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Sustainability Factor for the Cost–Benefit Analysis of Building-Integrated Greenery Systems

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Abstract: Building-integrated greenery (BIG) systems, which include green roofs and green facades, are well-established nature-based solutions (NBS) with proven scientific benefits. However, initial costs and economic apprehensions stemming from potential negative outcomes act as adoption barriers. Furthermore, the lack of standardized indicators and assessment methodologies for evaluating the city-level impacts of BIG systems presents challenges for investors and policy makers. This paper addresses these issues by presenting a comprehensive set of indicators derived from widely accepted frameworks, such as the Common International Classification of Ecosystem Services (CICES) and the NBS impact evaluation handbook. These indicators contribute to the creation of a 'sustainability factor', which facilitates cost–benefit analyses for BIG projects using locally sourced data. The practical application of this factor to a 3500 m^2 green roof in Lleida, Catalonia (Spain) demonstrates that allocating space for urban horticultural production (i.e., food production), CO_2 capture, and creating new recreational areas produces benefits that outweigh the costs by a factor value of nine during the operational phase of the green roof. This cost–benefit analysis provides critical insights for investment decisions and public policies, especially considering the significant benefits at the city level associated with the implementation of BIG systems.

Keywords: nature-based solutions; green roofs; green facades; cost–benefit ratio; sustainability; indicators; measurement; ecosystem services

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1. Introduction

In 2015, the United Nations (UN) established 17 Sustainable Development Goals (SDGs) as part of a global strategy aimed at reducing inequalities, eradicating all forms of poverty, and addressing climate change by 2030 [1]. Within this framework, the eleventh goal is dedicated to making cities and human settlements more inclusive, safe, resilient, and sustainable. This approach is critical because, for the first time, since 2008, the urban population has exceeded the number of people living in rural areas. This demographic shift has created new challenges related to inequity, poverty, limited opportunities, and scarcity of resources. As a result, it is essential to investigate approaches for transitioning from a stressed-out city to one that is sustainable and better adapted to human needs [1,2].

Urban areas are important hubs for innovation, cultural exchange, and commercial activity, and they play an important role in human and economic development. However, unprecedented urban growth has resulted in a significant demand for natural resources, with cities responsible for three-quarters of global waste and pollution [3]. Addressing these challenges involves implementing nature-based solutions (NBS) in urban environments [3], with the goal of mitigating impacts and promoting sustainable development. Building-integrated greenery (BIG) systems such as green roofs, green facades, and green walls are examples of NBS that integrate vegetation into the building envelope and provide a variety of ecosystem services.

While BIG systems have been technologically established for years, with successful implementations in cities around the world and well-documented scientific benefits, there is still a knowledge gap regarding the evaluation of their impact in real cases, which is required to confirm and ensure their long-term viability and sustainability [4]. In addition, the evaluation of economic, social, and environmental impacts of BIG systems is necessary for making informed decisions regarding capital investment and operational decisions [5]. As a result, it is important to understand the different dimensions of BIG systems in order to evaluate their contribution to sustainability and the overall project goals. Proper evaluations will provide decision makers with valuable data about their costs and benefits [4].

The benefits of BIG systems in urban areas, encompassing economic, environmental, and social impacts, have been extensively studied. These impacts include the reduction in greenhouse gases, increased biodiversity, urban farming, mitigation of the heat island effect, decreased rainwater runoff, and enhanced property values [6,7]. When these benefits are acknowledged, quantified, and assessed, property owners, investors, and other stakeholders can actively promote their development at the local level [8]. Quantifying and assessing these benefits addresses a current research need [9] and provides necessary data on the cost–benefit relationship associated with BIG systems in urban areas.

Previous studies have established frameworks, decision-making tools, and evaluation systems for specific ecosystem services offered by BIG systems in urban areas. In a study conducted by Ledesma et al. (2020) [9], an extensive green roof was analyzed, providing several indicators related to a school building. Manso et al. (2020) [7] provide a review of ecosystem services that green roofs and green walls can offer to urban environments. They also present a comprehensive list of the benefits and costs associated with green infrastructure, along with various indicators. Finally, the study conducted by Tabatabaee et al. (2019) [10] provides a range of indicators, including some qualitative aspects such as the creation of new garden and leisure areas, as well as improvements in aesthetics. However, most of the indicators considered in previous studies are specific to the case studies presented and usually require expert judgement to evaluate the impact of BIG systems when applied to a building.

Various classification systems for ecosystem services and their principal indicators have been created to serve as a foundational reference for quantifying and assessing the benefits of NBS in a broader context. One notable example is the Common International Classification of Ecosystem Services (CICES) v5.1. This list provides generic indicators that are grouped into three sections: provisioning (related to energetic outputs from living systems), regulation and maintenance (related to modifications to the environment), and cultural (related to the ES affecting the physical and mental well-being of people). The CICES table provides a general overview of various classifications and types of indicators for established ecosystem services. It encompasses a large array of topics with a wide range of indicators grouped into multiple sections and subsections. The challenge lies in refining this extensive list to obtain a specific set of indicators that can group the BIG system benefits. The current version, CICES v5.1, is the result of an effort by the European Environment Agency (EEA) to quantify, account for, and assess ecosystem services [11]. CICES v5.1 is a validated framework that standardizes an accepted vocabulary for different stakeholders regarding this topic.

Another classification scheme for the incorporation of common indicators can be found in the European Commission's practitioner handbook. This document contains a comprehensive catalogue of indicators associated with NBS and their respective units of measurement [12]. BIG systems, such as green roofs, green alleys, and green walls/facades, are classified as Type 3 in this handbook due to their ability to generate novel ecosystem services. This handbook, similar to CICES, provides a comprehensive list of generic indicators without taking into account the scale of application. Integrating validated indicators from these frameworks will create a precise classification system with a common nomenclature for estimating the benefits of BIG systems, facilitating their integration into management and accounting systems [13].

This paper proposes an assessment methodology for the main indicators of the impact of BIG systems in urban environments, ranging from individual buildings to the broader urban context. This methodology provides a formula that enables the calculation of the so-called "BIG sustainability factor" for any project using local data.

