



Methodological framework for impact evaluation of Building-Integrated Greenery (BIG-impact)

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ABSTRACT

Building-Integrated Greenery systems, i.e., green roofs, walls, and facades, are Nature-based Solutions that make possible the renaturing of cities when there is no room for traditional greenery solutions. These green systems provide several ecosystem services at both the building and city level, such as urban heat island effect mitigation and noise reduction, support for biodiversity, runoff control, thermal and acoustic insulation, etc. However, once implemented in real cases, their impact is almost never evaluated. This fact limits the possibility of carrying out cost-benefit analyses that contribute to justifying their long-term maintenance, thus putting at risk their long-term sustainability and consequently the provision of benefits. Unlike existing approaches, the method presented here offers a comprehensive and practical tool that addresses the gap in BIG systems' impact evaluation, facilitating informed decision-making and promoting the long-term sustainability of BIG systems.

- In its design, the current references at European and global level for building-integrated systems impact assessment has been considered.
- It is easily replicable in any real project and enables the collaboration of involved stakeholders.
- The method is unprecedented and allows a holistic assessment of the impact of BIG in real cases, in terms of ecosystem services provided.

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Background

Motivation and justification

In recent years, the world has become more than half urban for the first time in history (57 percent of the population in 2022) [1]. Even though there are 44 megacities in the world (urban areas with >10 million inhabitants) and a total of 100 urban areas with 5000,000 or more inhabitants in 2022, the average urban resident in the world lives in an urban area with a population of approximately 625,000.

In this context, a nature-based approach to urban and peri-urban development and management has grown in popularity over the last decade [2]. Nature-based Solutions (NbS) have been consolidated in recent years as one of the most important strategies on the path to future resilient, sustainable, and circular cities within the Sustainable Development Goals (SDG11. Sustainable cities and communities). The EU Research and Innovation policy agenda on Nature-based Solutions and *Re-naturing Cities* defines “nature-based solutions to societal challenges as solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes, and seascapes, through locally adapted, resource-efficient and systemic interventions”. NbS intrinsically provide benefits for biodiversity and support the delivery of ecosystem services; furthermore, the multitude of environmental, social, and economic collateral benefits delivered by NbS are becoming increasingly recognized [3].

Among the multiple NbS that can be applied at the city scale, those that make possible the integration of vegetation and nature into building envelopes (such as green roofs, green walls, and green facades) stand out for their ability to re-fill the scarce surfaces of opportunity in the densely built environment [4–6]. Thus, the so-called Building-Integrated Greenery systems (BIG) enable the renaturing of cities when there is no room for traditional solutions, e.g., urban parks, gardens, street trees or urban forests, among others. This fact is of great relevance when the mobility of citizens is limited (e.g., the elderly, children, sick people, people with reduced mobility or people with mental disabilities, demanding work schedules, etc.), as well as under situations of lockdown such as the one recently experienced owing to the COVID-19 crisis. BIG systems should also be consolidated as a good option to improve connectivity of elements of traditional urban greenery.

In this context, BIG systems are fully established construction technologies and magnificent examples can be found all over the world, regardless of the climate, the type of building (rehabilitated or newly built) and its use (schools, residential, offices, industrial, equipment, etc.). In cities such as Barcelona (Catalonia, Spain), the city council has promoted in recent years the implementation of BIG systems, which has led to not only the existence of successful examples of application, but to the growth of an economic sector with its own entity, i.e., the green roof and walls sector, different from conventional urban gardening.

The Porxos d'en Xifré semi-intensive green roof project is a good example of implementation in a 185-year-old residential building that was awarded a New European Bauhaus award in the year 2021 (Fig. 1).

The biodiverse green roof located in the Urbaser building is a fantastic example of how to implement an element of support for urban biodiversity, in an industrial and office building located in an industrial area with a lack of green spaces (Fig. 2).

The extensive green roof and urban vegetable garden located in the industrial building of the cooperative for social integration of the TEBVerd building is an example of how to use BIG systems in capacity building activities (Fig. 3).

The green wall on Berlin street is a very good example of how nature can be integrated into those densely built spaces of the city, taking advantage of wasted spaces such as dead facade walls separating buildings (Fig. 4).

BIG systems provide several ecosystem services at both the building and city level. The most commonly observed benefits at the urban scale are: mitigation of the urban heat island effect [7,8]; decrease in storm water runoff [9–13]; enhancement of biodiversity



Fig. 1. Example of Building-Integrated Greenery systems in Barcelona. Porxos d'en Xifré Semi-intensive green roof.



Fig. 2. Example of Building-Integrated Greenery systems in Barcelona. Urbaser biodiverse green roof.



Fig. 3. Example of Building-Integrated Greenery systems in Barcelona. TEBVerd Extensive and urban vegetable garden green roof.

in densely urban areas [14–18]; purification of air and water runoff [19–26]; reduction of urban noise; activation of the economy by creating jobs and stimulating urban agricultural production; improving the health of the population thanks to the psychological effects associated with having access to nature [27–29]. On a building scale, BIG systems reduce the sensible heat flux due to the cooling effect, thus decreasing the heating and cooling demands of a building [30–34]; improving human thermal comfort; improving acoustic insulation [35–40]; protecting the buildings' materials from the influence of climate; and increasing buildings' property values by improving their appearance and aesthetics [4].

But despite the abundant scientific evidence available for these benefits, there are still some aspects that hold back not only the new implementation but also the long-term viability of living architecture systems. Once the BIG systems are implemented in a building, the following barriers become prominent: the need for maintenance, the diversity within the BIG context, the lack of monitoring and evaluation of their operation and the construction systems' adaptation to the climate and to its increasing fluctuations.

- Need for BIG systems maintenance

Maintenance of BIG is necessary and involves associated costs. These construction systems are placed in remote places on the building envelope, sometimes difficult to access, such as roofs and walls, etc. which implies new maintenance and complex procedures, new work activities (e.g., vertical gardening), etc. In addition, the conditions in which the plants must grow are often extreme: high temperatures and sun exposure, pollution, drought, thin artificial substrate layers, etc.

- Diversity within the BIG systems context

The context of life architecture is very complex and must be taken into consideration. It is worth highlighting not only the different types and uses of buildings that support the green systems, but also the different, and often divergent, interests of the involved stakeholders. Thus, the process of integrating a green wall into a hundred-year-old residential building has little in common with doing it in a new building for hospital use. On the other hand, multiple interest groups can be identified, such as direct beneficiaries (e.g., users), or indirect beneficiaries (e.g., neighbours), building owners, implementation and maintenance companies, public



Fig. 4. Example of Building-Integrated Greenery systems in Barcelona. Green wall Berlin street.

administration, architects and landscape designers, research centres, etc. Unfortunately, their interests are still divergent, and this represents a drawback for the economic and functional sustainability of BIG systems. Real estate developers want to build and sell as many buildings as possible and use BIG as a sales pitch. Beneficiaries and owners want to enjoy the benefits without spending too much money on maintenance. Maintenance companies and installers are interested in new projects to be maintained. Municipalities are interested in BIG systems as a means of advancing towards the re-naturalization of the city, at the same time as they offload some maintenance tasks to municipal gardening services. The complexity of municipal service departments leads to conflicting interests, for example between the ecological transition department, which aims to promote BIG in municipal buildings, and the building maintenance department, which seeks to minimize maintenance costs.

- Lack of performance monitoring of BIG systems once implemented in real cases

Although plentiful scientific evidence exists on the benefits of BIG systems, there is still a lack of knowledge and standards on how to monitor and evaluate their impacts during the operational phase; that is, in real cases. Previous NbS projects have generated a large volume of indicators and methodologies to quantify the ecosystem services provided by NbS at multiple scales. Unfortunately, these indicators tend to be scientifically complex, some of them designed to be applied on a large scale, and difficult to implement in BIG real cases (i.e., buildings). These facts, in addition to the heterogeneity of the benefits provided (provisioning, regulating, cultural and supporting ecosystem services), are seriously hindering the creation of viable protocols for monitoring and quantifying BIG system's impacts during the service life of the building into which they are integrated [3].

- Adaptation of construction systems to the climate

Buildings' construction systems tend to be based on generalist solutions that serve economies of scale, globally. In the case of BIG systems, this mercantilist strategy clashes with the world's climatic diversity and the local adaptation of these systems in which vegetation is the key element.

This fact leads, in practice to the application of incorrect construction systems for a certain climate, or the modification of the generalist solution to adapt it to the specific climatic conditions of an area with potentially uncertain long-term results.



Fig. 5. “H buildings” at the Lleida Agri-food Science and Technology Park (PCiTAL) Lleida, Spain. Example of a green roof in operation but not receiving the expected benefits.



Fig. 6. BIG-impact method within the Life Cycle of NbS. Adapted from Kumar, P. et al. [41].

As a result of these barriers, some examples of failed BIG-based projects have already emerged. In some cases, the problem is limited to poor aesthetic appearance and a failure to meet initial expectations, in terms of benefits provided (Fig. 5). In the worst-case scenario, the green element is dismantled.

However, beyond these constraints, which also represent further research challenges, there are interesting opportunities that should be considered: the fact that administrations are attempting to determine “NbS Impact Monitoring and Evaluation”, and that BIG systems are the closest to citizens’ urban green infrastructure.

- Public bodies are attempting to determine “NbS Impact Monitoring and Evaluation”

In March 2021, the European Union launched the handbook “Evaluating the impact of Nature-based Solutions” [3]. This document highlights the idea of considering the entire life cycle of NbS, including “Monitoring and Evaluating”, in order to ensure their long-term sustainability and the provision of ecosystem services (Fig. 6).

