof), and those cells with a value equal to or below 20% were assigned a value of 1 (suitable roof).

Shading analysis

Shading can significantly reduce power generation. Seasonal variation in shading was captured by running the simulation for four days, March 21, June 21, September 21, and December 21 using the Hillshade tool in ArcGIS with the DSM as input surface. This tool requires the altitude and azimuth of the sun as an input data, obtained hourly for the year 2019 from SoDa (Solar Energy Services for Professionals) web service. The shading analysis was conducted every hour from 10 AM to 14 PM, corresponding with the main sunshine hours.

The cells suitable for PV installation will be those that are not affected by shadows in the central four hours of the day throughout the four selected days. The output raster ranges between 0, when the stronger the shadow is, to 255 when the weaker the shadow is. To exclude excessively shaded roof cells, the Shading_raster was reclassified into a binary raster, where all cells with values ranging from 1 to 255 were assigned a value of 1 (no shading; suitable), whereas the rest of the cells remained unchanged, with a value of 0 (shading, or no sun; unsuitable).

Solar radiation

The ArcGIS Solar Radiation (ASR) was used to perform insolation analysis for the whole year with monthly intervals for calculations. The output raster represents the total amount of incoming solar insolation (direct and diffuse) calculated for each pixel of the DSM in watt-hours per square meter (Wh/m^2).

Estimation of the supply potential

Energy: Photovoltaic

In order to obtain the real area for the PV panels (APV), it should be considered two reduction coefficients of the available area depending on the roof slope. For sloped roofs (>15°), some free space should be accounted for maintenance and access, so a reduction coefficient of 0.95 has been applied. For flat roofs (≤15°), the reduction coefficient is 0.43 for PV panels mounted at optimal tilt angle (**β**=38°) to avoid self-shading.

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 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).

Cadastral data

The Dirección General del Catastro not only includes geometric information on each of the buildings and plots that form the built environment but also includes alphanumeric information on the uses and functions of these buildings and plots (Dirección General del Catastro, 2013). This information allows linking to each roof geometry its corresponding: associated plot surface, gross floor area, residential gross floor areas and the number of dwellings. In addition, given that the plot surfaces are an administrative and not a physical reality (Fleischmann et al., 2020), a voronoi geometry has been assigned to obtain the floor area associated with each roof, calculated from each centroid of the roof.

RESULTS SECTION

The following tables depict the results from the survey.

Appendix 4.1 Results of the survey related to work status and household occupation

		TOTAL	originary fabrics	housing estates	single-family housing
Working status	working with contract	451	162	151	138
	working without contract	20	8	9	3
	Record of Temporary Employment Regulation due to pandemic	9	4	3	2
	unemployed	117	45	40	32
	student	25	5	11	9
	retiree	461	171	128	162
	do not know/ do not answer	17	5	8	4
Number of household members	One	127	51	41	35
	Two	425	151	121	153
	Three	270	107	92	71
	Four	225	69	81	75
	More than four	53	22	15	16
Average household members		2.69	2.66	2.75	2.68

Appendix 4.2 Results of the survey related to residents' preferences to implement on their roofs

		TOTAL	originary fabrics	housing estates	single-family housing
WOULD YOU IMPLEMENT LOCAL FOOD FARMING ON THE ROOF OF YOUR BUILDING? OPEN-AIR FARMING	quite unlikely	29.5%	29.3%	29.4%	30.0%
	unlikely	43.8%	42.5%	46.0%	43.1%
	neutral	0.5%	0.8%	0.3%	0.3%
	likely	18.9%	20.8%	16.6%	19.1%
	very likely	2.3%	3.0%	1.7%	2.0%
	do not know/do not answer	5.0%	3.8%	6.0%	5.4%
WOULD YOU IMPLEMENT LOCAL FOOD FARMING ON THE ROOF OF YOUR BUILDING? ROOFTOP GREENHOUSES	quite unlikely	29.3%	27.0%	29.4%	31.7%
	unlikely	45.5%	45.5%	46.6%	44.6%
	neutral	0.6%	0.8%	0.0%	1.1%
	likely	18.4%	21.5%	16.9%	16.3%
	very likely	1.5%	2.3%	1.1%	1.1%
	do not know/do not answer	4.6%	3.0%	6.0%	5.1%
WOULD YOU IMPLEMENT A GREEN ROOF ON YOUR BUILDING?	quite unlikely	24.2%	21.8%	25.7%	25.4%
	unlikely	44.5%	44.0%	48.0%	41.4%
	neutral	0.5%	0.5%	0.0%	1.1%
	likely	22.4%	26.8%	17.4%	22.3%
	very likely	2.7%	3.0%	1.7%	3.4%
	do not know/do not answer	5.7%	4.0%	7.1%	6.3%
WOULD YOU IMPLEMENT SOLAR PANELS ON THE ROOF OF YOUR BUILDING?	quite unlikely	4.5%	6.0%	3.4%	4.0%
	unlikely	12.5%	15.5%	11.1%	10.3%
	neutral	0.8%	1.0%	0.6%	0.9%
	likely	56.2%	50.0%	62.0%	57.4%
	very likely	20.5%	22.5%	16.9%	22.0%
	do not know/do not answer	5.5%	5.0%	6.0%	5.4%
WOULD YOU IMPLEMENT RAINWATER HARVESTING ON THE ROOF OF YOUR BUILDING?	quite unlikely	16.1%	18.8%	15.7%	13.4%
	unlikely	31.8%	33.3%	36.0%	26.0%
	neutral	1.5%	2.0%	0.9%	1.4%
	likely	34.9%	31.5%	32.6%	41.1%
	very likely	7.7%	7.5%	5.4%	10.3%
	do not know/do not answer	8.0%	7.0%	9.4%	7.7%
WOULD YOU IMPLEMENT A COMBINATIONOF ALL OF THEM ON THE ROOF OF YOUR BUILDING?	quite unlikely	19.9%	20.0%	20.0%	19.7%
	unlikely	30.3%	30.0%	31.4%	29.4%
	neutral	4.8%	5.8%	4.3%	4.3%
	likely	25.3%	25.5%	23.4%	26.9%
	very likely	1.9%	2.0%	1.4%	2.3%
	do not know/do not answer	17.8%	16.8%	19.4%	17.4%