This paper is organized as follows: Section 2 outlines the research process, describing the different steps involved in extracting a concise set of indicators from major NBS frameworks. It also provides information on measurement units, valuation procedures, and offers insights into the case study where the proposed "sustainability factor" was implemented.

In Section 3, the results are presented and discussed. This includes tables showing the recommended indicators for the three pillars of sustainability, as well as the methodologies used to monetize these indicators. Furthermore, the definition of the sustainability factor is detailed along with all its subfactors and is then applied to a real case, a green roof located in Lleida, Catalonia (Spain), to demonstrate its practical utility.

2. Materials and Methods

Figure 1 illustrates the detailed methodology used for calculating the sustainability factor. This factor is crucial in assessing the impact of building-integrated greenery (BIG) systems and facilitating the implementation of cost–benefit analyses.

The methodology is organized into the following five steps:

(1) Selection of suitable key indicators for assessing the impacts of BIG systems from CICES v5.1.
(2) Alignment of these indicators with the NBS valuation standards defined in the EU handbook.
(3) Analysis of which indicators can be recorded systematically.
(4) Establishment of economic evaluation criteria for these indicators.
(5) Creating a formula to calculate the impact on specific building projects outfitted with BIG systems, such as green roofs, green walls, and green facades.

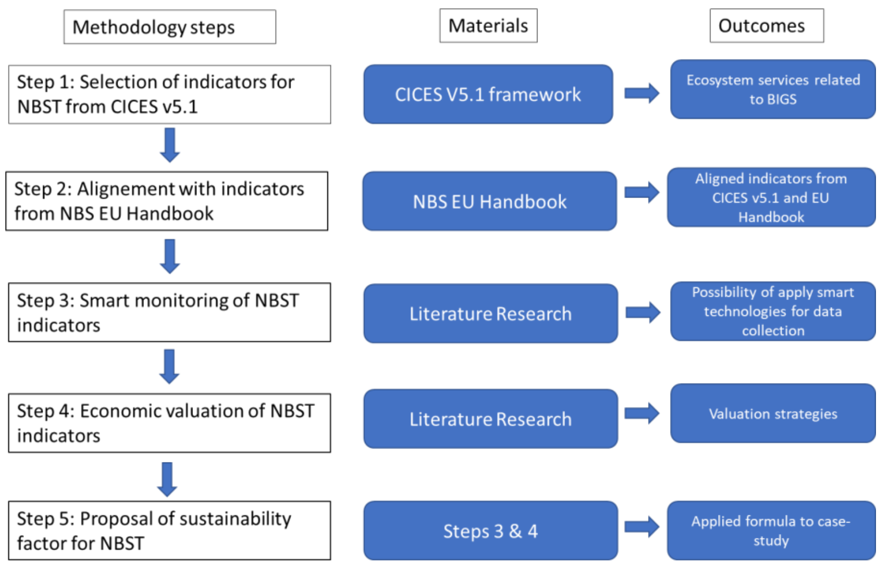

Figure 1. Outline of the definition process of the BIG sustainability factor.

2.1. Step 1: Selection of the Indicators for BIG Systems from CICES v5.1

The CICES v5.1 framework is an elaborate structure that includes a comprehensive list of indicators and metrics for various ecosystem services and nature-based solutions (NBS) [11]. Indicators pertaining to specific BIG systems benefits were identified through extensive literature research and reviews. Subsequently, these indicators were compared with those in the CICES v5.1 framework, with units of measurement assigned where applicable.

Indicators identified in both the literature research and the CICES v5.1 table were selected. Table 1 summarizes this process, illustrating the alignment between BIG systems benefits and the framework. The indicators are listed in Table 1 as either quantitative or qualitative.

Table 1. Ecosystem services CICES V5.1 related to BIG systems (green roofs, green walls, and green facades) and the suggested measurement parameters.

Ecosystem Services CICES V5.1					**Suggested Parameters and Measure Units at Site/Building Level (Small Scale)**
Section	**Division**	**Group**	**Class**	**Code**	
Provisioning	**Division**	**Group**	**Class**	**Code**	
Provisioning (Biotic)	Biomass	Cultivated terrestrial plants for nutrition, materials, or energy	Cultivated terrestrial plants (including fungi, algae) grown for nutritional purposes	1.1.1.1	Crops by amount, type [$Kg{\cdot}m^{-2}$]
			Fibers and other materials from cultivated plants, fungi, algae, and bacteria for direct use or processing (excluding genetic materials)	1.1.1.2	Material by amount, type, use [$Kg{\cdot}m^{-2}$]
Provisioning (Abiotic)	Water	Surface water used for nutrition, materials, or energy	Surface water for drinking	4.2.1.1	Rainwater captured on the roof [$L{\cdot}m^{-2}$]
			Surface water used as a material (non-drinking purposes)	4.2.1.2	Rainwater captured on the roof [$L{\cdot}m^{-2}$]
Regulation and Maintenance	**Division**	**Group**	**Class**	**Code**	
Regulation and Maintenance (Biotic)	Transformation of biochemical or physical inputs to ecosystems	Mediation of nuisances of anthropogenic origin	Smell reduction	2.1.2.1	Still not studied
			Noise attenuation	2.1.2.2	Acoustic insulation capacity [dBA]
			Visual screening	2.1.2.3	Qualitative evaluation, valuation of perception
	Regulation of physical, chemical, biological conditions	Regulation of baseline flows and extreme events	Hydrological cycle and water flow regulation (Including flood control, and coastal protection)	2.2.1.3	Runoff control [$L{\cdot}m^{-2}$] Detention capacity. Delay time to sewage system [h] Retention capacity [$L{\cdot}m^{-2}$] [C-value]
			Wind protection	2.2.1.4	Contribution to energy savings
			Seed dispersal	2.2.2.2	Floristic surveys, qualitative research % cover by species Shannon Diversity Index Other
		Atmospheric composition and conditions	Regulation of chemical composition of atmosphere and oceans	2.2.6.1	CO_2 sequestration [$Kg{\cdot}m^{-2}$] Pollutants capture [$Kg{\cdot}m^{-2}$] Dust capture [$Kg{\cdot}m^{-2}$]
			Regulation of temperature and humidity	2.2.6.2	External building facade surface temperature [°C] Energy savings [kWh] Indoor temperature [°C] Indoor Relative Humidity [%]