This document establishes the bases and provides multiple indicators and metrics in order to design specific monitoring and evaluation plans for the different types of NbS. It is a very good reference and a starting point for the BIG-impact method. This

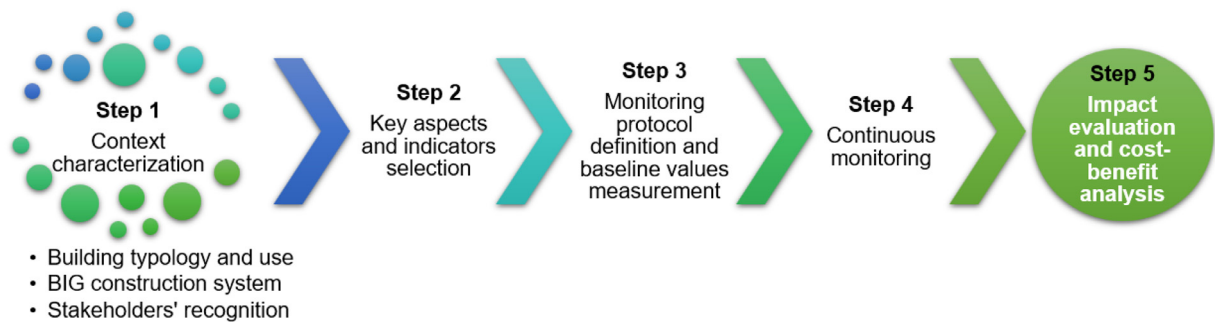


Fig. 7. BIG-impact method steps.

manual collects the scientific knowledge acquired during the latest research projects and European initiatives on NbS over the last decade and motivates the appearance of proposals such as the BIG-impact method, which is aimed at the monitoring and evaluation of specific NbS, i.e., BIG systems.

- BIG systems are the closest to citizens' urban green infrastructure

One of the most valuable characteristics of BIG is its proximity to people. This fact should not only be considered for the biophilic effect (connection with nature, improvement of health and well-being, aesthetics, etc.), but also as an opportunity for shared monitoring and maintenance with municipal administrations.

The proximity of BIG systems provides an opportunity to design participatory and collaborative strategies for greenery management and maintenance, as well as to apply continuous monitoring processes on the operation and impacts of BIG systems.

The “Verd de proximitat BCN” project (Barcelona proximity green project)

In this context, the “*Verd de proximitat BCN*” research project has been carried out for 21 months in the city of Barcelona, during which six real cases of green roofs have been monitored. The general objective of the “*Verd de proximitat BCN*” research project was to design and implement a plan for monitoring and evaluating the operation and impact of the integration of vegetation onto a building's envelope, specifically green roofs, walls and facades [42]. The project, conducted in the city of Barcelona, was created to design a method that must be inclusive and participatory, economically viable and sustainable over time.

Based on the reference handbook [3] and the lessons learned during the information collection phase for the monitored projects in Barcelona, a selection of the most suitable key aspects and indicators that can be part of the monitoring and impact evaluation framework for building-integrated greenery was conducted.

The most important issues that were addressed and resolved during the design phase were:

- Choosing the most important and viable key aspects and indicators for green roofs and facades.
- Analysing which of them can be monitored automatically and which cannot.
- Choosing the most suitable methodology for their measurement and analysis, and/or testing more than one method to finally decide which could be the most suitable (in-situ observations, direct manual and/or automatic measurements, surveys, counting, interviews, etc.).
- Defining new key aspects and indicators that were not previously defined or resolved in previous research.

The results of the “*Verd de proximitat BCN*” project have contributed to the model design, but they are not the subject of this method's article in which the theoretical-conceptual framework of the method for monitoring of BIGs and evaluation of impacts is presented, in a general way, to be applied to any BIG project anywhere. Nevertheless, in section “2.7. Method validation,” the results from of a semi-intensive green roof case study are shown.

Purpose and scope

The “BIG-impact” method provides a general methodological framework for performance monitoring and impact evaluation of Building-Integrated Greenery in real existing cases. Its application will contribute to its positive service life in terms of both their long-term sustainability and the continuous provision of their ecosystem services. The method could be applied both during the operational phase (retrospective evaluation), or in the design phase (prospective evaluation).

Method

This section outlines the methodological framework employed for the implementation of the “Big-Impact” method, comprising a sequence of steps designed to accurately assess the impact of interventions (Fig. 7). The process begins with Context Characterisation, where relevant variables of the environment in which the method will be applied are analysed and defined. Following this, Selection

of Key Aspects and Related Indicators is undertaken, which are crucial for ongoing monitoring. Once these indicators are established, a Monitoring Protocol and Baseline Measurement is defined, setting a reference point for evaluation. The next step involves Continuous Monitoring of the selected indicators, allowing for data collection over time. Finally, an Impact Evaluation and Cost-Benefit Analysis is conducted to ensure that outcomes are adequately quantified, and decisions are justified.

BIG-impact method steps

To apply the BIG-impact method to any BIG project, the phases in Fig. 7 must be followed.

First, it is necessary to characterize the context in which the BIG-impact method will be applied (step 1), fundamentally the building typology and use, the construction of BIG system, and recognition of the involved stakeholders. This initial analysis will facilitate the choice of key aspects and indicators that will be monitored and consequently evaluated in each particular BIG project (step 2). The BIG-impact method includes up to 34 key descriptive aspects of the ecosystem services provided by BIG, out of which the ones that best suit each particular project must be chosen.

In step 3, the monitoring protocol and the auxiliary means necessary to carry it out will be established, either by manual data collection or through sensors, for each of the selected key aspects (indicators). In this phase, the baseline value will be measured; that is, the value that will serve as a reference to evaluate the indicators' progress. Once the continuous monitoring has started (step 4), data will be recorded and the continuous assessment of the impact of BIG can be carried out, which will allow for appropriate maintenance management, by applying the continuous improvement mechanisms, as well as carrying out cost-benefit analyses during the operational phase of BIG (Step 5).

Context characterization (step 1)

The provision of ecosystem services by BIG systems is highly dependent on the type of BIG construction system (green roof, green wall or green facade, and the different variations of each of them), the type of building (one floor, several floors, new construction, historic building rehabilitation, etc.), also on its use and consequently the type of users (school, residential, hospital, offices, etc.), and finally on the stakeholders involved.

Therefore, when drafting a plan for monitoring and evaluating the impacts of a BIG project, it will be necessary to carry out a prior analysis of the context in which it is integrated, including a) the building typology and use, b) the stakeholders and the possibility of involving them in monitoring, evaluation and even BIG maintenance tasks, and c) the type of BIG construction system being used.

This analysis of the context will allow the correct choice of the key aspects to be monitored.

Building typology and use

The typology of the building into which the BIG project is integrated will determine not only its operation but also the maintenance and management tasks. Consequently, the provision of ecosystem services will also depend on this typology. As an example, we could mention that the construction systems and materials surrounding the building (both roof and facade) will influence the acoustic and thermal transmission of the building. Also, the ability to capture rainwater or runoff will vary depending on the roof slope (flat or sloped roof). The accessibility of the roofs and facades will influence the partitioning of users, with regard to the ability to carry out activities, as well as maintenance tasks.

At the same time, the use of the building determines the type of user and therefore the possibilities of whether or not to make use of certain ecosystem services. Thus, in a residential building the main purpose is to provide spaces for contact with nature and relaxation, similar to those of conventional gardening, while in a hospital the benefits linked to the improvement of health and the well-being can be maximized. In a school the activities for education and environmental awareness will be important.

Furthermore, depending on the user, the possibilities of involving them in the monitoring and evaluation of impacts (even on maintenance) will be variable.

BIG construction system

BIG systems include any type of construction system that enables the integration of vegetation onto the envelope of a building, i.e., green roofs, green walls and green facades. The differences between construction systems and the materials used in BIG cannot be ignored when choosing the key aspects and indicators to monitor and evaluate their impacts.

In general, green roofs are classified between extensive and intensive systems, although an intermediate "semi-intensive" solution also appears in the standardized classifications [43]. Table 1 summarizes the main green roof typologies and main features.

In terms of construction systems, vertical greenery systems can be differentiated between green walls (also known as living walls), and green facades [44,45].

Green walls can be divided into two main groups. The first one corresponds to systems that use continuous geotextile felts to host plants in small pockets. The second group includes systems that use rigid modules or panels (mainly plastic), filled with growing media, to be hung on lightweight vertical supports anchored to the buildings' walls.

On green facades, mainly climbing plants and hanging shrubs are used to cover the desired area of the building's facade (Table 2). Green facades can be divided into three different systems: on traditional or direct green facades, climber plants use the facade material as a support; on double-skin green facades, light structures (e.g., steel mesh) are installed to create green curtains placed away from the building's facade. Finally, some building facade compositions include flowerpots for establishing hanging shrubs.

In addition to these general classifications, it will be necessary to take into account the specific variations of the technical solutions provided by the different commercial brands, which involve different layers, layer thicknesses and materials.

Table 1

Green roof typologies and main features.

Green Roof systems	Extensive	Semi-intensive	Intensive
Weight at maximum water capacity	50–150 kg•m ⁻²	120–350 kg•m ⁻²	>350 kg•m ⁻²
Substrate layer thickness	6–20 cm	10–25 cm	>25 cm
Plant typologies	Succulents, herbaceous and grasses	Herbaceous, grasses and shrubs	Grasses, shrubs and trees
Slope	< 100 %	< 20 %	< 5 %
Irrigation	Never or periodically	Periodically	Regularly
Maintenance costs	Low	Moderate	High
Implementation costs	Low	Middle	High

Table 2

Vertical greenery systems and their main features.