Appendix 4.3 Household vegetable consumption survey results

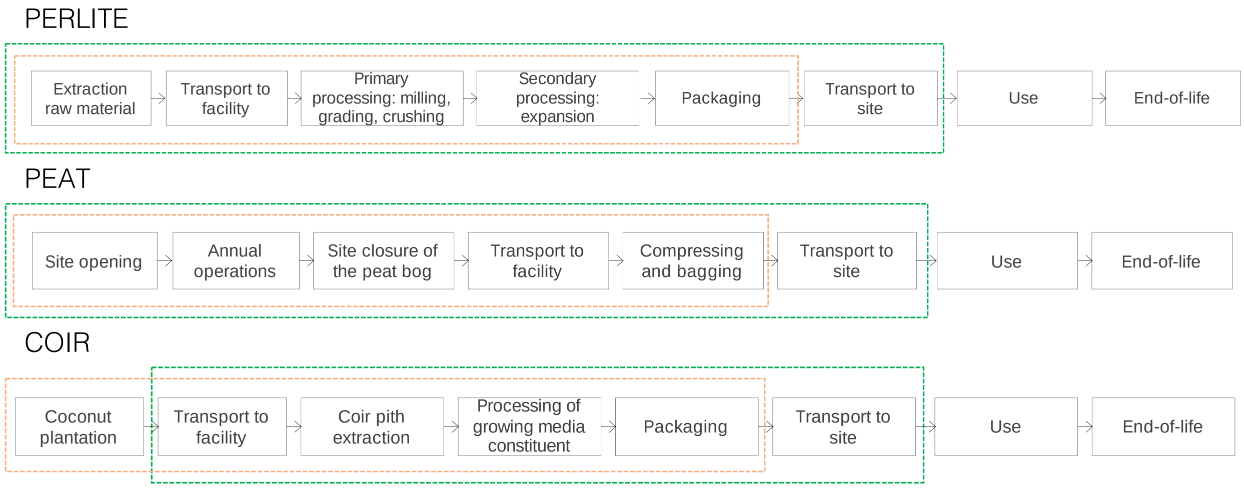
HOUSEHOLD VEGETABLE CONSUMPTION		TOTAL	originary fabrics	housing estates	single-family housing
POTATOES	do not consume	49	21	12	16
	consume	1010	367	323	320
	do not know	41	12	15	14
AVERAGE NUMBER OF KILOGRAMS OF POTATOES CONSUMED BY THE HOUSEHOLD PER WEEK		1.79	1.90	1.82	1.65
TOMATOES	do not consume	32	8	14	10
	consume	1036	378	328	330
	do not know	32	14	8	10
AVERAGE NUMBER OF KILOGRAMS OF TOMATOES CONSUMED BY THE HOUSEHOLD PER WEEK		1.39	1.38	1.38	1.42
ONIONS	do not consume	25	10	5	10
	consume	1034	369	337	328
	do not know	41	21	8	12
AVERAGE NUMBER OF KILOGRAMS OF ONIONS CONSUMED BY THE HOUSEHOLD PER WEEK		1.10	1.13	1.10	1.08
LETTUCES, SPINACHS, ETC	do not consume	83	31	33	19
	consume	995	363	307	325
	do not know	22	6	10	6
AVERAGE NUMBER OF KILOGRAMS OF LETTUCES, SPINACHS.. CONSUMED BY THE HOUSEHOLD PER WEEK		1.12	0.97	1.18	1.25
PEPPERS	do not consume	119	48	34	37
	consume	949	341	307	301
	do not know	32	11	9	12
AVERAGE NUMBER OF KILOGRAMS OF PEPPERS CONSUMED BY THE HOUSEHOLD PER WEEK		1.01	0.99	0.98	1.06
CARROTS	do not consume	113	44	41	28
	consume	956	343	300	313
	do not know	31	13	9	9
AVERAGE NUMBER OF KILOGRAMS OF CARROTS CONSUMED BY THE HOUSEHOLD PER WEEK		0.84	0.80	0.85	0.88
ZUCCHINIS	do not consume	153	55	51	47
	consume	917	332	291	294
	do not know	30	13	8	9
AVERAGE NUMBER OF KILOGRAMS OF ZUCCHINIS CONSUMED BY THE HOUSEHOLD PER WEEK		1.08	1.10	1.13	1.03

GREEN BEANS	do not consume	89	30	31	28
	consume	979	358	308	313
	do not know	32	12	11	9
AVERAGE NUMBER OF KILOGRAMS OF GREEN BEANS CONSUMED BY THE HOUSEHOLD PER WEEK		0.86	0.87	0.85	0.85

5. Appendix 5. Supporting information for chapter 8

METHODS SECTION

Appendix 5.1 illustrates the system boundaries of each growing media constituent.



Appendix 5.1 System boundaries of each growing media constituent. Green line is the system boundary in E- LCA and orange line is the system boundary in S-LCA

Appendix 5.2 depicts the inventory for the three different growing media by functional unit (1m^3 of growing medium).

Appendix 5.2 Inventory for each growing media constituent

Functional unit: 1 m³						
Stage	**Materials / processes**	**Lifetime**	**Value/year**	**Unit**	**Ecoinvent 3.5**	**Comments**
extraction/production	perlite	1	1	m³	Expanded perlite {RoW}| production | Cut-off	Bulk density: 0.3 g/cm³- Electricity mix & water from Turkey
transportation	lorry		1841	tkm	Transport, freight, lorry 16-32 metric ton, EURO5 {RoW}| transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off	3682 km from Turkey
extraction/production	peat	1	1	m³	Peat moss {RoW}| peat moss production, horticultural use | Cut-off	Bulk density: 0.084 g/cm³ Electricity mix & water from Germany
transportation	lorry		130	tkm	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off	1543 km from Germany
extraction/production	coir	1	1	m³	LK: Coconut fibre (type bristle, brown) (GaBi database) - Cut-off	Bulkdensity: 0.065 g/cm³ It includes the soaking of the coconut husks, the washing of the coir and the puffering of coir. There is not coconut production allocation. The coir by-product is burden-free
transportation	ship		1078	tkm	Transport, transoceanic freight ship/OCE	16583 km from Philippines

Appendix 5.3 shows the parameters used for the sensitivity analysis in each growing medium.

Appendix 5.3 Sensitivity analysis changing energy needed for the perlite production and the transportation for each growing medium

Stage	Materials / processes	Ecoinvent 3.5
extraction/production	perlite	Electricity, medium voltage {FR}| market for | Cut-off Heat, district or industrial, other than natural gas {FR}| treatment of coal gas, in power plant | Cut-off
transportation	lorry	Transport, freight, lorry 16-32 metric ton, EURO6 {RoW}| transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off
transportation	Peat -lorry	Transport, freight, lorry 16-32 metric ton, EURO6 {RER}| transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off
transportation	Coir- ship	Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off

SURVEY- Site-specific data for perlite, peat and coir

The design protocol was approved by the Ethics Committee on Animal and Human Experimentation of the Autonomous University of Barcelona (https://www.uab.cat/web/human-research/presentation-1345735629170.html (number 4808). The steps for the questionnaire were as follows:

1. Objectives of the survey
    a. Analyse the growing media sector from a social perspective.
    b. Obtain social indicators through different companies and organisations that represent the sector.
2. Methodology to be used:

An online survey was conducted. Different organisations and institutions helped us to identify the companies in this sector.

What is needed?

- Survey in pdf format to be able to fill it out.

- Participation of companies and bodies in this sector.

The preparation requirements were:

Step 1: Prepare the survey

- Develop the questions. There were some first general questions, and then more specific ones, divided into three major topics:

- Health and Safety
- Human Rights
- Labour Rights and Decent Work

The survey was sent by email to each supplier/organisation in pdf format and was returned to us by email with the documentation provided.

Step 2: Contact companies and organisations

Different organisations such as the Perlite Institute and the Garden Industry Association (IVG) helped us contact most companies in the sector and the bodies responsible for the growing media sector. To try to reach as many participants as possible.

The questionnaire was sent to 22 companies and organisations and was replied to by 3 different companies.

Step 3: Data analysis

After receiving all the answers leaving a reasonable time, the corresponding data were analysed in order to extract social indicators to know the current state of the growing media sector.

RESULTS SECTION

Appendix 5.4 displays the outcomes of all the midpoints in every phase of the life cycle assessment.