Table 1. *Cont.*

Ecosystem Services CICES V5.1					Suggested Parameters and Measure Units at Site/Building Level (Small Scale)
Section	**Division**	**Group**	**Class**	**Code**	
Cultural	**Division**	**Group**	**Class**	**Code**	
Cultural (Biotic)	Direct, in situ, and outdoor interactions with living systems that depend on presence in the environmental setting	Physical and experiential interactions with natural environment	Characteristics of living systems that enable activities promoting health, recuperation, or enjoyment through active or immersive interactions	3.1.1.1	Activities by type Useful area for activities [m^2] Value of perception, qualitative research area for renting Property value

2.2. Step 2: Alignment with Indicators from NBS EU Handbook

The EU Commission handbook [12] provides a comprehensive list of indicators and definitions for evaluating the impact of NBS solutions. In this phase, the indicators selected for inclusion in Table 1 were compared with those listed in the EU Commission handbook. Quantitative indicators, along with their corresponding definitions, were chosen for summarization in Table 2. This selection is essential as it lays the foundation for the economic valuation strategies that will be applied in subsequent steps. The goal is to compile a small and focused set of indicators that are widely recognized and directly related to the benefits of building-integrated greenery (BIG) systems.

Table 2. Specific ecosystem services from CICES V5.1 related to BIG systems and aligned with the EU Commission evaluation handbook. Strategies for economic measurement.

Ecosystem Services CICES V5.1			Suggested Ecosystem Service Name	Suggested Indicators and Measurement Units at Site/Building Level (Small Scale)	Alignment with EU Commission Handbook [13]	Possibility to Apply Smart Technologies for Data Collection	Valuation Strategies
Section	**Class**	**Code**					
Provisioning	**Class**	**Code**					
Biotic	Cultivated terrestrial plants (including fungi, algae) grown for nutritional purposes/fibers and other materials from cultivated plants, fungi, algae, and bacteria for direct use or processing (excluding genetic materials)	1.1.1.1/ 1.1.1.2	Horticultural production	Crops by amount, type [$Kg{\cdot}m^{-2}$]; material by amount, type, use [$Kg{\cdot}m^{-2}$]	8.30	IoT-based solutions for crop growth monitoring [14]	Willingness to pay more for more on local production [15] Monetary valuation: (Market Value $\cdot Kg{\cdot}m^{-2}{\cdot}$year)
	Cultivated plants (including fungi, algae) grown as a source of energy	1.1.1.3		Material by amount, type, use [$Kg{\cdot}m^{-2}$]	8.30	IOT systems and autonomous control for smart food growing [16]	
Abiotic	Surface water for drinking/surface water used as a material (non-drinking purposes)	4.2.1.1/ 4.2.1.2	Alternative use of rainfall	Rainwater captured on the roof [$L{\cdot}m^{-2}$];	4.19; 4.23	Use of tipping bucket rain gauges to measure rain runoff [17]	Polynomial of factors to determine price and public services [18] Monetary valuation: (Market value$\cdot m^3\cdot$year)

Table 2. *Cont.*

Ecosystem Services / CICES V5.1			Suggested Ecosystem Service Name	Suggested Indicators and Measurement Units at Site/Building Level (Small Scale)	Alignment with EU Commission Handbook [13]	Possibility to Apply Smart Technologies for Data Collection	Valuation Strategies
Section	**Class**	**Code**					
Regulation and Maintenance	**Class**	**Code**					
Biotic	Filtration/ sequestration/ storage/accumulation by micro-organisms, algae, plants, and animals; regulation of chemical composition of atmosphere and oceans	2.1.1.2/ 2.2.6.1	Carbon credit market	CO_2 sequestration [$Kg{\cdot}m^{-2}$]	1.1	CO_2 sequestration [$Kg{\cdot}m^{-2}$] [19]	Valuation of CO_2 reduction at market value Monetary valuation: (market value·CO_2 reduction)
	Regulation of temperature and humidity, including ventilation and transpiration	2.2.6.2	Energy savings	External building facade surface temperature [°C]	2.10.1	Smart meters	determine a baseline and measure the savings after implementation of BIG systems Monetary valuation: (energy_value·kWh·year)
				Energy savings [kWh]	2.2		
				Indoor temperature [°C]	1.4; 2.9.1		
Cultural	**Class**	**Code**					
Biotic	Characteristics of living systems that enable activities promoting health, recuperation, or enjoyment through active or immersive interactions	3.1.1.1	Space for renting	Useful area for activities [m^2]	8.29; 14.8	N/A *	Monetary valuation (rental fee · m^2)
				New businesses created (amount of new entrepreneurships, amount of new local business)	14.8; 14.9	N/A *	
	Characteristics of living systems that enable aesthetic experiences	3.1.2.4	Property value increase	Value as a compositional and artistic element for architectural and landscaping designs, soft costs from design phase	20.14; 23.1.2	N/A *	Landscape architect costs as a percentage of the design value Monetary valuation: (Price of the project·1,1) [20]
	Characteristics or features of living systems that have an option or bequest value	3.2.2.2		Property value increase	23.2.1	N/A *	Increase in property value from 3% to 5% depending on the location and size of the green infrastructure [6] Monetary valuation: (Value property · 1.05)

* N/A: not possible to apply an intelligent monitoring system.

2.3. Step 3: Smart Monitoring of BIG System Indicators

The indicators in Table 2 can be monitored and registered, allowing for the creation of databases for subsequent analysis. The process of identifying smart indicators entailed a literature review aimed at sourcing references to technological systems equipped for data acquisition via sensors.

Selected literature references demonstrate the use of smart meters and the collection of data from real-case scenarios. These references are summarized in the 'Possibility to Apply Smart Technologies' column in Table 2.