Vertical Greenery Systems		Support structure	Plant typology
Green facades	Traditional	No support. Directly against the building facade	Climber plants
	Double-skin	Very light, steel wires or mesh	Climber plants
	Perimeter flowerpots	Flowerpots	Climber and hanging shrubs
Green walls	Geotextile	Geotextile felts supported by light frame structures anchored to the building's facade	Shrubs and hanging shrubs
	Modular panels	Plastic panels supported by frame structures anchored to the building's facade	Shrubs

Stakeholder recognition

The BIG-impact method is based on a participatory, collaborative, and transdisciplinary approach that considers all interest groups and disciplines involved in the processes of integrating nature into buildings through green roofs, walls and facades.

The use of collaborative approaches makes it possible to introduce improvements in the design of monitoring that will make it more viable and sustainable over time:

- Increasing the level of knowledge of users and other interested parties about indicators, metrics and monitoring methodologies, also increasing the level of trust, thus ensuring that they know the reasons why maintenance and continuous monitoring is necessary.
- Making it possible to identify local needs, new ways of collecting data and to better know which results need to be evaluated.
- Collaborative environments foster more business opportunities, entrepreneurship, networking, and trust building.

Although care has been taken to meet the robustness requirements inherent in monitoring and obtaining scientific data and results, the development of the BIG-impact method is inspired by the spirit of the “do-it-yourself” (DIY) movement; i.e., the reintroduction (often to urban and suburban dwellers) of the old patterns of personal involvement and use of skills in the maintenance of a house or apartment, maintenance of technical equipment, computers, websites, etc. all applied to citizen science.

This approach is necessary to ensure that the designed method is viable and sustainable over time, making monitoring possible via multiple approaches and levels of technical knowledge: all types of users, maintenance technicians, students, etc. However, this approach requires that the selected indicators should be really viable, in terms of the possibility of being recorded and processed by the interest groups of the BIG systems sector, without any need for intervention by specialized external agents, nor the use of complex techniques or expensive equipment that is difficult to use. It leads to obtaining a set of very simple indicators, some specific and others of continuous recording, which together should facilitate a final assessment of the impact of any green roof, wall or facade project (Table 3).

From the analysis carried out in real cases during the “*Verd de proximitat BCN*” project, five main types of stakeholders were identified (Fig. 8): Owners-promoters, Direct beneficiaries (users), Indirect beneficiaries, Companies, and Administration. Meanwhile, there are others who play a fundamental role in the promotion of BIG systems implementation as well as further maintenance, management, and activation, thereby ensuring its long-term sustainability. These people have been called “Key People”.

When devising a new plan for monitoring and evaluating impacts in a real BIG project, it will be necessary, starting from these general groups of stakeholders, to characterize them in detail with regard to the creation of collaboration networks and the future assignment of roles and tasks. The analysis of stakeholders will also influence the choice of key aspects and indicators to monitor.

Selection of key aspects and related indicators (step 2)

For the development of the BIG-impact method, the review work carried out in “*Evaluating the impact of Nature-based Solutions. A Handbook for Practitioners*” has been taken as the main reference [3]. This manual is intended to serve as a guide for the development and implementation of scientifically valid monitoring and evaluation plans for the assessment of NbS impacts. The manual not only defines how the plans for monitoring and evaluating the impacts of multiple types of NbS should be developed, it is also accompanied by an *Appendix of Methods* which provides a brief description of each indicator determination method, along with guidance for end-users regarding the appropriateness, advantages and drawbacks of each method in different contexts.

This manual defines up to 12 areas of social challenges associated with NbS: 1. Climate Resilience; 2. Water Management; 3. Natural and Climate Hazards; 4. Green Space Management; 5. Biodiversity; 6. Air Quality; 7. Place Regeneration; 8. Knowledge and

Table 3
Defined key aspects for the BIG-impact method.

Social Challenge Area	Key aspect	No
1. Climate resilience	1.1. Stored carbon	1
	1.2. Energy savings	2
2. Water management	2.2. Rainwater use	3
	2.2. Water use	4
3. Natural and climate hazards	3.1. Urban Heat Island effect reduction	5
	3.2. Urban Runoff control	6
4. Green space management	4.1. Ecosystem Services provision	7
	4.2. Accessibility	8
	4.3. Percentage of green area	9
	4.4. Maintenance cost	10
5. Biodiversity enhancement	5.1. Connectivity	11
	5.2. Species	12
	5.3. Pollinator species	13
6. Air quality	6.1. Pollution capture	14
	6.2. Ambient smell	15
7. Place regeneration	7.1. Perceived Quality of Space	16
	7.2. Sense of belonging with the site	17
	7.3. Materials used	18
	7.4. Viewpoint effect	19
8. Knowledge and social capacity building Transformation	8.1. Participation	20
	8.2. Environmental awareness	21
9. Participatory planning and governance	9.1. Stakeholders' diversity	22
	9.2. Co-participation	23
10. Social justice and social cohesion	10.1. Social cohesion	24
	10.2. Safety	25
11. Health and wellbeing	11.1. Physical activities	26
	11.2. Wellbeing and happiness	27
	11.3. Acoustic comfort	28
	11.4. Thermal comfort	29
12. New economic opportunities and jobs	12.1. Property value	30
	12.2. Job creation	31
	12.3. Implementation cost	32
	12.4. Food production	33
	12.5. Energy production	34



Fig. 8. Involved stakeholders in the context of Building-Integrated Greenery.

Social Capacity Building for Sustainable Urban Transformation; 9. Participatory Planning and Governance; 10. Social Justice and Social Cohesion; 11. Health and Well-being; 12. New Economic Opportunities and Green Jobs. For each of these areas, the manual defines multiple recommended indicators and other additional ones, together with different methodologies for their monitoring.

However, the manual considers any nature-based solution, and at any scale. Therefore, it was necessary to review it in detail, narrowing the whole set of indicators defined to all typologies of NbS to those that really make sense to be applied within the context of building-integrated greenery, i.e., green roofs and facades. In addition, the methodologies that are suggested in the manual often do not fit properly into the context of BIG systems, which then involves having to adapt the indicators, the units of measurement, as well as the monitoring methodologies.

Table 3 summarizes the 34 key aspects selected, by social challenge area, which can be applied for the evaluation of the impact of BIG systems, and which configure the framework of the BIG-impact method.

Each of these 34 key aspects will be calculated individually in the BIG-impact method, so that it can be monitored independently and finally evaluate its specific impact. The calculation methods and references for each indicator are detailed in “Annex A. BIG-impact. Key aspects and indicators description”.

“Annex A.”, lists, for each key aspect, a brief description, the associate indicator to measure the impact, the correspondence with the indicators suggested in the reference handbook for NbS [3], if applicable, the unit of measurement, the frequency with which they must be recorded, the most suitable methodology for monitoring, also some observations regarding the state-of-the-art and previous research that supports the data used in the calculations, and finally a summary of the data necessary to collect the records in a database, in the event that one is used.

In Annex A, the following information is provided for each of the key aspects:

- Short description
- Indicator
- Correspondence with reference [3]: Evaluating the impact of Nature-Based Solutions. A handbook for practitioners. European Commission. Directorate-General for Research and Innovation. March 2021.
- Unit of measure
- Frequency
- Measurement method
- Observations
- Database
 - Question
 - Answer
 - Frequency
 - Target respondent
 - Observation

The BIG-impact method proposes an opening question for each of the key aspects and indicators, as well as the unit of measurement for the answer. This simplified system must allow the method to be used by any stakeholder involved in the management of the monitoring and evaluation of the impact of the BIG.

In “Annex B. BIG-impact. Key aspects and indicators. Summary (excel)”, the indicators, key questions and measurement units to be considered for each of these key aspects are presented in spreadsheet format. Annex B also specifies, when necessary, the intermediate formula that makes it possible to calculate, based on the scientific knowledge achieved to date, the value for the indicator. The table also specifies the need (or absence of same) for continuous monitoring, and in the latter case, some observations on the methodology for data capture (equipment, questionnaires, etc.).

Monitoring protocol definition and baseline values measurement (step 3)

Once the key aspects that can be analysed in each particular BIG project have been chosen, depending on the type of BIG as well as the type and use of the building, it will be necessary to define “who” will be the people (stakeholders) in charge of managing the different monitoring activities according to what is established for each key aspect in Table 3, Annex A and Annex B, by assigning tasks and responsibilities.

For those indicators that require monitoring by means of equipment, it will be necessary to decide the location of the sensors and the storage systems for the recorded data.

The drafting of a “monitoring and impact assessment plan” detailing these tasks and responsibilities, assigned to specific people, as well as the description of the sensors and their location, will be essential to guarantee the success of long-term monitoring and evaluation.

Continuous monitoring (step 4)

Once the monitoring process has started, it is necessary to record the values for the different key aspects. It is recommended to link a database in which to record the raw and processed data, and in this way observe the indicators’ evolution. In many cases a

spreadsheet on which to periodically record the values obtained will be more than enough. The manager of the green infrastructure will be, in general, the key figure who can gather all the information and consequently the person in charge of managing the entire process.

Impact evaluation and cost-benefit analysis (step 5)

With the resulting values of the different indicators, the BIG project manager can make an evaluation of the evolution of each of the key aspects, as well as of the whole BIG impact. This will allow the manager to make decisions regarding the maintenance tasks of the BIG system, as well as to make interventions to improve its design, if necessary. Likewise, it will also serve to maintain and improve the provision of ecosystem services.