Appendix 5.4 Outcomes of the life cycle assessment performed

Impact category	Unit	Perlite	Lorry (Turkey)	Peat moss	Lorry (Germany)	Coir	Ship (Phillipines)
Global Warming	kg CO2 eq	3.04E+02	3.19E+02	1.27E+02	2.15E+01	2.02E+01	1.16E+01
Stratospheric Ozone Depletion	kg CFC11 eq	1.50E-04	2.36E-04	3.24E-06	1.57E-05	1.55E-06	4.74E-06
Ionizing Radiation	kBq Co-60 ec	4.84E+00	5.32E+00	6.42E-01	4.14E-01	5.76E-04	1.37E+00
Ozone Formation, HH	kg NOx eq	1.11E+00	1.03E+00	1.91E-02	6.81E-02	4.01E-02	1.56E-01
Fine Particulate Matter Formation	kg PM2.5 eq	8.84E-01	3.61E-01	5.76E-03	2.38E-02	2.61E-02	6.42E-02
Ozone Formation, TE	kg NOx eq	1.28E+00	1.06E+00	1.94E-02	6.99E-02	4.02E-02	1.58E-01
Terrestrial Acidification	kg SO2 eq	1.20E+00	8.10E-01	1.46E-02	5.38E-02	7.02E-02	2.04E-01
Freshwater Eutrophication	kg P eq	2.14E-01	2.68E-02	4.92E-03	1.73E-03	2.30E-03	2.01E-03
Marine Eutrophication	kg N eq	1.45E-02	2.17E-03	3.20E-04	1.35E-04	9.23E-03	1.38E-04
Terrestrial Ecotoxicity	kg 1,4-DCB	3.49E+02	5.47E+03	2.63E+01	2.82E+02	9.69E+00	2.23E+01
Freshwater Ecotoxicity	kg 1,4-DCB	1.02E+01	7.37E+00	3.92E-01	3.26E-01	7.02E-04	6.30E-02
Marine Ecotoxicity	kg 1,4-DCB	1.38E+01	1.26E+01	5.12E-01	5.83E-01	8.39E-03	1.13E-01
Human Carcinogenic Toxicity	kg 1,4-DCB	1.61E+01	6.89E+00	3.10E-01	4.38E-01	6.01E-03	2.98E-01
Human Non-carcinogenic Toxicity	kg 1,4-DCB	3.20E+02	2.33E+02	7.16E+00	1.24E+01	9.10E-01	1.91E+00
Land Use	m2a crop eq	8.60E+00	1.29E+01	2.96E+01	8.92E-01	5.47E-02	4.96E-02
Mineral Resource Scarcity	kg Cu eq	3.20E+00	1.19E+00	1.67E-02	4.11E-02	2.37E-03	1.42E-02
Fossil Resource Scarcity	kg oil eq	1.31E+02	1.08E+02	3.43E+01	7.50E+00	2.40E+00	3.60E+00
Water Consumption	m3	2.66E+00	4.62E-01	1.22E-03	2.66E-03	2.28E-02	1.31E+00

Appendix 5.5 displays the outcomes of the sensitivity analysis.

Appendix 5.5 Outcomes of the sensitivity analysis performed

Impact category	Unit	Perlite	Lorry (Turkey)	Peat moss	Lorry (Germany)	Coir	Ship (Phillipines)
Global Warming	kg CO2 eq	2.41E+02	3.12E+02	1.27E+02	2.11E+01	2.02E+01	1.01E+01
Stratospheric Ozone Depletion	kg CFC11 eq	1.27E-04	2.22E-04	3.24E-06	1.53E-05	1.55E-06	7.11E-06
Ionizing Radiation	kBq Co-60 eq	1.54E+01	5.27E+00	6.42E-01	4.94E-01	5.76E-04	1.05E-01
Ozone Formation, HH	kg NOx eq	8.99E-01	5.12E-01	1.91E-02	3.36E-02	4.01E-02	2.11E-01
Fine Particulate Matter Formation	kg PM2.5 eq	6.36E-01	2.96E-01	5.76E-03	1.90E-02	2.61E-02	6.73E-02
Ozone Formation, TE	kg NOx eq	1.03E+00	5.39E-01	1.94E-02	3.55E-02	4.02E-02	2.12E-01
Terrestrial Acidification	kg SO2 eq	9.51E-01	6.18E-01	1.46E-02	4.01E-02	7.02E-02	2.09E-01
Freshwater Eutrophication	kg P eq	1.58E-01	2.67E-02	4.92E-03	1.58E-03	2.30E-03	3.98E-04
Marine Eutrophication	kg N eq	1.11E-02	2.16E-03	3.20E-04	1.35E-04	9.23E-03	3.83E-05
Terrestrial Ecotoxicity	kg 1,4-DCB	3.23E+02	5.46E+03	2.63E+01	3.84E+02	9.69E+00	2.70E+01
Freshwater Ecotoxicity	kg 1,4-DCB	8.33E+00	7.35E+00	3.92E-01	5.03E-01	7.02E-04	1.08E-01
Marine Ecotoxicity	kg 1,4-DCB	1.12E+01	1.25E+01	5.12E-01	8.64E-01	8.39E-03	1.55E-01
Human Carcinogenic Toxicity	kg 1,4-DCB	1.24E+01	6.86E+00	3.10E-01	4.50E-01	6.01E-03	2.28E-01
Human Non-carcinogenic Toxicity	kg 1,4-DCB	2.50E+02	2.33E+02	7.16E+00	1.57E+01	9.10E-01	1.81E+00
Land Use	m2a crop eq	7.43E+00	1.29E+01	2.96E+01	9.17E-01	5.47E-02	3.60E-02
Mineral Resource Scarcity	kg Cu eq	3.18E+00	1.19E+00	1.67E-02	8.21E-02	2.37E-03	2.56E-02
Fossil Resource Scarcity	kg oil eq	1.03E+02	1.06E+02	3.43E+01	7.28E+00	2.40E+00	2.99E+00
Water Consumption	m3	2.44E+00	4.60E-01	1.22E-03	1.52E-03	2.28E-02	6.08E-04

Appendix 5.6 shows the sources of the outcomes from country and sector specific indicators

Appendix 5.6 Sources of the three growing media for table 4 of the manuscript. NA: not available

SOURCES	Perlite (Turkey)		Peat (Germany)		Coir (Philippines)	
	country specific	sector specific	country specific	sector specific	country specific	sector specific
LOCAL COMMUNITY						
Community Infrastructure						
Drinking water access	Progress on drinking water, sanitation and hygiene. 2017 update and SDG baselines. (World Health Organization & UNICEF, 2017)		Progress on drinking water, sanitation and hygiene. 2017 update and SDG baselines. (World Health Organization & UNICEF, 2017)		Progress on drinking water, sanitation and hygiene. 2017 update and SDG baselines. (World Health Organization & UNICEF, 2017)	
Children out of school	The UNESCO Institute for Statistics (UIS) (UNESCO, 2017)		The UNESCO Institute for Statistics (UIS) (UNESCO, 2017)		The UNESCO Institute for Statistics (UIS) (UNESCO, 2017)	
Hospital beds per 1,000 population	Hospital beds per 1,000 population (Our World Data, 2017)		Hospital beds per 1,000 population (Our World Data, 2017)		Hospital beds per 1,000 population (Our World Data, 2017)	
SOCIETY						
Community Infrastructure (Contribution to Economic Development)						
Employment share (Positive impacts)	Perlite sector vs mineral sector, (TURKSTAT, 2017)		Socio-economic impact of the peat and growing media industry on horticulture in the EU, 2008, pp 62 (Schmilewski, 2008)		Agriculture sector, 2018 (Phillipine Statistics Authority, 2020a)	
	Perlite sector vs total Turkey				Coconut sector vs agricultural sector, 2018 (Phillipine Statistics Authority, 2020a)	
GDP contribution (Positive impacts)	Mining sector, (TURKSTAT, 2017)		Socio-economic impact of the peat and growing media industry on horticulture in the EU, 2008, pp 64 (Schmilewski, 2008)		Coconut sector, Philippine Statistics Authority, 2019 (Phillipine Statistics Authority, 2020a)	
					Agriculture sector, 2019 (Phillipine Statistics Authority, 2020a)	
National poverty line (% population)	National poverty line (% population) (2017) (The World Bank, 2020)		Poverty rate OECD (2017) (OECD, 2020a)		National poverty line (% population) (2015) (The World Bank, 2020)	
Human Rights						
Gender inequality	Social Institutions and Gender Index (SIGI) index (2019) (OECD, 2020b)		SIGI index (2019) (OECD, 2020b)		SIGI index (2019)(OECD, 2020b)	
Child labour	Child labour force, 2012 (TURKSTAT, 2012)		Child labour in Europe (International Labour Organization (ILO), 2017)		Child labour (2011) (Phillipine Statistics Authority, 2020b)	
WORKER						
Health & Safety						
Fatal injuries (number)	Number of injuries- (perlite) (Social Security Institution Turkey, 2018)		Heavy ceramics (2019) (VBG Ihre gesetzliche Unfallversicherung, 2019)		Agriculture sector, 2015 (Phillipine Statistics Authority, 2020a)	
Incidence rate: Occupational Injuries per 1,000 Employed Persons	(%) Number of injuries/number of employed (Social Security Institution Turkey, 2018)					