2.4. Step 4. Economic Measurement of BIG System Indicators

Given that a building-integrated greenery (BIG) system typically involves integrating green spaces atop or on the surface of a building's skin, extensive literature research was carried out to derive formulas and estimate values. Several factors were considered during this process, including the area covered (measured in square meters), potential market values for specific indicators (where available), and other relevant parameters.

The references were selected with the objective of determining a monetary value. This led to the exclusion of some qualitative indicators due to the inherent difficulties in establishing a definitive market value. On the other hand, indicators that could be quantified through smart sensors or market valuation were selected. The 'Valuation Strategies' column in Table 2 summarizes these findings.

2.5. Step 5. Proposal of Sustainability Factor for BIG Systems

Using the selected indicators, the sustainability factor will be formulated as a relation between the benefits and costs of a BIG system; for every indicator, a formula for monetizing the contribution and the cost will be established. Using local data with the case-study, the sustainable factor will be calculated for different scenarios considering the area (in square meters) dedicated to different activities; the ratio will indicate how the benefits overcome the costs for the different scenarios.

The main aim of calculating the "sustainability factor for BIG systems" is to introduce a singular metric that encapsulates the triple bottom line of sustainability (economy, society, and environment) in the context of BIG systems. This parameter is designed to be adaptable to a given location without requiring expert judgment, thereby providing swift and valuable insights for stakeholders and decision makers. To validate the proposed methodology, this research applied the model to an actual case study: a 3500 m^2 extensive green roof located at the Lleida Agri-food Science and Technology Park (PCiTAL) in Lleida, Catalonia (Spain) [21]. The extensive green roof system used, a commercial product known as "ecological roof" [22], comprises several layers: a protective geotextile felt, a waterproof membrane, an air/water chamber formed by plastic supports, a filtering geotextile felt, an insulation and drainage slab with one layer for thermal insulation and another made of porous concrete, a substrate layer, and, finally, the vegetation layer. As a particular characteristic of this system, the filter layer, by falling through the slab joints, not only acts as a filter by preventing the pass of substrate particles to the drainage layer but also allows stored water to rise via capillarity to the substrate layer, making it available for plants [23,24]. In this particular project, the extensive green roof has two different types of top finishing roof materials, non-pedestrian green areas, and pedestrian areas finished with gravel that can be seen in Figure 2. In gravel areas, the vegetation and the substrate layer were replaced by a single 8 cm gravel layer.

The green roof is only used as a rest and recreation area for office workers and occasional meetings. Minimal maintenance is conducted, consisting of periodic cleaning and weeding.

Given its specific location, the data used to assess the selected indicators were collected from different sources:

- Information on market prices will be obtained from official sources, such as Eurostat or local agencies;
- Information on the productivity of the green roof will be obtained from a literature review in the area of study;
- Information on local parameters will be obtained from managers and/or local authorities.

Figure 2. Extensive green roof on H-buildings at Lleida Agri-food Science and Technology Park (PCiTAL).

3. Results and Discussion

This section presents the results obtained from selecting indicators within the CICES classification for analyzing the impact of BIG systems, specifically green roofs and facades. This novel information is detailed in Section 3.1 and summarized in Table 1.

Subsequently, Section 3.2 and Table 2 show the alignment of the CICES indicators for BIG systems, as identified in Table 1, with the indicators from the NBS EU handbook. Table 2 also includes additional information regarding the potential for automatic monitoring of these indicators (smart indicators monitoring), as well as the methods for assessing monetary values for each of them.

Finally, Sections 3.3 and 3.4 present the results of developing the sustainability factor for BIG systems, which is then applied to a real case study in Section 3.5 to demonstrate its usefulness.

3.1. Ecosystem Services Selection from CICES

Within the ecosystem services related to environmental benefits, the initial phase of the selection process involves delineating the distinct contributions that BIG systems make to urban environments. Table 1 shows the chosen indicators from the extensive assortment of metrics and their varied application domains within the CICES framework. Additionally, this table proposes a measurable and quantifiable parameter for each identified class, when possible.

Moreover, Table 1 has the same hierarchical structure as the CICES framework, so it is possible to find benefits from services like biomass production, atmospheric regulation, and cultural benefits derived from the activities of humans in green environments. For the selected indicators, a brief description and units of measurement are provided in order to build databases. For indicators that do not have a unit, qualitative methods should be used to gather information on the perception of the stakeholders.

3.2. Ecosystem Services Selection from EU Commission Handbook

After extracting indicators from the CICES v5.1 table, a corresponding list of indicators from the EU Commission handbook has been selected to align the two frameworks. The EU Commission categorizes NBS into three types: Type 1 is aimed at protecting and improving the use of existing ecosystems; Type 2 involves extensive management practices for the sustainable development of ecosystems; and Type 3 consists of NBS that are designed to create new ecosystems [12]. The ability to create new ecosystems is a feature of green roofs, walls, or facades that add green environments to cities; for this reason, indicators were selected for Type 3 NBS that specifically [12] related to the BIG systems addressed in this paper. The result is a limited set of indicators that offer an evaluation of ecosystem services and the possibility to measure the specific impact of BIG systems in urban environments. These indicators are consistent with those previously selected and listed in Table 1, sharing key characteristics: they are measurable and quantifiable using smart meters, and they can be assigned market value based on the ecosystem services they offer.

Table 2 shows the correlation between the two frameworks, including a column for the corresponding EU Commission handbook code. Additionally, this table presents strategies derived from the existing literature for the smart monitoring of these indicators using technologies like smart meters for data acquisition. The data thus collected will inform the economic valuation of the ecosystem services provided by BIG systems infrastructure, benchmarked against the prevailing market rates for equivalent goods or services. For indicators that cannot be measured technologically, such as increases in property value, valuation will be determined by the current market prices for the respective services.

In addition, Table 2 has been expanded to include a new column that lists the ecosystem services integrated into the sustainability factor calculation formula. These services, detailed in Section 3.3, include horticultural production, alternative use of rainfall, carbon credit market, energy savings, space for renting, and property value increase. Section 3.3 not only provides comprehensive details of the 'sustainability factor' formula but also offers in-depth descriptions and justifications for the selection of each of these ecosystem services.