By knowing the periodic costs for the maintenance of the BIG system and having recorded the values of the ecosystem services provided by the BIG, it will be possible to monetize them to finally proceed with the calculation of the cost-benefit balance of the BIG project.

Method validation

For the validation of the BIG-impact method, the semi-intensive green roof placed on the Pérez-Iborra school located in the Eixample district of the City of Barcelona, and currently in operation, was selected.

Step 1. context characterization

Building typology and use. The building is located in the Eixample district of Barcelona, built at the end of the 19th century, and presents the construction typologies of that time. The green roof project dates from 2019 and was designed by the architecture office “Espai Qbic Arquitectura”.

The roof is located 24 m from the street, in a mixed-use (residential and educational) building that consists of 7 floors (a ground floor, mezzanine, 4 floors and an attic).

The green roof is located above the original roof of the building, a “Catalan roof” type, which consists of an air chamber of variable height between 40 and 100 cm resulting from the formation of drainage slopes.

The communal staircase of the building gives access to the attic floor. The access to the green roof takes place through a corridor and two exit doors, overcoming a 75 cm difference in level in one of the accesses and 100 cm in another by means of stairs.

The building has a mixed residential-school use, although the green roof is used for activities of the school located in the building, as shown in Fig. 9.

BIG construction system. The green roof consists of four distinct areas: an urban vegetable garden space, a leisure space, an elevated observation space located in the central part and a non-passable extensive green roof.

The vegetable garden space, of 104 m², consists of three work areas. On the one hand, two flower beds of about 15 m² with 30 cm of substrate thickness. On the other, in the central part of the terrace, and resting directly on the pavement, there are 4 modular planters made of galvanized steel for hydroponic cultivation. The leisure space is an 84 m² terrace made up of an area of aromatic shrubs and another of grass. The elevated observation area is a central terrace raised between 2 and 3 metres above the other areas and accessed by a metal staircase. The landscape design of this space consists of several flowerbeds of aromatic plants and climbing plants around the perimeter.

Finally, the non-passable roof space is covered with an extensive green roof replacing the original gravel ballasted roof. Eight 285 W photovoltaic solar panels have been installed on this roof. The refurbishment project included the improvement of the thermal insulation of the roof with the incorporation of XPS panels above the habitable areas of the roof (non-walkable space).

The project included the installation of eight water tanks of 200 litres each, for the collection of rainwater. Currently, six of them are used for rainwater harvesting.

The green roof construction system consists of the following layers from top to bottom:

- Layer of vegetation, variable depending on the area, from extensive to semi-intensive.
- Substrate layer for green roofs, depending on the area, ranging from extensive, semi-intensive and for urban horticulture.
- 100 g/m² pre-compressed and thermo-welded SF filter layer.
- Drainage layer Floradrain FD 40, Zinco recycled polyolefin (mainly PE) 40 mm thick.
- Separating and protective layer SSM45 ZINCO synthetic fibre mixed polyester/polypropylene 5 mm thick.
- ALKORPLAN L 35,177 1.2 mm thick PVC waterproofing sheet.
- 150 gr non-adhered protective geotextile layer.

In total, 38.90 m² of extensive green roof and 172.31 m² of semi-intensive green roof have been measured (including the vegetable garden beds and the perimeter planters).

Stakeholder recognition. Based on a couple of interviews with the managers of this BIG project, it was possible to assess the main stakeholders linked to the BIG project and their potential to participate in monitoring and evaluating the impact of the BIG project.

In the case study, the result was that of Table 4. This project, being linked to an educational activity, and also having contracted a maintenance service with a company expert in the maintenance of green roofs, has great potential to carry out the monitoring and evaluation of long-term impacts in a collaborative way involving the main stakeholders.



Fig. 9. Semi-intensive green roof located at Pérez-Iborra school, Barcelona.

Table 4
Stakeholder recognition for the case study.

Stakeholder	Yes/No?	Who?	Potential level of involvement for:	
			Monitoring	Impact evaluation
Owners-promoters	Yes	School Director	Moderate	High
Direct beneficiaries-users	Yes	Students	High	Moderate
		Teachers	High	High
		Administrative staff	Low	Low
		A couple of teachers in charge of managing the activities on the green roof and the school director	High	High
Key Figures	Yes			
Indirect beneficiaries	Yes	Students' families	Low	Moderate
		Neighbours in the building	Low	Moderate
		Neighbours from the neighbourhood	Low	Low
		Citizens	Low	Low
		Green roof maintenance	High	High
Companies	Yes			
Administration	No	–	–	–

Step 2. selection of key aspects and related indicators

According to the previous analysis, carried out in steps 1 and 2, it is possible to determine which will be the key aspects that can be monitored, and therefore, which will be viable to make an impact assessment in a specific project. In the case study, the key aspects selected are those in Table 5, “Selection” column.

Step 3. monitoring protocol definition and baseline values measurement

Once the key aspects have been chosen, the recording methodology of the chosen indicators can be defined, and the baseline values assigned. These initial values may be unknown, they may be estimated based on data available at the initial time, or they may be an initial measurement at the start of monitoring. In the case study, the key aspects of Table 5 were chosen.

Table 5
Summary of main values for Step 3 and Step 4 for the case study.

Social Challenge Areas	Key aspect	Unit	Selection	Baseline Value	After 1 year Monitoring	Comments	Potential involved stakeholders
1. Climate resilience	1.1. Stored carbon	kg C	Yes	251.85	No changes	Estimated	Teachers; Students
	1.2. Energy savings	°C	Yes	Not available	- 3.2	Measured and calculated. Reduction in average surface summer temperature between green roof and conventional ceramic roof	Teachers; Students; Maintenance companies
2. Water management	2.2. Use of rainwater	m ³ /year	Yes	Not available	11.8	Measured and calculated	Teachers; Students; Maintenance companies
	2.2. Use of water	m ³ /year	Yes	Not available	94	Measured and calculated	
3. Natural and climate hazards	3.1. Reduction of Urban Heat Island effect	°C	Yes	Not available	- 5	Reduction in average outdoor summer temperature between green roof and conventional ceramic roof	Teachers; Students; Maintenance companies
	3.2. Urban runoff control	m ³ /year	Yes	32.42	NA	Estimated	
4. Green space management	4.1. Provision of Ecosystem Services	Number	Yes	20	No changes	–	School Director; Teachers
	4.2. Accessibility						
	A) Access to people in general	Scale 1–5	Yes	3	No changes	Self-assessment	School Director; Teachers; Administration
	B) Access to people with disabilities	Scale 1–5	Yes	1	No changes	Self-assessment	School Director; Teachers; Administration
	C) Access for maintenance	Scale 1–5	Yes	2	No changes	Self-assessment	School Director; Teachers; Maintenance companies; Administration
	4.3. Percentage of green area	%	Yes	55	No changes	Calculated	School Director; Teachers; Maintenance companies
	4.4. Maintenance costs	€/m ² /year	Yes	40	No changes	Count for 2022	School Director; Teachers; Maintenance companies
5. Biodiversity	5.1. Connectivity	Number	Yes	5	No changes	Potential connexion with 5 urban green areas	School Director; Teachers; Administration
	5.2. Species	Number	No	–	–	Not yet implemented	Teachers; Students; Maintenance companies
6. Air quality	5.3. Pollinators species	Number	No	–	–		
	6.1. Pollution capture	PM2.5	No	–	–	Not yet implemented	Teachers; Students; Maintenance companies
		PM10	No	–	–		
		O3	No	–	–		
		NO2	No	–	–		
		SO2	No	–	–		
	6.2. Ambient smell	N°/year	Yes	Not available	69	Count for 6 months during 2023	Teachers; Students

(continued on next page)

Table 5 (continued)

Social Challenge Areas	Key aspect		Unit	Selection	Baseline Value	After 1 year Monitoring	Comments	Potential involved stakeholders
7. Place regeneration	7.1. Perceived quality of space		Scale 1–5	Yes	Not available	2	More pleasant	Teachers; Students
	7.2. Sense of belonging/identity with space		Scale 1–5	No	–	–		Teachers; Students
	7.3. Materials used	Vegetation layer	Scale 1–5	Yes	3	No changes	Expert self-assessment	School Director; Teachers; Maintenance companies; Administration
		Substrate layer	Scale 1–5	Yes	4	No changes		
		Filter layer	Scale 1–5	Yes	2	No changes		
		Drainage layer	Scale 1–5	Yes	2	No changes		
		Protection layer (of the waterproofing sheet)	Scale 1–5	Yes	2	No changes		
	7.4. Viewpoint effect	From	Scale 1–5	Yes	Not available	4	The green roof substantially improves the urban landscape	Teachers; Students; Maintenance companies
		Towards	Scale 1–5	No	–	–	Not implemented	Neighbours from the neighbourhood
8. Knowledge and social capacity building for sustainable urban transformation	8.1. Participation	Number of accesses	N°/year	Yes	Not available	2038	Count for 6 months during 2023	Teachers; Students; Maintenance companies
		Number of activities	N°/year	Yes	Not available	375		School Director; Teachers;
		Total number of participants	N°/year	Yes	Not available	7500		
	8.2. Environmental awareness	Environmental educational activities	N°/year	Yes	Not available	19		School Director; Teachers;
		Total number of participants	N°/year	Yes	Not available	700		
		Communication and dissemination impacts	N°/year	Yes	Not available	37	Count for 2023 Website:1 Blog:1 Instagram:35	
9. Participatory planning and governance	9.1. Diversity of stakeholders		Number	Yes	5	No changes		School Director; Teachers;
	9.2. Co-participation	A) Design and construction	Scale 1–5	No	–	–	Not implemented	School Director; Teachers; Students
		B) Maintenance	Scale 1–5	No	–	–	Not implemented	Teachers; Students; Maintenance companies
		C) Management	Scale 1–5	No	–	–	Not implemented	School Director; Teachers; Students
10. Social justice and social cohesion	10.1. Social cohesion		Scale 1–5	Yes	Not available	3.9	The perceived level of integration and support is moderate-high	Teachers; Students
	10.2. Safety		Scale 1–5	Yes	–	–	Not implemented	Teachers; Students; Maintenance companies