Non-fatal injuries (number)	Number of injuries- (Social Security Institution Turkey, 2018)		
Incidence rate: Occupational Injuries per 1,000 Employed Persons	(%) Number of injuries/number of employed (Social Security Institution Turkey, 2018)		
Human Rights			
Gender inequality (woman representation in labour force)	(%) of women - (mining) (Social Security Institution Turkey, 2018)	NA	Agriculture sector, 2019 (Phillipine Statistics Authority, 2020a)
Labour Rights & Decent Work			
Child labour	Industry sector (TURKSTAT, 2012)	Not a topic, regulated by SA8000	Agriculture sector, 2018 (Phillipine Statistics Authority, 2020a)
Excessive work hours	Total week hours (mining sector)/ total national average (ILO, 2019)	Socio-economic impact of the peat and growing media industry on horticulture in the EU (Schmilewski, 2008). Experts in the sector, Dr. Arne B. Hückstädt	total week hours / total national average - Agriculture sector, 2018 (Phillipine Statistics Authority, 2020a)
	Monthly average gross wage (mining) (2014) (Social Security Institution Turkey, 2018)	Monthly average gross wage (peat) (Experts in the sector, Dr. Arne B. Hückstädt)	Monthly average gross wage (coconut farms) 2018 (Philippine Coconut Authority, 2018)
Fair salary		Monthly average gross wage (mining) / Monthly average gross wage Turkey (Social Security Institution Turkey, 2018)	Monthly average gross wage (coconut farms) / Monthly average gross wage Philippines (Philippine Coconut Authority, 2018)

Appendix 5.7 Primary data from responses of the three companies about the social performance of the company and growing media

Questions			Answers		
			Perlite company	Peat company	Coir company
General questions					
	General data		20.000 tones of perlite annual capacity- Worldwide exports	One of the most important peat companies in Germany- more than 100 years of history	Global leader in coir-based products. They process more than 40.000 coconuts/year- Worldwide exports
1	Have you heard about the method and/or guidelines Social Life Cycle Assessment (SLCA)?		No	Yes	No
2	Has your organisation carried out any social impact assessment or have any of these reports?		Sustainability Report Social Report Corporate Social Responsibility Report	Sustainability Report (provide link)	None of them
3	What are from your perspective the positive social impacts the growing media sector offers to the workers and the community (e.g. creating jobs, fair wage, new infrastructures, etc.)?		-Job creation - Fair wage - Support more females workers and managers	- Local and regional labor market. - Positive impact on the neighbouring economy	- Creating jobs - Using coconut waste streams - Fair wages - Creating income from using waste
4	Does your organization have any ongoing social or community development initiatives or infrastructures (roads, community centers, schools, etc.) in local communities where the growing media are extracted?		No	Yes. The promotion of nature conservation,restoration and protection. The promotion of science, research and of education	- Provide local jobs - Paint schools and temples - Provide student bursaries
Specific questions					
5	What do you consider as relevant social concerns in the growing media sector?				
		Labor rights:			
		Low wages	No relevant	relevant	No relevant
		Forced labour	No relevant	relevant	No relevant
		Child labor	No relevant	relevant	No relevant
		Excessive working time	No relevant	relevant	No relevant
		No freedom of Association, etc.	No relevant	relevant	No relevant
		Risk to migrant workers	No relevant	relevant	No relevant
		Human Rights:			
		Unequal female representation workforce	No relevant	relevant	No relevant
		High conflicts	No relevant	relevant	No relevant
		Health & safety:			
		Fatal injuries	No relevant	relevant	No relevant
		Non-fatal injuries	No relevant	relevant	relevant
		Occupational Cancer risks	No relevant	relevant	No relevant
		Noise exposure	No relevant	relevant	No relevant
		Dust exposure	No relevant	relevant	relevant
		Hazardous materials exposure	No relevant	relevant	No relevant
		Others:	-	-	-
Health & Safety					
6	Does the growing media sector have a Code of conduct that addresses worker rights, health and safety?		Yes	Yes. All the workers' rights of our staff are fulfilled through rigorous compliance of the law and pertinent legal provisions of the countries where our peat extraction centers and substrates manufacturing are located. Strict compliance with the SA-8000 Certification	Yes. Follow ILO Rules: ISO 9000 Production
7	Does the growing media sector control the noise, dust and hazardous material exposures in the companies and their surroundings?		Yes	Yes. This is internal information that cannot be provided	No
	Do they measure these parameters? If yes, if it is possible, please provide measurement reports.		Not available	Yes. This is internal information that cannot be provided	No
8	Does the growing media sector keep any statistics on:				
		a.Fatal and non-fatal injuries	No	Yes. This is internal information that cannot be provided	Not available
		b.Total Staff Hours Worked per week (included overtime)	No	Yes. This is internal information that cannot be provided	40 h/week
Labor Rights and Decent work					
9	Does the growing media sector have Human Resource Policies in place in the following areas?				
		a.Non-discrimination and equal opportunity in employment	Yes	Our organisation fulfils the law to guarantee equal treatment and opportunities between women and men in employment and occupation	Yes
		b.Working hours and overtime	Yes, 9-18h	Our organisation complies with the national legal provisions regarding working hours, collective bargaining agreements and job titles	Yes
		c.Freedom for workers to form or join trade unions	Yes	Our organisation complies with the law of freedom association	Yes
10	What is the sector's monthly minimum wage based on the standard working month excluding the overtime? Is it higher or lower compared to the country sector specific wage?		Legal minimum wage published by government. It is overall higher than other sectors	This is internal information that cannot be provided. In any case it complies the minimum inter-professional wage	Equal to country sector specific wage
11	Out of the total how many (%) are locals and how many (%) are migrants		100% local	20% are migrants- 80 % locals	100% local
12	Out of the total how many (%) are women?		30 % women	33% are women	70% women
13	What is the gender distribution (%) in management positions?		25% women-75% men-	100% men	50 % women- 50% men

The answers to the questionnaires of the three companies are displayed in Appendix 5.7

Appendix 5.8 depicts the answers related to the questions asked to companies about the current growing media in the market.