3.3. Sustainability Factor for BIG Systems

As described in previous sections, benefits from BIG systems are goods and services that create value in different ways (goods for human consumption, raw materials for other processes, reductions in electricity bills, measurement of the CO_2 captured, etc.). Aside from these environmental benefits, there are other services provided by BIG systems related to the economic and social use of the urban space that create value for the people that use them.

Using the triple bottom line framework, which includes economic, environmental, and social dimensions, this section conducts a thorough examination of the quantifiable indicators presented in Table 2 and further defines methodologies for their monetization.

The categorization of indicators proceeds as follows: first, the economic benefits derived from the production of goods are determined through financial transactions. Second, the environmental benefits, specifically CO_2 sequestration, are quantified and assigned a monetary value in accordance with current carbon credit markets. Finally, the social value is economically quantified, leveraging market valuations of social activities that the green infrastructure facilitates, such as commercial leasing opportunities for small enterprises.

The analysis not only includes the benefits but also the maintenance costs and savings generated by BIG system services, such as captured rainfall and reduced electricity consumption.

After the measurement of the indicator, a "sustainability factor" will be presented. This will be a relationship between the monetary benefits and costs for a BIG system, which will make it possible to design solutions with different sustainability goals in mind.

3.3.1. Measuring Economic Sustainability

BIG systems infrastructures create new areas for growing and cultivating products for human consumption, like vegetables and other goods. In addition, the same surface area is used to buffer the water from rainfall seasons, especially during heavy storms. These ecosystem services can be measured if there is a possibility to trade or provide an alternative use for these resources. This section provides a way to monetize the value of indicators from the "provisioning" section of Table 2 in order to obtain a monetary value of these economic goods.

Horticultural Production

The ecosystem service under discussion involves the use of BIG areas for local food production, enhancing food security, and providing economic benefits. Smart technology integration in agricultural systems, such as soil sensors and databases [25], promotes efficient resource utilization and helps in crop monitoring. However, the quantification of final profitability depends mainly on manual methods, such as crop counting and sales price analysis.

Products for local consumption may contribute to the local supply chain and improve food safety [26]. Contemporary consumers are increasingly concerned about nutrition and are willing to pay more to obtain sustainable products sourced locally [15]. In order to quantify and measure this urban horticultural production (Bc), the area of growing (A), the amount of goods produced (Tp), and the market value of these commodities (Mv) in a certain period (y) can be considered. Thus, the quantification of this benefit can be calculated as follows:

$$\mathrm{Bc} = \mathrm{Tp} * \mathrm{Mv} * \mathrm{y} * \mathrm{A} \quad (1)$$

Rainwater as an Alternative Resource

BIG systems contribute to ecosystem services by efficiently retaining rainfall, reducing runoff into sewage systems, and mitigating flood risks. The structural attributes of BIG systems, including materials and design [27,28], influence their water absorption capacity. For instance, the use of recycled rubber crumbs has been found to enhance retention. Furthermore, monitoring methods, such as smart meters and real-time sensors [17,29], facilitate the quantification of water retained [26]. This not only presents an alternative resource for reducing maintenance costs but also supports sustainable water management practices.

In order to obtain monetary value, the water can be measured as a fixed value plus a consumption-dependent value; it is also possible to obtain government aid in some cases for some social sectors [18], which generates a local tariff for consumers (Ti). The economic value of this rainwater (Ca) ecosystem service can be expressed as the amount of collected liters (L), a local tariff (Ti) during a certain period (y). Nevertheless, this benefit cannot be considered as income as it is not a service directly generated by the BIG system itself. Instead, it could be accounted for as savings on the system's regular operation [30], resulting in reduced maintenance costs.

$$\mathrm{Ca} = \mathrm{Ti} * \mathrm{L} * \mathrm{y} * \mathrm{A} \quad (2)$$

BIG systems also present economic maintenance costs as part of their normal operation. During the lifecycle of the green infrastructure, maintenance costs (Tc) must be considered. These costs encompass fixed expenses associated with raw materials, equipment, and necessary inputs for regular operations (Cmp). Additionally, the costs of labor for routine maintenance (Chh) should be considered [31].

$$\mathrm{Tc} = \mathrm{Cmp} * \mathrm{A} + \mathrm{Chh} * \mathrm{A} \quad (3)$$

3.3.2. Measuring Environmental Sustainability

BIG systems provide a series of benefits to the environment that can help fight against climate change. Savings in energy and CO_2 sequestration can add value to the building and for stakeholders. Here, these benefits are measured as a way to monetize indicators from the "regulation and maintenance" section in Table 2 in order to add monetary value to the benefits that BIG systems provide to the environment.

Carbon Market

BIG systems play a significant role in carbon sequestration [32], thereby mitigating the urban heat island effect and contributing to the reduction in global warming. Long-term studies on green roofs have demonstrated consistent CO_2 absorption throughout the year [19,20], which may also result in potential monetary gains [33].

In the European Union Emissions Trading System, green bonds traded in the carbon market provide investors incentives to invest in sustainability [34]. To benefit from CO_2 sequestration, investors must possess some assets in the form of "green bonds" or "carbon bonds". To monetize these assets, it is necessary to conduct measurements over a specified period to verify the reduction in CO_2 emissions [35]. These verified reductions can then be certified and traded on the carbon market at their market value. Research suggests that investment in such assets can mitigate the risk in stock portfolios characterized by conventional or non-renewable energies, principally by means of diversification [36]. The environmental benefits of BIG systems (Bgb) can be measured as the market price of green bonds (Vgb) by the amount of CO_2 sequestrated by the green area (A).