(continued on next page)

Table 5 (*continued*)

Social Challenge Areas	Key aspect		Unit	Selection	Baseline Value	After 1 year Monitoring	Comments	Potential involved stakeholders
11. Health and well-being	11.1. Physical activities		N°/week	Yes	Not available	0.5	This green roof is not a regular space for physical exercise	School Director; Teachers;
	11.2. Well-being and happiness	Self-declared stress	Scale 1–5	Yes	Not available	2.6	Low to moderate	School Director; Teachers; Students
		Self-declared happiness	Scale 1–5	Yes	Not available	4.4	High	School Director; Teachers; Students
	11.3. Acoustic comfort	Perceived acoustic comfort	Scale 1–5	Yes	Not available	2	Green roof more silent than street	School Director; Teachers; Students
		Traffic Noise Index (TNI)	dB	Yes	Not available	61.2 dB	4 months average	Teachers; Students; Maintenance companies
	11.4. Thermal comfort	Perceived thermal comfort	Scale 1–5	Yes	Not available	2.6	Summer Green roof seems to be colder to equally cold than street	School Director; Teachers; Students
UTCI index		°C	Yes	Not available	35.4	Summer 3.7 °C higher for conventional roof	Teachers; Students; Maintenance companies	
12. New economic opportunities and green jobs	12.1. Property value	Self-declared property sales value	%	Yes	Not available	6–10	Average increase	School Director; Teachers; Students
		Self-declared property purchase value	%	Yes	Not available	6–10	Average increase	
	12.2. Job creation		Number of FTE	Yes	1.3	No changes	Full-time equivalent (FTE) jobs	School Director; Teachers; Maintenance companies
	12.3. Implementation cost		€/m²	Yes	726	No changes		School Director
	12.4. Food production	Total amount	Kg	Yes	Not available	600	Estimated. 60 m2 effective vegetable garden area x 10 kg/m2/year produced	Teachers; Students; Maintenance companies
		Different types	N°	Yes	Not available	29	Counted for 2022	
	12.5. Energy production		kWh/year	Yes	2196	No changes	Biosolar green roof	School Director; Teachers; Students

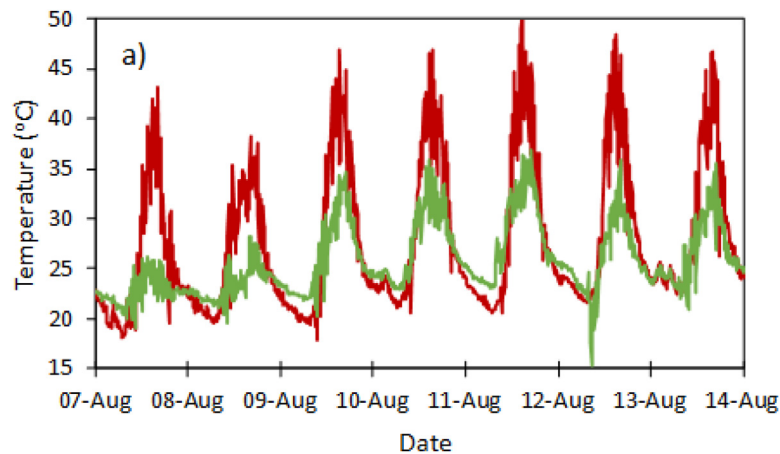


Fig. 10. The “Verd de proximitat BCN” project. Examples of weekly records of surface temperatures, in the summer period (August 2023), obtained on the three roofs evaluated: a) Escola Pérez-Iborra, b) TEBverd, c) Urbaser (high vegetation zone), d) Urbaser (low vegetation zone). Conventional roofs (red lines) are compared with vegetated roofs (green lines).

Step 4. continuous monitoring

The data in Table 3 show the potential of the proposed method in the collection of monitoring data. Clearly, one of the main challenges is to maintain data collection over time. That is why it is important to draw up a monitoring plan that specifies the annual data collection protocols and the roles of the people responsible for each of the established tasks.

For each specific project, it will be necessary to carry out an analysis of which of the identified stakeholders (Table 4) can carry out the monitoring of each of the key aspects of Table 5.

In the case study, for the Pérez Iborra school, an assignment of roles is suggested for each of the key aspects, which is detailed in the “Potential involved stakeholders” column in Table 5.

The frequency of data collection will depend on each of the key aspects and the methodology chosen within each key aspect, in accordance with what is specified in Annex A and Annex B.

During the year 2023, and as part of the “Verd de Proximitat BCN” project, data from the Pérez Iborra-school’s roof was collected.

Results from the continuous monitoring process of some of these key aspects, are briefly discussed below (See Annex A and Annex B to facilitate the interpretation of these results).

- Climate Resilience

On the one hand, regarding the “stored carbon” (0.14 kg C/m² in extensive green roofs, 1.43 kg C/m² for semi-intensive roofs) and considering that the roof of the Pérez-Iborra school is formed for 39.90 m² of extensive green roof and 172.31 m² of semi-intensive green roof, 251.85 kg of stored carbon are estimated (See Annex A and Annex B to facilitate the interpretation of the results).

On the other hand, with regard to the key aspect of “energy savings”, Fig. 10 shows the results from three monitored green roofs a) Escola Pérez-Iborra, b) TEBverd c) Urbaser (high vegetation) d) Urbaser (low vegetation). It can be observed that green roofs reduce the average surface roof temperatures compared to the equivalent conventional roofs without vegetation, by 3.2 °C in the Pérez Iborra School, 2.2 °C (low vegetation) and 4.8 °C (high vegetation) in Urbaser, and 3.1. °C in TEBverd, contributing to the building’ energy savings (See Annex A and Annex B to facilitate the interpretation of the results).

- Water management

With regard to the use of rainwater, continuous monitoring of the rainwater that reaches the rain gauge and the level of water contained in the storage tanks was carried out (See Annex A and Annex B for to facilitate the interpretation of the results).

Fig. 11 shows an example for two episodes of rain in the month of April 2023. When there is an episode of rain, the volume of water that falls on the roof (Vrain) is determined by multiplying the data recorded by the rain gauge (L /m²) for the roof surface. On the other hand, from the record of the water level in the tanks and knowing their shape and dimensions, the volume of water collected (Vwater tank) is calculated.

Finally, the average is made, for the different rain episodes, of the percentage $V_{\text{water tank}} / V_{\text{pluja}} * 100$.

According to this methodology, a rainwater storage capacity of 34 % was calculated.

In reference to “water use” and considering the number of times that the rainwater tank is emptied due to its use for irrigation, an amount of 11.8 m³/year has been calculated, which made it possible to save 12.5 % of the water used for irrigation (94 m³/year).

- Natural and Climate Hazards

To measure the reduction of the Heat Island effect, continuous simultaneous monitoring of the air temperature was carried out, both in the central area of the green roof and in an equivalent conventional roof without vegetation (See Annex A and Annex B to facilitate the interpretation of the results).

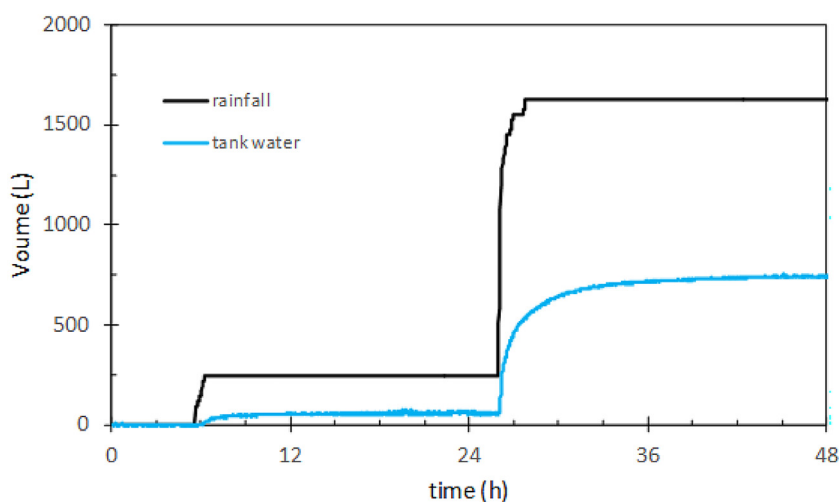


Fig. 11. Example that shows the evolution of the volumes of water, of rain on the roof and arrival in the tanks, for two episodes of rain that occurred on April 29 and 30, 2023 at the Pérez-Iborra school.