Appendix 5.8 Answers of the companies related to suitable growing media for urban rooftop farming. NC: No answer

Survey						
What do you think are the best growing media to grow vegetables on roofs?	Growing Media					
	Perlite company		Peat company		Coir company	
	Rank		Rank		Rank	
	1	**Perlite**	4	**Perlite**	4	**Perlite**
		Pros It is an excellent growing media for aeration (43% air rate)		**Pros** It is the lightest growing media and can be reused a few times		**Pros** Lightweight, good air fill porosity, uniformity
		Cons Poor water holding capacity (50%)		**Cons** It is considered a professional growing media and it demands specific installations (watering, fertilising, etc.) to grow vegetables in it. After using it, it becomes a waste difficult to recycle		**Cons** Too light. Blows away and dries out too easily. Messy
		Peat	1	**Peat**	3	**Peat**
		Pros Optimum water holding capacity (14%)		**Pros** It is the cheapest and less technical growing media.		**Pros** Water-holding capacity, CEC
		Cons bad aeration (air rate 14%)		**Cons** Large amounts of CO2 are liberated while peat extraction.		**Cons** Non sustainable input, low pH. Becomes hydrophobic when dry. Shrinkage
		Coir	2	**Coir**	1	**Coir**
		Pros NC		**Pros** Easy to use, eco-friendly		**Pros** Lightweight and long lasting, water-holding capacity, CEC, Rewets Easily
		Cons NC		**Cons** Compared with peat has a higher bulk density, so it weights more		**Cons** Will require blending with Perlite/Pumice/Scoria
		Rock wool	5	**Rock wool**	5	**Rock wool**
		Pros NC		**Pros** In amateur cultures NONE		**Pros** Lightweight, Consistency
		Cons NC		**Cons** The same as perlite		**Cons** Structure breaks down easily and will not last past 2 years
		Bark	3	**Bark**	2	**Bark**
		Pros NC		**Pros** It can be considered, in Spain, a national/regional product, so improves the CO2 balance		**Pros** Good quality can last long
		Cons NC		**Cons** Bark has to be correctly composted, otherwise cultures will have growing problems.		**Cons** Availability. Nitrogen drawdown
	others:	NC		In our opinion blends of peat, coconut fibre, perlite, and other materials are much more suitable for rooftops cultures than raw materials themselves		Terracotta tile waste mixed with coir

6. Appendix 6. GROOF GUIDELINES FOR SOCIAL ASSESSMENT

Social aspects

By Susana Toboso (UAB) – Xavier Gabarrell (UAB) – Gara Villalba (UAB) – Cristina Madrid (UAB) -Ramiro Gonzalez (UAB)

Aim: Providing a general framework of the elements to take into consideration for a social analysis and also a step-by-step methodology for different types of rooftop greenhouse *implementations.*

See all details in this website:

https://groof-project.wixsite.com/groof/prep-phase-social-aspects

Introduction

Urban roof greenhouse projects need an exhaustive analysis including environmental (refer to chapter II.6), technical (refer to chapter II.2 of the guidelines) and economic (refer to chapter II.3) aspects. This chapter is focused on social analysis.

As part of the InterReg NWE GROOF project (Greenhouses to reduce CO_2 on Roofs), we offer the methodology to socially analyze your rooftop greenhouse:

- Providing a general framework of the elements to take into consideration for a social analysis of this type of project.
- Providing a step-by-step methodology for different types of rooftop greenhouse implementations.

General Framework

Urban agriculture is normally associated with crops at ground level and is appreciated for its benefits to the community. Indeed, it is mainly perceived as a socially-oriented activity, including recreational and leisure projects that are highly valued by citizens. However, for-profit urban agriculture initiatives are less accepted, since food security is currently not perceived as a problem in most European cities (this point is changing faster due to the COVID19, and it relies on a recreational goal that is currently prioritized over commercial vision. Among consumers, products from urban agriculture are expected to be fresher and to have higher quality because the harvest is performed just before consumption. Consumers prefer urban agriculture products to conventional rural products if the former fulfil specific criteria: high quality, regionality, organic production, or the inclusion of additional social benefits.

There are different considerations to examine when a novel project is implemented. The greenhouses on rooftops are quite a new system in cities, and the social part should be considered too. Different studies have analyzed the social acceptance of these projects among stakeholders using different quantitative and qualitative methods (Sanyé-Mengual et al., 2016; Specht et al., 2016; Specht and Sanyé-Mengual, 2017). Other studies have examined the barriers (refer to chapter II.2) and opportunities of their implementation on urban roofs (Zambrano et al., 2020) (Cerón-Palma et al., 2012), concluding that there still are some barriers related to reaching into an agreement among neighbors, and organizational issues to overcome.

Therefore, we propose a reflection in two directions at the beginning of the project. The first one is the consumption pattern of the residents' urban area where the rooftop greenhouse (RTG) is proposed. The consumption pattern can vary considerably depending on the employment status, age group, or type of family structure (Toboso-Chavero et al., 2020). A survey about consumption patterns is an option to be considered before the project's development. The second one is to consider the residents' opinions for the successful implementation of the RTG. Many studies advocate for different forms of participation involving the general public and stakeholders in the decision-making that affects their daily life (Bidwell, 2016; Walker and Devine-Wright, 2008). Different opinions are important and collect this diversity can help to overcome possible issues. This can be done using participatory processes or questionnaires.

General purpose

The general purpose is to recommend a methodology to carry out a social analysis in this type of project. With the purpose of their social acceptance and the long-term success of these novel projects.

Phase a) (Pre-project phase: before)

Operational steps of the social analysis

A wide range of methodologies are used in the social analysis, split between quantitative and qualitative. In this case, we advise performing different methodologies in different stages of the life cycle of the project. See Appendix 6.3 for a better understanding.

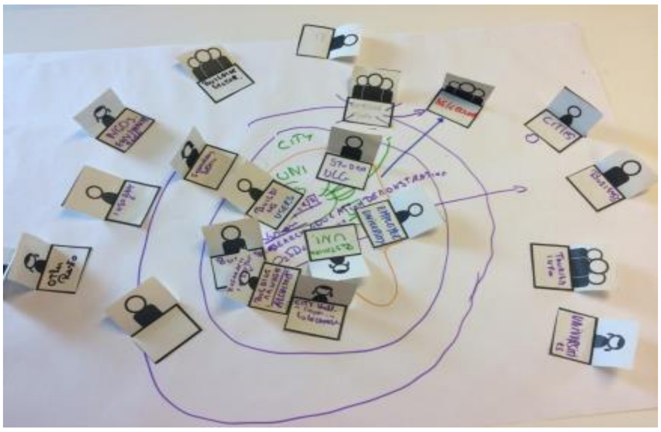
HOW?

a) Stakeholder mapping

The project leader organizes a workshop to develop, with its team, a matrix of the key stakeholders that are important in the pilot process: potential users of the RTGs, current users & owners of the building, local authorities, neighborhood.

How to do the mapping workshop (Appendix 6.1):

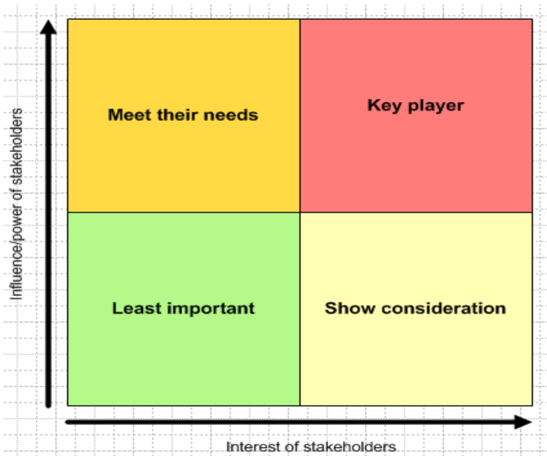
1. In the centre, write the vision of the pilot. Why is this pilot created? The Why that Andreas Gaber talked about (see this video of Simon Sinek).
2. Identify all the stakeholders of your project.
3. Identify all the existing flows between your project and the stakeholders. Identify all the existing flows between the stakeholders. Are they monetary, information (one sense flow) or collaboration (double sense) flows?
4. Be creative and think about all the new flows you could create between all these entities.