Depending on the type of BIG system and the variety of plants utilized in the green infrastructure, the economic gains from CO_2 absorption can be estimated as revenue from carbon credit sales, or Certified Emission Reductions (CERs). In a lifecycle analysis of green roofs on elementary schools in South Korea, the CER was valued at USD 4.49/tCO2 equivalent, and the CO_2 absorption by a certain type of plant was set at 5.0 $kg \cdot m^{-2} \cdot year$ [37]. This study shows that benefits from CO_2 reduction can be monetized in the carbon market, offering more value throughout the BIG system structure's lifecycle.

$$Bgb = A * Vgb \tag{4}$$

Energy Savings Achieved through BIG Systems

BIG systems contribute significantly to energy efficiency in urban areas, particularly in reducing electricity consumption for air conditioning systems. Their effectiveness is influenced by the type of BIG and their physical characteristics, as well as local weather conditions [7]. For example, green roofs, a type of BIG, act as insulation, reducing heat fluxes and stabilizing indoor temperatures [38], thereby allowing for more efficient and rational use of heating, ventilation, and air conditioning (HVAC) systems [39,40].

This is also an alternative benefit because it makes it possible to minimize the operational costs of a building. Lower energy consumption (Ce) can be expressed as the unit price of the energy (VkWh) by the lower energy consumed by the building (CkW) during a certain period (y).

$$Ce = CkW * VkWh * y * A \tag{5}$$

3.3.3. Measuring Social/Cultural Sustainability

New Rental Space

This section presents strategies for measuring the indicators in the cultural/biotic section of Table 2 with the aim of monetizing the benefits that BIG systems can create from new spaces for small business in a green environment and the increase in property value.

Implementing BIG structures on rooftops not only provides environmental benefits but also cultural ecosystem services by creating new spaces for human interaction and businesses. Green roofs enhance citizens' access to green areas, improving overall well-being and presenting opportunities for new businesses [6]. The revitalization of these spaces, designed with social interaction in mind, can be monetized and quantified through metrics such as the creation of new businesses, contributing to local employment [12].

In addition, investing in nature-based solutions could help to add value to other intangible assets, like a company's brand or reputation. In relation to these assets, it is possible to add value to the extent to which BIG systems help to contribute to customers' positive perception, causing sales to increase or raising brand awareness. Reputation and other intangible assets make it possible to win more trust from stakeholders in the company [5].

Apart from intangible assets, which are difficult to measure, the possibility of adding property value is a variable to consider when measuring the benefits of BIG systems.

Enhancing the existing building stock is critical from a social perspective across urban landscapes. Rather than demolishing old infrastructure, it is preferable to revitalize these spaces, creating opportunities for real estate investment. BIG systems play an important role in revitalizing old neighborhoods by increasing property value as buildings and houses approach obsolescence [7]. Moreover, it is also possible to add value by using the new areas created by BIG systems as rental spaces for small-scale businesses, such as rooftop bars, open spaces, and small convenience stores. Depending on size and technical feasibility, the benefits obtained from renting space (Br) can be calculated as a lease fee (Lf) by the area (A) reserved for this activity in a period of the year (y). It also creates indirect benefits like entrepreneurship and the development of new products and services at the city scale:

$$\mathrm{Br} = \mathrm{Lf} * \mathrm{A} * \mathrm{y} \tag{6}$$

Property Value Increase

BIG systems offer advantages in the real estate market, potentially increasing property values by 3 to 5% [24]. This increase leads to higher rental fees for building owners. The benefits of BIG systems extend beyond aesthetics and biodiversity enhancement, including the provision of leisure spaces and relaxation areas. The presence of BIG systems fosters the creation of new businesses, jobs, products, and services, ultimately increasing property values for both the building and its surrounding area.

According to Azizi et al. (2015) [20], an attractive, functional, and environmentally balanced design is the job of the landscape architect, an estimated 10% of the total project cost. Depending on the location of these green infrastructures, the added value of these properties in regular operation could cause their value to increase by 2% to 5%, a range that depends on the location of the building, the type of BIG system, and its aesthetic aspects [6]. Thus, it is possible to define the value of the social/cultural benefits of the BIG (Bs) as the factor due to the implementation of the project (Fi) and the value added to the property itself (Fa) by the actual property value (Pv).

$$\mathrm{Bs} = \mathrm{Fi} * \mathrm{Pv} + \mathrm{Fa} * \mathrm{Pv} \tag{7}$$

3.4. Proposal of "BIG Sustainability Factor"

There are a wide variety of indexes to assess sustainability in the built environment. Some of them require an expert opinion (which may be subjective) and some data specific to the field of application. Some indexes are used to obtain a standardized sustainability value for entire countries that use different methods to weigh and normalize variables in order to make comparisons and establish public policies, some of which may be criticized due to their lack of utility for the decision making process [41]. The impact of BIG structures must be clearly measured if certain building sector certificates (LEED, BREEAM, DGNB, etc.) are to be obtained. Experiences at universities in Australia, for example, have shown that green building rating systems focus on the sustainable design and operation of campus buildings rather than campus facilities [42]. Some studies also criticize the lack of repeatable measurements and the presence of some subjective assessments [43].

The aim of this paper is to propose a simple and direct approach to calculating the relationship between benefits and costs of BIG systems, offering a clear view, using objective data, to decision makers. Moreover, it can also be used as a simulation tool for designers to evaluate different scenarios by using local data. The "sustainability factor" is based on the economic measurement of the triple bottom line of sustainability to analyze and compare different BIG systems projects:

$$\mathrm{BIGS\_SF} = \frac{\mathrm{Bc} + \mathrm{Bgb} + \mathrm{Bs} + \mathrm{Br}}{\mathrm{Tc} - \mathrm{Ce} - \mathrm{Ca}} \tag{8}$$

This sustainability factor is the relationship between the sum of the most relevant benefits that BIG systems provide during the operational phase and the operational costs of this green infrastructure. This model requires the variables to be measured and monetized in some way; for this reason, the proposed model offers a specific list of variables that can be measured regardless of the geographic location of a BIG system. This model also offers designers the possibility of creating areas with specific goals; for example, it is possible to create a specific area for horticultural production and the rest for leisure and landscaping; the amount of the area in one direction or another can raise or lower the factor, improving the decision making process of stakeholders. This model also helps to measure the impacts of BIG systems in sustainable cities and also offers a way to register the impacts of costs during the operational phase of the lifecycle, helping to close some gaps in the research [44].