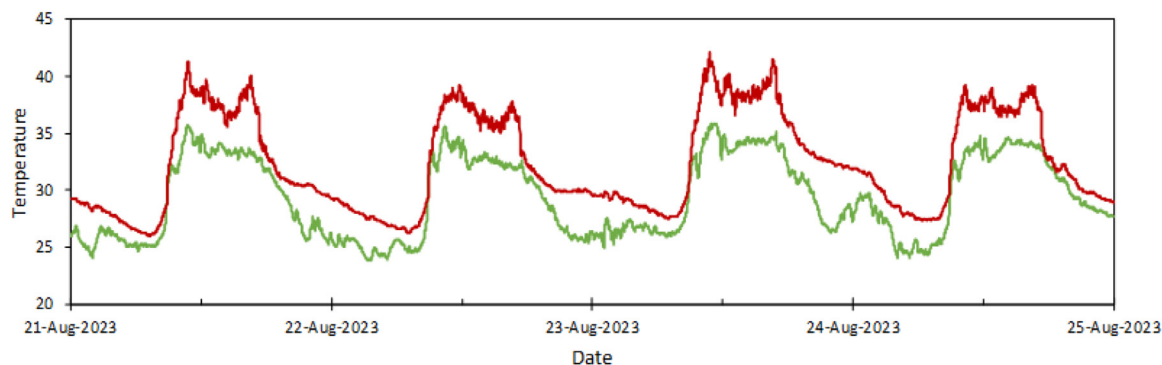


Fig. 12. Evolution of air temperatures on the Urbaser green roof (green line) and on a conventional Catalan tile roof without vegetation (red line).

In Fig. 12, the evolution of ambient temperatures during the summer period of 2023 in the Pérez-Iborra school green roof, compared to the equivalent roof without vegetation, can be seen. A reduction of 5 °C was measured in the green roof.

- Knowledge and Social Capacity Building for Sustainable Urban Transformation

One of the innovative indicators of the BIG-impact method is the automatic counting of people who access the green roofs using sensors (See Annex A and Annex B to facilitate the interpretation of the results).

This system not only allows you to know the total number of accesses, as an indicator of the success of the green roof in terms of participation, 2427 in the Pérez-Iborra school in a period of three months (from February to April), but also gives very valuable information for the manager of the green infrastructure regarding the dynamics of use. Fig. 13 shows access to the deck by day of the week and by time of day.

In addition, in this project 19 specific activities were planned for environmental awareness, involving 700 participants. Up to 37 communication and dissemination impacts were carried out during 2023.

Step 5. impact evaluation and cost-benefit analysis

Through the application of the BIG-impact method, based on the results of Table 5, a global assessment of the impact of the green roof of the Pérez Iborra School was made, both at city and building level, for each of the Social Challenge Areas:

1. Climate Resilience

The Pérez Iborra school green roof stores 251.85 kg of carbon. An increase in biomass, through good maintenance, can improve this value by 30 %. In addition, the green roof contributes to energy savings in the building. Despite not being able to quantify the exact value of the reduction in energy consumption (it is a real case), this fact is evident from the reduction of the average surface temperature of 3.2 °C compared to the conventional twin roof without vegetation.

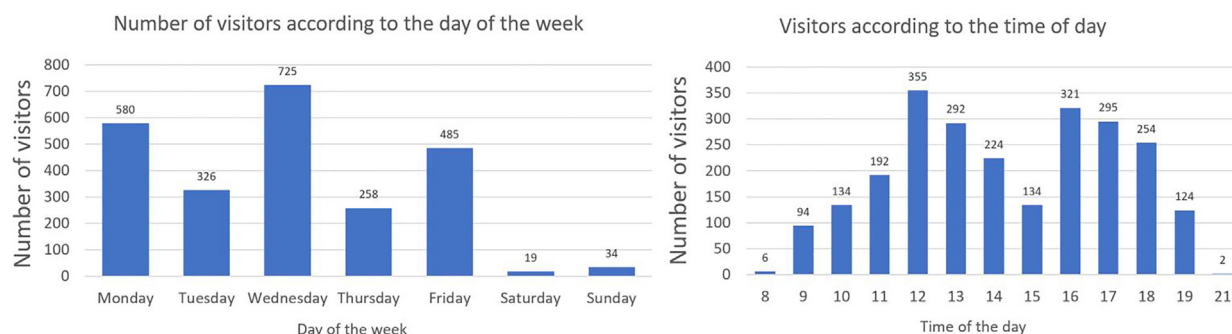


Fig. 13. Participation access to the green roof of Pérez-Iborra by days of the week and by hours of the day during a period of around three months from 2023.

2. Water management

In this green roof, 34 % of the rainwater was collected in the water tanks during the study period. This rainwater (11.8 m³/year) made it possible to save 12.5 % of the water used for irrigation (94 m³/year). It should be noted that 2023 was a year in which rainfall was half the usual average in the Barcelona area.

3. Natural and Climate Hazards

In the green area of the Pérez-Iborra green roof, temperatures during the summer period were 5 °C lower than their equivalents in the twin roof without vegetation, thus contributing to the reduction of the Urban Heat Island effect.

4. Green Space Management

The Pérez-Iborra green roof has a great potential to provide ecosystem services, up to 19 out of 20 of those listed in Table 3. Regarding accessibility, the questionnaire for users reached a value on a scale of 1–5 of 3.00 ± 1.27 , i.e., reasonably accessible, but with a wide dispersion in the answers. On the other hand, the self-evaluation highlights that there is room for improvement in terms of accessibility, especially for people with disabilities and for maintenance.

The percentage of green area of the green roof is 55 %. Despite not being a high value, the large number of activities that are carried out with groups of students, justifies the need for pedestrian and useful space for activities.

The maintenance cost is around 40€/m²/year, which is high. This is a clear case in which a municipal incentive for maintenance would help preserve the green roof and consequently the ecosystem services it provides to the city.

5. Biodiversity

The location of the green roof, in the heart of the city, serves as a structural connecting element for biodiversity with other green elements. Up to 5 green elements have been detected in a radius of 500 m around. It is therefore confirmed that the green roof of Pérez-Iborra acts as a connecting element for urban biodiversity.

6. Air Quality

In the different odour monitoring campaigns carried out, up to 69 pleasant odours have been quantified. Thus, green roofs contribute to improving the olfactory landscape of urban environments.

It is worth noting that 38 unpleasant odours were also detected, often related to urban and food smells, coming from the smell and smoke exits from the buildings. This latter information should be of great help for the improvement of future designs and for the management of green roofs.

7. Place Regeneration

From the collection of data on the perceived quality of the space, it emerged that the green roof is a more pleasant space than a conventional roof or the street. With reference to the materials used, an expert self-evaluation showed that the inner layers, for protection and drainage, can be improved in terms of sustainability. Finally, the green roof clearly generates new perspectives of great landscape value towards the immediate urban environment (viewpoint effect).

8. Knowledge and Social Capacity Building for Sustainable Urban Transformation

The green roof of the Pérez-Iborra school is an excellent example of the generation and transmission of Knowledge and Social Capacity Building for Sustainable Urban Transformation. In 2023, up to 375 activities were planned on the green roof with a total of 7500 participants. With the automatic access counting system, 2038 accesses were recorded in less than six months. 19 specific activities were planned for environmental awareness, involving 700 participants. Up to 37 communication and dissemination impacts were carried out during 2023.

9. Participatory Planning and Governance

This green roof is rich in terms of the diversity of stakeholders that can be involved: those of property and management, students, teachers, families, maintenance company, among others.

There is no data on co-participation in design and construction, maintenance, or management, but the potential is very high, and it is worth exploring it in the near future.

10. Social Justice and Social Cohesion

The responses to the questionnaires indicated that the green roof positively contributes to the creation of social relationships and social cohesion among users.

Table 6

Summary of main values for Step 5. BIG cost-benefit analysis for the case study.

Social Challenge Area	Key aspect	Kosanova S. 2019 €/m ²	Nurmi V. 2013 €/m ²	Koroxenidis E. 2021 €/m ²	Self- calculation €/m ²	Set for assessment €/m ²
1. Climate resilience	1.1. Stored carbon					
	1.2. Energy savings					
	Cooling	0.17	8.5			0.17
	Heating	0.14–0.52	22.86			0.14
2. Water management	2.2. Use of rainwater				0.07	0.07
	2.2. Use of water	0.07				0.07
3. Natural and Climate Hazards	3.1. Reduction of Urban Heat Island effect	0.01		21		0.01
	3.2. Urban Runoff control	0.02	1.9–3.4	10.1		0.02
4. Green Space Management	4.1. Provision of Ecosystem Services					
	4.2. Accessibility					
	4.3. Percentage of green area					
	4.4. Maintenance cost					–40
5. Biodiversity Enhancement	5.1. Connectivity					
	5.2. Species	0.02				0.02
	5.3. Pollinators species					
6. Air quality	6.1. Pollution capture	0.02	4.8–6.9			0.02
	6.2. Ambient smell					
7. Place Regeneration	7.1. Perceived Quality of Space	6.7–35				6.7
	7.2. Sense of belonging/identity with the space					
	7.3. Materials used					
	7.4. Viewpoint effect					
8. Knowledge and Social Capacity	8.1. Participation					
Building Transformation	8.2. Environmental awareness					
9. Participatory Planning and Governance	9.1. Diversity of Stakeholders					
	9.2. Co-participation					
10. Social Justice and Social Cohesion	10.1. Social cohesion					
	10.2. Safety					
11. Health and Wellbeing	11.1. Physical activities					
	11.2. Well-being and happiness					
	11.3. Acoustic comfort	25	20			20
	11.4. Thermal comfort					
12. New Economic Opportunities and Jobs	12.1. Property value	35–359				35
	12.2. Job creation					
	12.3. Implementation cost					
	12.4. Food production				4.6	4.6
	12.5. Energy production				0.8	0.8
Potential benefits for the city/society					€/m ²	6.84
Potential benefits for the property					€/m ²	20.71

11. Health and Well-being

The answers to the questionnaires showed that being on the green roof, users show a moderate-low level of stress and a high level of happiness. They also considered that the perceived comfort, both thermal and acoustic, is better on the green roof than in the street. In fact, and based on recorded climatological data, the UTCI index was 3.7 °C lower in the green roof than its conventional twin roof during the summer period. Physical activities are not usually done on this green roof.