Appendix 6.1 Stakeholder mapping

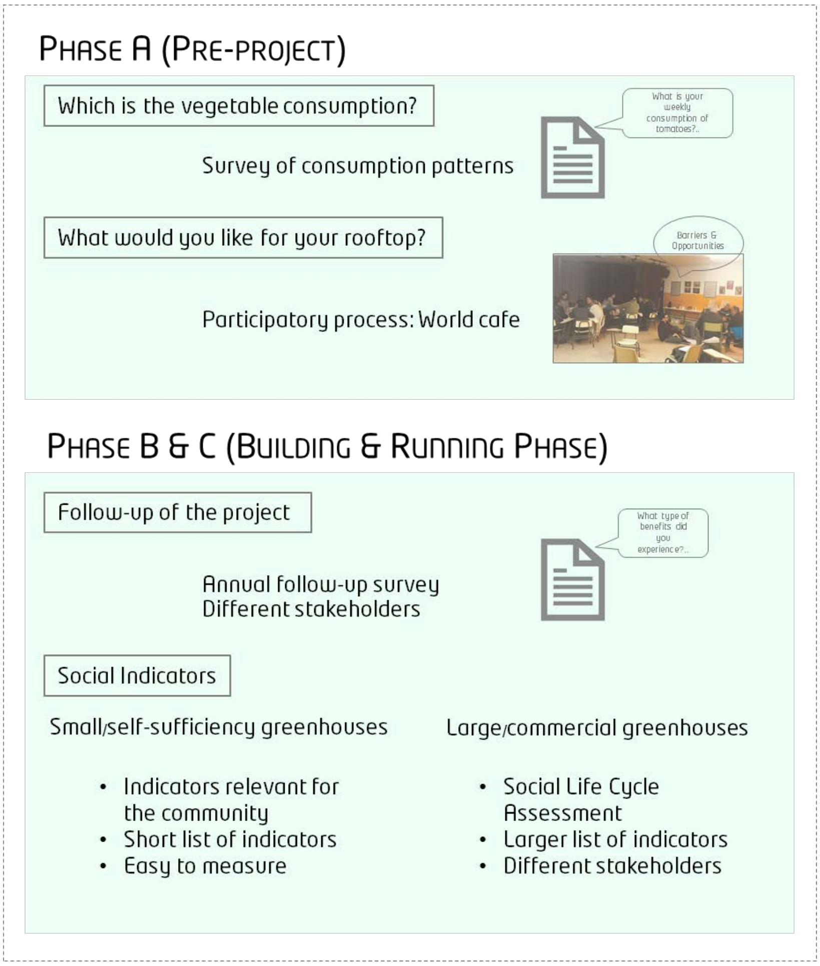
Build a matrix

List all stakeholders in a table. Identify their needs and their power and select who are the key players; these key players will be the most important targets of your communication/actions (Appendix 6.2).



Appendix 6.2 Matrix example

b) Consumption pattern questionnaire to characterise the metabolic pattern of the residents. It will help to know the actual food necessities of the residents and plan the crops accordingly in the greenhouse. (See an example here: https://doi.org/10.5565/ddd.uab.cat/226152)



Appendix 6.3 Diagram of the different parts of the social analysis

Participatory process to analyze the suitability to implement an RTG. Stakeholder participation to agree on what they want, what it will be successful, in this case we propose the World Cafe method. The World Cafe is based on a constructive conversation related to critical questions and collaborative learning. It assumes that the knowledge that we are searching is already present (Fouché and Light, 2011). This method is particularly useful when you want to make sure you are exploring a topic from different perspectives, to make sure everyone in the room is contributing to the conversation. It is a method constituted of several rounds of small-group conversation (4-5 people) to know different opinions and perspectives in a relaxed environment. It can be employed for capturing the residents' preferences on implementing food, energy, or/and water and greenhouse systems on the roofs. The essence of the methodology lies in conveying those ideas are being shared, without competing, simply by exploring possibilities (Brown, 2005).

There are different main steps to carry out this methodology:

- Invite the participants to take part in a face-to-face session.

- Organize a working team to prepare the session (4/5 people) depending on the number of participants. This team will prepare the questions to discuss in each small-group conversation, the technical support for the session, and the hosts will be in charge of coordinating the groups and of taking notes of all the comments.
- Prepare the discussion tables and the place where it will take place so that all the participants feel comfortable. With 4/5 people for each table and a projector to display the questions. All participants will move for all the tables, answering all the questions proposed and mixing with all participants to have more richness and criticism in the responses. There will be a host in every table to collect all the opinions generated, and the discussion time will be no longer than 15 minutes. The hosts are in charge of collecting all the information, later this information will be coded and analysed.

Appendix 6.4. shows a World Cafe session carried out about barriers and opportunities of urban agri-green roofs

(https://bcnroc.ajuntament.barcelona.cat/jspui/bitstream/11703/116237/1/Cobertes_Mosaic.pdf)

Appendix 6.4 A World Cafe session example

More complex methodologies at urban planning can be applied, e.g., the Roof Mosaic methodology (Toboso-Chavero et al., 2019). This methodology was applied to a neighborhood, which combines life cycle assessment with two rooftop guidelines, to analyze the technical feasibility and environmental implications of producing food and energy and harvesting rainwater on rooftops through different combinations at different scales. See an example of this methodology in the paper published in the Journal of Industrial Ecology, https://doi.org/10.1111/jiec.12829 .

Furthermore, it can also apply a combination of the Roof Mosaic with the study of the metabolic pattern, using the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism

(MuSIASEM) of the area under study and different participatory processes, as shown Appendix 6.5 methodology was applied to a municipality of housing estates (Toboso-Chavero et al., 2020).

Other multi criteria analysis can also performed, e.g., a sustainability analysis using the Integrated Value Model for Sustainability Assessment (MIVES). MIVES is a Multi-Criteria Decision Making (MCDM) methodology based on the Multi-Attribute Utility Theory (MAUT) with a value function concept, in order to perform quantitative and objective assessments. See an example of this methodology in the paper published on the Science of Total Environment https://doi.org/10.1016/j.scitotenv.2018.01.191 .

Phase b) (Building phase: during)

This part can include indicators (see methodology in the next phase c) to analyze the social aspects within the two groups of installations: small rooftop greenhouses for self-sufficiency and large and commercial rooftop greenhouses. It can be used indicators related to health & safety such as noise levels, dust levels or any indicator aim to measure the possible inconveniences of the infrastructure construction. See complete methodology in the next section.