3.5. Case Study

As an example of the potential and possibilities of the proposed sustainability factor for BIG systems, it was applied to the H-buildings in the city of Lleida, Catalonia, Spain, which form part of the Lleida Agri-food Science and Technology Park (PCiTAL).

This complex currently has a 3500-square-meter area dedicated to a large extensive green roof that is now utilized for meetings and leisure purposes. Considering the location of the H-buildings, the available data from site managers, other studies, and official databases, it is possible to build factors (1), (2), (3), (4), and (6) for the sustainability factor. Detailed information regarding the sustainability aspects is shown in Table 3.

Table 3. Parameters used in the "Sustainability Factor" case study at PCiTAL Lleida, Catalonia (Spain).

	Sustainable Value Generated	**Valuation Parameters**	**Data Sources for Parameters**
Horticultural production (Bc) (1)	Economical: production of goods traded in the university local area	Average price of tomatoes in Spain (in EUR), average production of vegetables per square meter (ton per square meter).	Data from Eurostat, and data from private company related to green roof implementations
Alternative use of rainfall (Ca) (2)	Environmental and Economic: reduces runoff peak in local sewage, rainfall water can be reused reducing irrigation costs	Local pluviometry data (total amount in cubic meters, annual), average cost of drinking water in Catalonia (in EUR per cubic meters)	Data from local sources in Catalonia
Maintenance costs (Tc) (3)	None, this a regular fee for maintenance	Average cost of maintenance (in EUR per square meter).	Data from academic research, considering the worst case scenario regardless of the type of green roof
Carbon credit market (Bgb) (4)	Environmental: CO_2 reduction to the local university environment, green image for the university.	Amount of CO_2 that a green roof can absorb in a worst case scenario (in ton per square meter), average price of CER (in EUR)	Pricing data from https://www.sendeco2.com (accessed on 18 November 2021), academic research
Space for renting to small business (Br) (6)	Social: new spaces support local entrepreneurship, social commitment image for the university	Average price of square meter for local restaurants in Lleida city (in EUR per square meter)	Data from local sources

For the PCiTAL extensive green roof, seven future scenarios were simulated, varying the space allocated to different activities. These ranged from full dedication to horticulture, exclusively assessing BIG systems for agricultural yield, to complete rental space utilization, which would redefine the space as a conventional flat roof, diverging from a nature-based approach. There is an eighth scenario, which is simulating the entire surface for CO_2 capture: this implies that the roof is just completely covered by vegetation with no other activities.

Table 4 presents a summary of the different scenarios considered (1–8) to study the variations in the sustainability factor. These variations are determined by the square meters designated for horticultural activities, CO_2 capture, or renting roof space.

Table 4. Variation in the sustainability factor based on area reserved for diverse activities on the PCiTAL roof.

Simulated Scenarios	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
Area for horticulture activities (m^2)	3500	3000	2500	1166	500	500	0	0
Area for CO_2 capture (m^2)	0	250	500	1166	1000	500	0	3500
Area for renting to small businesses (m^2)	0	250	500	1166	2000	2500	3500	0
Sustainability factor	1.585	3.155	4.725	8.912	14.487	17.969	24.761	0.390

Figure 3 shows the results of the seven progressive scenarios studied. The quantitative results show that, when the area is distributed similarly among the three pillars of sustainability, the benefits outweigh the costs by factor of 8.912. In addition, as more space is allocated to renting activities, the variation in the sustainability factor increases.

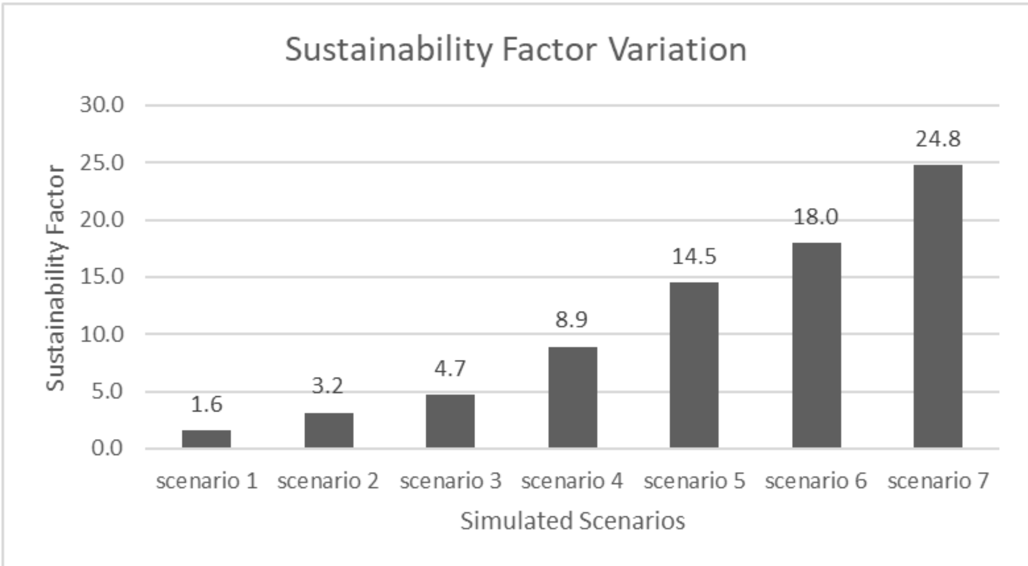

Figure 3. Sustainability factor variation for PCiTAL case study.

The results show that sustainability metrics can vary across scenarios during the operational phase. This variation enables the development of performance indicators for sustainable green infrastructure, which encompasses economic, environmental, and social dimensions [42]. In the intermediate scenarios (2 to 6), which represent the most logical and usual cases for a green roof, the sustainability factor varies from 3.2 to 14.5. These results indicate that diversifying activities on a green roof can yield benefits that surpass the associated maintenance costs. This provides viable options for stakeholders thinking about BIG systems to revitalize their infrastructure. Furthermore, BIG systems with varied activities can positively influence public and business perceptions, thereby increasing their interest to pay or invest in the implementation of such sustainable solutions [45].