12. New Economic Opportunities and Green Jobs

Although little data was recorded for this indicator, the self-reported increase in property value was between 6 and 10 %. On the other hand, it was calculated that the green roof involves 1.3 full-time equivalent jobs, including both maintenance tasks as well as the management and teaching tasks. On the green roof, around 600 kg of agricultural products are produced a year, about 10 kg/m² in the vegetable garden area. In addition, the solar panels produce an amount of 2196 kWh/year.

The cost-benefit analysis of BIG systems must consider, in its most simplified conception, on the one hand the maintenance costs, and on the other the benefits linked to the ecosystem services provided. In the study example, the maintenance cost is approximately 40 euros/m² per year. Unfortunately, monetization of some of the ecosystem services is often very difficult. In fact, this is one of the “wicked issues” of BIG systems, since many of these benefits, especially the social ones, are very difficult to monetize. Very few references are commonly found on the monetary value of the benefits provided by green roofs and green facades. A theoretical assessment has been made based on the few bibliographical references for green roofs [46–51]. Some of those references are not located in the Mediterranean climate, but are still suitable for an approximate assessment. [Table 6](#)

summarizes the values that have been considered in the calculation and the cost-benefit calculation. According to the previous references for the key factors where monetary values are available, the smallest value has been selected.

When making the cost-benefit balance, the total was calculated, which represents 27.55 €/m² of economic benefit. On the other hand, when the direct benefits for the property of the building are analysed separately, with respect to the benefits for the city, the former represent 20.71 €/m², and the latter 6.84 €/m² of economic benefit.

It must be considered that, on the one hand, the large number of benefits that cannot be quantified due to a lack of data on their monetary value is significant. On the other hand, it should be noted that the calculation presented is intended to illustrate the methodology to be followed, on the understanding that the lack of available data means that the result obtained is only an approximation.

Limitations

The BIG-impact method should be very useful for the management of BIG infrastructures, contributing to their long-term service life, and what is more important, favouring the provision of ecosystem services during their useful life span. BIG-impact is a working methodology which, without losing scientific rigor, is accessible to involved stakeholders in the management and use of BIG projects, and which makes it possible to capitalize on the research and results obtained on BIG to date.

The complexity of the context of BIG in real projects, as well as the heterogeneity of ecosystem services has made it difficult to comprehensively monitor and evaluate their impacts. The BIG-impact method has been designed to overcome these barriers, on the understanding that it has been necessary to make adaptations and simplifications, which despite slightly moving away from scientific rigor, will make it possible to carry out the evaluation of the impacts in BIG real cases.

The BIG-impact method will be applied to specific BIG cases in specific contexts, and therefore comparisons of results between projects should be avoided. The purpose of the BIG-impact method is to provide a tool that allows the continuous improvement of specific BIG projects, providing continuous information on their operation and improving their maintenance and management.

Main limitations of the current version of the BIG-impact method are:

1. Implicit difficulties in monitoring and capturing data in real cases.
2. The heterogeneity of the ecosystem services to be monitored and evaluated.
3. The difficulty of monetizing some of the ecosystem services, especially those linked to social and well-being aspects.
4. In future versions, dysfunctions and compensations between ecosystem services should also be considered.

Conclusions

- A Methodological framework for impact evaluation of Building-Integrated Greenery (BIG-impact) has been provided.
- In its design, the current references at European and global level for the establishment of plans for monitoring and evaluating the impacts of nature-based solutions has been taken into consideration. A specific adaptation for the Building-integrated Greenery systems has been conducted.
- The system is replicable in any real project of integration of vegetation onto the building envelope.
- It is easily applicable by managers of green infrastructures and allows the collaboration of involved stakeholders, i.e., direct users, maintenance companies, etc.

Ethics statements

The data collected through questionnaires to obtain the key aspects of social types are completely anonymous and it is impossible to know the identity of any of the people who answered them.

Declaration of competing interest

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

CRediT authorship contribution statement

Gabriel Pérez: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Supervision, Project administration. **Marcelo Reyes:** Formal analysis, Investigation, Writing – review & editing. **Julià Coma:** Data curation, Formal analysis, Investigation, Writing – review & editing. **Aleix Alva:** Formal analysis, Software, Data curation, Investigation. **Fanny E. Berigüete:** Investigation, Writing – review & editing. **Ana M. Lacasta:** Investigation, Validation, Writing – review & editing.

Data availability

Data will be made available on request.

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Supplementary materials

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References

- [1] Demographia World Urban Areas (Built Up Urban Areas or World Agglomerations). 19th Annual Edition. August 2023. <http://www.demographia.com/db-worldua.pdf>.
- [2] R. Marchal, G. Piton, E. Lopez-Gunn, P. Zorrilla-Miras, P. van der Keur, K.W.J. Dartée, P. Pengal, J.-H. Matthews, J.M. Tacnet, N. Graveline, et al., The (Re)insurance industry’s roles in the integration of nature-based solutions for prevention in disaster risk reduction—insights from a European survey, *Sustainability* 11 (2019) 6212, doi:10.3390/su11226212.
- [3] European Commission, Directorate-General for Research and Innovation, Evaluating the impact of nature-based solutions – A handbook for practitioners, Publications Office of the European Union, 2021, doi: 10.2777/244577.
- [4] G. Pérez, K. Perini, Nature Based Strategies for Urban and Building Sustainability, Imprint: Butterworth-Heinemann, Elsevier, 2018 eBook ISBN: 9780128123249. Paperback ISBN: 9780128121504, doi:10.1016/C2016-0-03181-9.
- [5] I. Suter, Č. Maksimović, M. van Reeuwijk, A neighbourhood-scale estimate for the cooling potential of green roofs, *Urban Clim.* 20 (2017) 33–45, doi:10.1016/j.uclim.2017.02.007.
- [6] M. Santamouris, Cooling the cities - A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments, *Sol. Energy* 103 (2014) 682–703, doi:10.1016/j.solener.2012.07.003.
- [7] W. Leal Filho, L. Echevarria Icaza, V.O. Emanche, A. Quasem Al-Amin, An evidence based review of impacts, strategies and tools to mitigate urban heat islands, *Int. J. Environ. Res. Publ. Health* 14 (2017), doi:10.3390/ijerph14121600.
- [8] T. Susca, S.R. Gaffin, G.R. Dell’Osso, Positive effects of vegetation: urban heat island and green roofs, *Environ. Pollut.* 159 (2011) 2119–26c, doi:10.1016/j.envpol.2011.03.007.
- [9] S. Musa, M. Arish, N. Arshad, M. Jalil, H. Kasmin, Z. Ali, M.S. Mansor, Potential of storm water capacity using vegetated roofs in Malaysia, in: *Proceedings of the international conference on civil engineering practice (ICCE08)*, Malaysia: Kuantan, Pahang, 2008, pp. 12–14.
- [10] M. Shafique, R. Kim, K. Kyung-Ho, Green roof for stormwater management in a highly urbanized area: the case of Seoul, Korea, *Sustainability* 10 (2018) 584, doi:10.3390/su10030584.
- [11] M. Uhl, L. Schiedt, Green roof storm water retention—monitoring results, *Edinburgh: 11th International Conference on Urban Drainage*, 2008.
- [12] T.L. Carter, T.C. Rasmussen, Hydrologic Behaviour of vegetated roofs, *JAWRA J. Am. Water Resour. Assoc.* 42 (2006) 1261–1274, doi:10.1111/j.1752-1688.2006.tb05299.x.
- [13] E. Burszta-Adamiak, Analysis of the retention capacity of green roofs, *J. Water Land Dev.* 16 (I–VI) (2012) 3–9 PL ISSN 1429–7426, doi:10.2478/v10025-012-0018-8.
- [14] F. Mayrand F, P. Clergeau, Green roofs and green walls for biodiversity conservation: a contribution to urban connectivity? *Sustainability* 10 (2018) 985, doi:10.3390/su10040985.
- [15] N. Dunnett, Green roofs for biodiversity: reconciling aesthetics with ecology, in: *Proceedings of the 4th annual greening rooftops for sustainable communities*, Boston, 2006, pp. 11–12.
- [16] N.S.G. Williams, J. Lundholm, J.S. MacIvor, FORUM: do green roofs help urban biodiversity conservation? *J. Appl. Ecol.* 51 (2014) 1643–1649, doi:10.1111/1365-2664.12333.
- [17] S. Brenneisen, Space for urban wildlife: designing green roofs as habitats in Switzerland, *Urban habitats* 4 (2006) <http://www.urbanhabitats.org/v04n01/wildlife.pdf.pdf>.
- [18] R. Collins, M. Schaafsma, M.D. Hudson, The value of green walls to urban biodiversity, *Land Use Pol.* 64 (2017) 114–123, doi:10.1016/j.landusepol.2017.02.025.
- [19] J. Yang, Q. Yu, P. Gong, Quantifying air pollution removal by green roofs in Chicago, *Atmos. Environ.* 42 (2008) 7266–7273, doi:10.1016/j.atmosenv.2008.07.003.
- [20] D.B. Rowe, Green roofs as a means of pollution abatement, *Environ. Pollut.* 159 (2011) 2100–2110, doi:10.1016/j.envpol.2010.10.029.
- [21] T.A.M. Pugh, A.R. MacKenzie, J.D. Whyatt, C.N. Hewitt, Effectiveness of green infrastructure for improvement of air quality in urban street canyons, *Environ. Sci. Technol.* 46 (2012) 7692–7699, doi:10.1021/es300826w.
- [22] V. Jayasooriya, A. Ng, S. Muthukumaran, B. Perera, Green infrastructure practices for improvement of urban air quality, *Urban For. Urban Green* 21 (2017) 34–47, doi:10.1016/j.ufug.2016.11.007.
- [23] J. Czemieli Berntsson, Green roof performance towards management of runoff water quantity and quality: a review, *Ecol. Eng.* 36 (4) (2010) 351–360, doi:10.1016/j.ecoleng.2009.12.014.
- [24] D.B. Rowe, Green roofs as a means of pollution abatement, *Environ. Pollut.* 159 (8–9) (2011) 2100–2110, doi:10.1016/J.ENVPOL.2010.10.029.
- [25] S. Pradhan, S.G. Al-Ghamdi, H.R. Mackey, Greywater recycling in buildings using living walls and green roofs: a review of the applicability and challenges, *Sci. Total Environ.* (2018), doi:10.1016/j.scitotenv.2018.10.226.
- [26] V. Prodanovic, B. Hatt, D. McCarthy, K. Zhang, A. Green walls for greywater reuse: understanding the role of media on pollutant removal, *Ecol. Eng.* 102 (2017) 625–635, doi:10.1016/j.ecoleng.2017.02.045.
- [27] N. Kabisch, M. van den Bosch, R. Laforzetta, The health benefits of nature-based solutions to urbanization challenges for children and the elderly—A systematic review, *Environ. Res.* 159 (2017) 362–373, doi:10.1016/j.envres.2017.08.004.