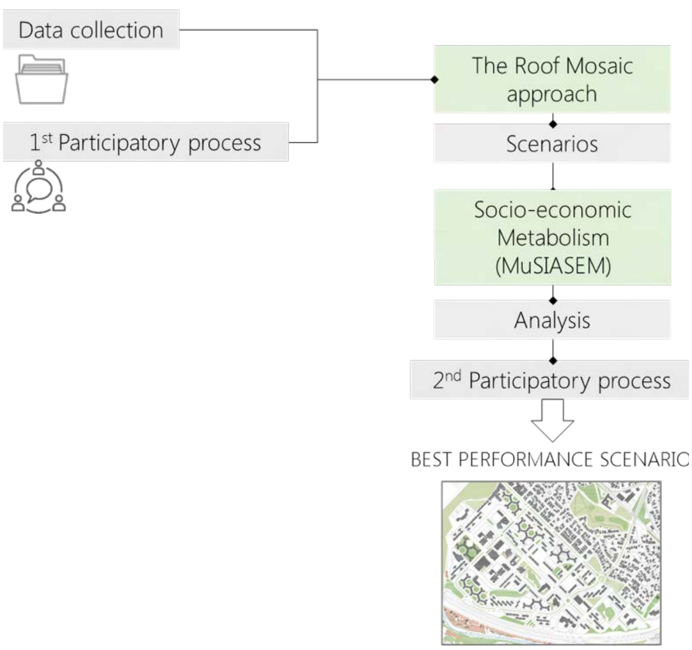
Phase c) (running phase = after)

Use phase (after)

Perception about the product & facility (neighbors, and residents of nearby buildings):

1. Follow-up survey of different stakeholders, users, and residents nearby the greenhouse. Hydroponic or soilless crops are commonly used in this case because they adapt easily to rooftop constraints (e.g., weight limit in floors). However, the acceptance of the produce derived from this system is controversial due to European legislation is not considering them as ecological agriculture. Therefore, consumers' acceptance of this kind of local food should be considered. See an example about the valuation of taste by potential consumers and their perception in the following paper, "*Analysis of the consumer's perception of urban food products from a soilless system in rooftop greenhouses: a case study from the Mediterranean area of Barcelona (Spain)",* published in Agriculture and Human Values, https://doi.org/10.1007/s10460-019-09920-7 . This paper seeks to answer, among others, two main questions: how is the quality of the products grown in soilless rooftop agriculture perceived by consumers? and how do consumers value the soilless production systems for rooftop agriculture? (See website for the Fertilecity questionnaire example.). The complete survey included 27 open and closed questions and was structured into four sections.

Appendix 6.5. Methodology to decide the systems to deploy on urban roofs.



2. General information: This section included closed questions (i.e., multiple choice) regarding the socio-economic profile of the participants, namely age, gender, level of education, profession, and income. These data were collected for statistical analysis purposes.

3. Perception of the product quality: This section consisted of closed questions that evaluated different aspects of the quality of the product, i.e., appearance, texture, size and flavor, and ripeness. The Likert scale method can be used for rating each aspect. This scale is a psychometric response scale primarily used in questionnaires to assess subject's perception and usually holds a 5-point scale (ordinal data), assigning a numeric value to each level. For example, the question "How do you rate the condition of the tomato eaten?" had 5 options: "very good", "good", "acceptable", "bad" and "very bad".

4. Sale of the product: This section encompassed closed and open questions regarding the motivations and preferences for purchasing food products from soilless cultivation system from rooftop greenhouses, including willingness to pay, preference for type of packaging, preferred sales channel, regularity of purchase and environmental information about the product. This third section was only performed in the second campaign with the aim of take some tips about how business models should be focused.

5. Final comments: The survey finished with an open question referred to the methods for food production and supply, i.e. Is there any comment or opinion you want to add to the answers?

Social indicators

There are different methodologies to calculate the social indicators, some more complex than others. Therefore, it is recommendable to differentiate between two groups of installations:

I. Small rooftop greenhouses for self-sufficiency: short list indicators, easy to measure.
II. Large and commercial rooftop greenhouses: Social Life Cycle Assessment (SLCA) (Appendix 6.6)

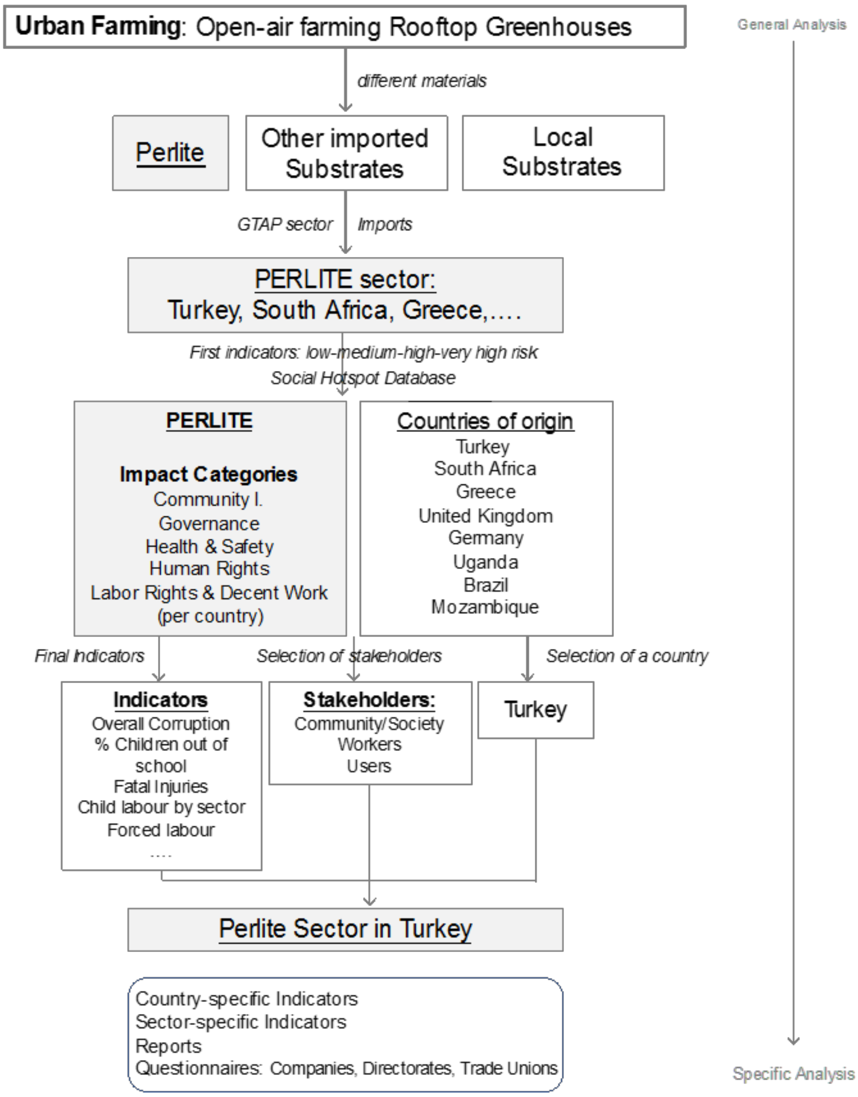
Appendix 6.6 Levels of an SLCA

For small RTGs for self-sufficiency, a relevant list of social indicators will be advisable. These social indicators should be easy to measure and can be quantitative or qualitative. Therefore, it is not recommendable to perform an SLCA, because many data will be required, and they will be difficult to obtain. Moreover, it is advisable to decide in the pre-project participatory process with the residents, the social indicators that we will measure based on the resident's interests.

Some of the proposed social indicators are:

- Coverage of residents' diet (in % and/or absolute values)
- Maintenance investment (hour/household/year) (Toboso-Chavero et al., 2020)
- Community engagement- Organizational support for community initiatives: using questionnaires/interviews) (Benoît-Norris et al., 2013)
- Local Employment (in % and/or absolute values) (UNEP/SETAC, 2013)
- Increase of wellbeing: using questionnaires/interviews (Ambrose et al., 2020)

For large and commercial RTGs is more suitable to perform an SLCA. This methodology aims to assess the social and socio-economic aspects of products along their life cycle. The SLCA guidelines framework distinguishes five stakeholders' groups: Workers, Local community, Society, Consumers, Value chain actors. Subsequently, a second level of six impact categories: human rights, working conditions, health and safety, cultural heritage, governance, and socio-economic aspects, and a third of impact subcategories and social indicators (see Fig II.10. 4., and the Appendix for an example of social indicators). SLCA studies are usually aimed at a sector or company scale, or products produced in developing countries, with social conflicts or some special interest.