Taking into account a social perspective in project considerations [46] can contribute to the emergent field of quantifying the sustainable benefits in green infrastructure projects during the design phase. Scenario 4, as shown in Table 4, highlights that the value generated by various activities in green infrastructure can be as much as nine times greater than the associated maintenance costs. This evidence is encouraging for stakeholders considering BIG systems as a viable strategy for achieving sustainable development goals within urban landscapes given the universally applicable indicators. The analysis is adaptable to different contexts, allowing for sensitivity analysis and additional numerical correlations [47] to facilitate decision making during the operational phase of green infrastructure. In the context of cost–benefit analyses, academic research highlights a concern regarding the low estimation of intangible indicators or the difficulty of quantifying social or environmental benefits [4]. In this context, the sustainability factor provides relevant indicators that enable the assessment and quantification of these impacts at the city level.

Design decisions and market conditions also affect the variations in indicators and thus the value from sustainability factors. In scenario 1 (sustainability factor 1.6) proposed in Table 4, tomatoes were considered biomass produced by the green roof; this production may positively impact the local food supply and stabilize food prices [26]. Different biomass products can be cultivated, and, depending on their market value, different measurements and quantifications may be obtained. It is relevant that, in this scenario, the benefit-to-cost ratio is lower compared to other scenarios, emphasizing the potential for higher benefits when diversity in activities is present.

This proposed sustainability factor addresses the research gap concerning inconsistent data collection and the absence of international standards for building-integrated greenery [44]. The sustainability factor presented is versatile and applicable everywhere, allowing for data utilization from various BIGS structures and monetization in accordance with local market conditions. According to studies, valuing benefits is difficult due to different methodologies and varying assumptions [48]. Additionally, the lack of standardized and globally recognized approaches makes the valuation process difficult [4]. The review of accepted frameworks examined in this study contributes to this goal by potentially guiding the formulation of policies that encourage such investments and may even evolve into public policies.

Scenarios 6 and 7, which correspond to sustainability factors of 18 and 24.8, should be analyzed with caution. These scenarios mainly involve the use of space for leasing purposes, diverging from the concept of nature-based solutions. This results in significantly lower maintenance costs, with fiscal gains being exclusively derived from rental income.

In relation to the previous point, it is pertinent to note that the focus of projects associated with BIG systems must align with sustainable cities and human well-being [49]. Designing infrastructure solely for rental purposes perpetuates traditional construction logics and neglects the integration of sustainable aspects. In this case study, a standard rental fee for the area was considered, although this may vary depending on the activities and the people who use the infrastructure. In the building under study, other local research has proposed monetization strategies for spaces dedicated to specific social cohesion activities, such as picnic areas, zones for contemplative rest, hammock areas, and gardens. These activities are estimated to attract between 13 and 137 people, varying with the nature of the activity [50]. Given that the University of Lleida and Lleida's City Council jointly own the building, it offers new interactive spaces not only for the university's students, faculty, and administrative staff but also for the citizens of Lleida. Such activities could serve as future indicators for studies focusing on the sustainability factor presented in this paper, underscoring the need to reconsider spatial utilization and the various functions it may serve throughout its lifecycle.

This proposal introduces a metric system for evaluating the building-integrated greenery systems across the sustainability triple bottom line, economic, environmental, and social aspects. This cost–benefit analysis can be refined further by including additional indicators, such as city size. According to research studies, the economic feasibility of green roofs is higher in larger cities with more inhabitants [51]. Another element that should be considered is the possibility of maintenance cost subsidies [52,53]. Highlighting these issues emphasizes the importance of designing strategies that include a wider variety of sustainability metrics [54].

4. Conclusions

Building-integrated greenery systems have proven to be beneficial in enhancing urban settings by delivering a variety of ecosystem services aligned with sustainability goals. This research introduces a specific set of indicators from the Common International Classification of Ecosystem Services (CICES) v5.1 and the EU Commission handbook for NBS, specifically designed to measure the impacts of BIG systems. The result is a refined list that not only provides metric units for quantifiable assessment but also facilitates the integration of smart meters and monitoring systems.

This study quantitatively assesses the ecosystem services provided by BIG systems, presenting formulas to calculate their market value relative to specific activity areas. The introduced "sustainability factor" for BIG systems allows the quantification of benefits and costs, providing designers with a concise tool for evaluating sustainable options in projects while considering potential economic, environmental, and social impacts.

Simulations based on a case study of a 3500 m^2 extensive green roof at Lleida PCiTAL demonstrate that a careful allocation of space, balancing various objectives, results in a cost–benefit ratio of 8.9. This research emphasizes the potential for achieving a range of sustainable and economic gains throughout the operational lifespan of the building.

Considering human-scale development, this case study enables the analysis of a diverse range of social cohesion alternatives that can emerge from the implementation of BIG systems projects. Achieving a balance among the three pillars of sustainability not only yields more benefits than costs but also allows for better adjustment of each pillar. Given that the case study involves a building associated with a university, campus workers, students, and citizens may have a new space for relaxation. Academics have the opportunity to engage more deeply with their students, and, at the city level, the facilitation of community outreach or cultural events that utilize these new spaces becomes possible.

The strength of this approach lies in its utilization of locally sourced data, empowering managers and project designers with information for both conceptualization and operational phases. The ability to generate real-time data facilitates design validation and informed decision making to optimize the balance of benefits and costs.

Future applications will include real-world case studies that use sensor data to create digital models that are then combined with economic information, paving the way for researchers to develop predictive models using machine learning techniques. Creating databases with cost–benefit data may allow city councils to standardize assessments for BIG projects, such as subsidy applications or tax reductions, based on objective information.

Further research should focus on incorporating factors into the formula considering indicators not yet addressed, such as tax reductions, long-term benefits, creation and demolition costs, city size, subsidies, the lower costs due to the reduction in the heat island effect in the surrounding area, and refining calculations as more information becomes available about ecosystem services provided by BIG systems.

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