- [28] M. Hedblom, B. Gunnarsson, B. Iravani, I. Knez, M. Schaefer, P. Thorsson, et al., Reduction of physiological stress by urban green space in a multisensory virtual experiment, *Sci. Rep.* 9 (2019) 1–11, doi:[10.1038/s41598-019-46099-7](https://doi.org/10.1038/s41598-019-46099-7).
- [29] A.E. Van den Berg, J.E. Wesselijs, J. Maas, K. Tanja-Dijkstra, Green walls for a restorative classroom environment: a controlled evaluation study, *Environ. Behav.* 49 (2017) 791–813, doi:[10.1177/0013916516667976](https://doi.org/10.1177/0013916516667976).
- [30] O. Saadatian, K. Sopian, E. Salleh, C. Lim, S. Riffat, E. Saadatian, et al., A review of energy aspects of green roofs, *Renew. Sustain. Energy Rev.* 23 (2013) 155–168, doi:[10.1016/j.rser.2013.02.022](https://doi.org/10.1016/j.rser.2013.02.022).
- [31] I. Jaffal, S.E. Ouldboukhite, R. Belarbi, A comprehensive study of the impact of green roofs on building energy performance, *Renew. Energy* 43 (2012) 157–164, doi:[10.1016/j.renene.2011.12.004](https://doi.org/10.1016/j.renene.2011.12.004).
- [32] J. Coma J, G. Pérez, A. de Gracia, S. Burés, M. Urrestarazu, L.F. Cabeza, Vertical greenery systems for energy savings in buildings: a comparative study between green walls and green facades, *Build. Environ.* 111 (2017) 228–237, doi:[10.1016/j.buildenv.2016.11.014](https://doi.org/10.1016/j.buildenv.2016.11.014).
- [33] G. Pérez, J. Coma, S. Sol, L.F. Cabeza, Green facade for energy savings in buildings: the influence of leaf area index and facade orientation on the shadow effect, *Appl. Energy* 187 (2017) 424–437, doi:[10.1016/j.apenergy.2016.11.055](https://doi.org/10.1016/j.apenergy.2016.11.055).
- [34] G. Pérez, J. Coma, I. Martorell, L.F. Cabeza, Vertical Greenery Systems (VGS) for energy saving in buildings: a review, *Renew. Sustain. Energy Rev.* 39 (2014) 139–165, doi:[10.1016/j.rser.2014.07.055](https://doi.org/10.1016/j.rser.2014.07.055).
- [35] Z. Azkorra, G. Pérez, J. Coma, L.F. Cabeza, S. Burés, J.E. Alvaro, et al., Evaluation of green walls as a passive acoustic insulation system for buildings, *Appl. Acoust.* 89 (2015) 46–56, doi:[10.1016/j.apacoust.2014.09.010](https://doi.org/10.1016/j.apacoust.2014.09.010).
- [36] M. Connelly, M. Hodgson, Experimental investigation of the sound transmission of vegetated roofs, *Appl. Acoust.* 74 (2013) 1136–1143, doi:[10.1016/j.apacoust.2013.04.003](https://doi.org/10.1016/j.apacoust.2013.04.003).
- [37] G. Pérez, J. Coma, C. Barreneche, A. de Gracia, M. Urrestarazu, S. Burés, et al., Acoustic insulation capacity of vertical greenery systems for buildings, *Appl. Acoust.* 110 (2016) 218–226, doi:[10.1016/j.apacoust.2016.03.040](https://doi.org/10.1016/j.apacoust.2016.03.040).
- [38] T. Van Renterghem, D. Botteldooren, Reducing the acoustical façade load from road traffic with green roofs, *Build. Environ.* 44 (2009) 1081–1087, doi:[10.1016/j.buildenv.2008.07.013](https://doi.org/10.1016/j.buildenv.2008.07.013).
- [39] T. Van Renterghem, M. Hornikx, J. Forssen, D. Botteldooren, The potential of building envelope greening to achieve quietness, *Build. Environ.* 61 (2013) 34–44, doi:[10.1016/j.buildenv.2012.12.001](https://doi.org/10.1016/j.buildenv.2012.12.001).
- [40] T. Van Renterghem, D. Botteldooren, In-situ measurements of sound propagating over extensive green roofs, *Build. Environ.* 46 (2011) 729–738, doi:[10.1016/j.buildenv.2010.10.006](https://doi.org/10.1016/j.buildenv.2010.10.006).
- [41] P. Kumar, A. Druckman, J. Gallagher, B. Gatersleben, S. Allison, T.S. Eisenman, U. Hoang, S. Hama, A. Tiwari, A. Sharma, K.V. Abhijith, D. Adlakha, A. McNabola, T. Astell-Burt, X. Feng, A.C. Skeldon, S. de Lusignan, L. Morawska, The nexus between air pollution, green infrastructure and human health, *Environ. Int.* 133 (A) (2019) 105181, doi:[10.1016/j.envint.2019.105181](https://doi.org/10.1016/j.envint.2019.105181).
- [42] “Verd de Proximitat BCN” research project. <https://verdbcn.com/en/>
- [43] German Landscape Research (FLL) Green Roof Guidelines – Guidelines for the Planning, Construction and Maintenance of Green Roofs, 2018.
- [44] R.A. Bustami, M. Belusko, J. Ward, S. Beecham, Vertical greenery systems: a systematic review of research trends, *Build. Environ.* 146 (2018) 226–237, doi:[10.1016/j.buildenv.2018.09.045](https://doi.org/10.1016/j.buildenv.2018.09.045).
- [45] G. Pérez, L. Rincón, A. Vila, J.M. Gonzalez, L.F. Cabeza, Green vertical systems for buildings as passive systems for energy savings, *Appl. Energy* 88 (2011) 4854–4859, doi:[10.1016/j.apenergy.2011.06.032](https://doi.org/10.1016/j.apenergy.2011.06.032).
- [46] S. Konasova, Cost-benefit analysis of green roofs in densely built-up areas, 12th Economics & Finance Conference, IISES, Dubrovnik, 27 August 2019 ISBN, doi:[10.20472/EFC.2019.012.013](https://doi.org/10.20472/EFC.2019.012.013).
- [47] P. Rosasco, K. Perini, Evaluating the economic sustainability of a vertical greening system: a Cost-Benefit Analysis of a pilot project in mediterranean area, *Build. Environ.* 142 (2018) 524–533, doi:[10.1016/j.buildenv.2018.06.017](https://doi.org/10.1016/j.buildenv.2018.06.017).
- [48] V. Numi, A. Votsis, A. Perrels, S. Lehvävirta. Cost-benefit analysis of green roofs in urban areas: case study in Helsinki. REPORTS N° 2013:2. ISBN 978-951-697-788-4.
- [49] E. Koroxenidis, T. Theodosiou, Comparative environmental and economic evaluation of green roofs under Mediterranean climate conditions – Extensive green roofs a potentially preferable solution, *J. Clean. Prod.* 311 (2021) 127563, doi:[10.1016/j.jclepro.2021.127563](https://doi.org/10.1016/j.jclepro.2021.127563).
- [50] F. Fantozzi, C. Bibbiani, C. Gargari, R. Rugani, G. Salvadori, Do green roofs really provide significant energy saving in a Mediterranean climate? Critical evaluation based on different case studies, *Front. Archit. Res.* 10 (2) (2021) 447–465, doi:[10.1016/j.foar.2021.01.006](https://doi.org/10.1016/j.foar.2021.01.006).
- [51] P. Bevilacqua, D. Mazzeo, R. Bruno, N. Arcuri, Surface temperature analysis of an extensive green roof for the mitigation of urban heat island in southern mediterranean climate, *Energy Build* 150 (2017) 318–327, doi:[10.1016/j.enbuild.2017.05.081](https://doi.org/10.1016/j.enbuild.2017.05.081).