Appendix 6.7
Workflow used for the perlite SLCA

The above diagram shows an example of the perlite sector that was applied as a substrate in an RTG, since it is one of the most used materials in growing media, in this illustrative example the specific objective would be: to analyze the social impacts, from the extraction and production of perlite used for the implementation of agriculture in urban roofs, such as open-air farming and greenhouses on roofs.

7. Appendix 7. Protocol documents for surveys and participatory processes

Reference: CEEAH 4520

UAB
Universitat Autònoma de Barcelona

Vicerectorat d'Investigació

Comisión de Ética en la Experimentación Animal y Humana (CEEAH)

Universitat Autònoma de Barcelona
08193 Bellaterra (Cerdanyola del Vallès)

La Comisión de Ética en la Experimentación Animal y Humana (CEEAH) de la Universitat Autònoma de Barcelona, reunida el día **30-11-2018**, acuerda informar favorablemente el proyecto con número de referéncia **CEEAH 4520** y que tiene por título **"Transformant ciutats: la implementació del nexus d'aigua-energia-aliments en les cobertes de Badia del Vallès"** presentado por **Cristina Madrid López**

Elaborado:	**Aprovado:**
Nombre: Nuria Perez Pastor Cargo: Secretària de la CEEA de la UAB Fecha:	Nombre: José Luis Molina González Cargo: President de la CEEAH de la UAB Fecha:

Reference: CEEAH 4639

Transformant ciutats: la implementació del nexus d'aigua-energia-aliments en les cobertes de Badia del Vallès

Informació requerida per la CEEAH de la UAB

Num. CEEAH: 4639
Data: 19-02-2019

1. Títol del procediment de recerca

Transformant ciutats: la implementació del nexus d'aigua-energia-aliments en les cobertes de Badia del Vallès

2. Breu descripció del projecte

El projecte tracta de buscar solucions en àrees urbanes per reduir la dependència en recursos externs i incrementar l'autosuficiència en les ciutats. Una d'aquestes solucions seria col·locar nous sistemes en les cobertes dels edificis, com agricultura, plaques solars, tancs d'aigua de pluja, etc. En aquest cas es pretén avaluar la viabilitat socioeconòmica i la viabilitat ambiental dels patrons metabòlics del nexus d'aigua-energia-aliments en les cobertes dels edificis del polígon d'habitatges de Badia del Vallès, a escala de llars, edificis i municipi. És principalment un estudi quantitatiu però es vol complementar amb dos processos participatius amb els veïns del municipi, perquè formin part de la tria del millor escenari pel seu municipi que ja han estat aprovats per la comissió d'ètica, i també una enquesta d'hàbits de consum, que és la que es presenta ara.

Àrea del procediment d'experimentació amb humans

Ciències Socials i Polítiques

3. Dades de l'investigador responsable

Nom i cognoms	Cristina Madrid López

Reference: CEEAH 5539

Informació requerida pel CEEAH de la UAB

Identificador: **5539**

Núm. CEEAH: **5539**

Arxiu:

1. Títol del procediment de recerca

Municipis resilients a les pandèmies mitjançant el nexe de l'agricultura de proximitat, energia, aigua i residus

2. Breu descripció del projecte

Aquest projecte s'engloba dins del projecte Pandèmies 2020 de l'Agaur, encara pendent de resolució. L'equip que sol·licita el projecte procedeix de tres grups SGR: Gicom 2017SGR671, i Sostenipra 2017SGR 1683 de la UAB; i el Grup d' Investigació i Innovació de la Construcció 2017SGR227 de la UPC. Gicom forma part del centre Tecnològic BIO-GLS (Red Tecnio). Sota aquest projecte dos tesis doctorals formen part d'aquest estudi, la de Susana Toboso Chavero i Pietro Tonini, doctorands del professor Xavier Gabarrell Durany.
L'actual pandèmia per coronavirus ens ha demostrat que les ciutats no estaven preparades per aquest tipus de catàstrofes. Les ciutats concentren els serveis, els llocs de treball, afavoreixen les interaccions socials, etc. En canvi, també generen el 70% dels residus mundials, i consumeixen el 80% dels aliments produïts globalment. A causa d'aquests fets, s'ha pogut constatar la poca resiliència de les ciutats, expressada mitjançant el temor a possible mancances en la distribució d'aliments durant el confinament. Aquest projecte vol transformar les ciutats en espais resilients, sostenibles i més saludables per l'actual i futures pandèmies, mitjançant l'agricultura de proximitat i el reciclatge/reducció de residus.
Es planteja a) estudiar el metabolisme dels residus, ja que la situació viscuda durant l'estat d'alarma ha tingut una clara incidència en els hàbits de consum de les famílies; b) promoure el compostatge domèstic i comunitari en edificis i escoles; c) promoure l'agricultura de proximitat, especialment mitjançant la producció en coberta; d) analitzar ambientalment els diferents processos associats als tres plantejaments anteriors mitjançant la caracterització dels factors d'emissió de determinats compostos (N2O, Compostos Orgànics Volàtils i metà) i l'anàlisi del cicle de vida dels productes; d) escalar els sistemes de reciclatge i cultius en coberta al municipi. Es realitzarà un estudi de cas centrat en un/uns barri/s d'una ciutat de l'àrea metropolitana de Barcelona per conèixer i analitzar els patrons de consum i el malbaratament alimentari, així com els canvis en la generació de residus per l'increment en l'ús d'envasos d'un sòl ús a causa de les mesures higièniques recomanades per a la prevenció de contagis de la COVID-19. Per altra banda, es vol quantificar l'acceptació social de la utilització de les cobertes dels edificis per implementar agricultura de proximitat i l'autogestió de la fracció orgànica. Els factors d'emissió es determinaran en els pilots que es realitzaran en les instal·lacions experimentals de la universitat i en les escoles. Els resultats ens permetran proposar noves estratègies de circularitat i sistemes tancats d'agricultura de proximitat.

CARBON FOOTPRINT

INVENTORY					RESULTS	
	unit		days/times	Total	kg CO_2 eq	Total kg CO_2 eq
Car travels (BCN-UAB) Euro 3	km	20	580	11600	0.3447	3999
Train travels (BCN-UAB)	km	20	156	3120	0.0090	28
Conference travel 1 (air)	km	1844	2	3688	0.1003	370
Conference travel 2 (air)	km	1500	2	3000	0.1003	301
Berlin Travel stay (air)	km	1872	2	3744	0.1003	376
Electricity	kWh	1742	1	1742	0.6068	1057
Paper	sheet	20	40	800	0.0821	66
Computer	piece	1	1	1	177.0689	177

	kg CO_2 eq
Total	**6373**
per year	**1593**
per month	**136**
per day	**4.5**

MONETARY COST

COST				
	€	Company taxes		
Grant FPU (3 years and 11 months)	81179		33%	107968
Berlin stay	4000			
Survey 1	5082			
Survey 2	12899			
Participatory processes	150			
Conference Manchester	500			
Conference Pescara	500			
Conferece Fees (others)	300			
Office	1600			
Open-access journals	6290			
Courses	3000			
Softwares	20000			
PhD fees	2182			
English editing	1894			
Thesis defense	1000			
TOTAL	167365			

Per year	41841
Per month	3561
Per day	119

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