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Review

Nature-Based and Solar Façade Systems for a Net-Zero Built Environment: A Structured State-of-the-Art Review and Preliminary Comparative Assessment

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Abstract

Green building façades are increasingly recognized as a key strategy for decarbonizing the built environment, addressing climate change, urbanization, and the urban heat island effect. This paper investigates two main façade approaches: nature-based solutions (NBS), such as green façades and living walls, and Building-Integrated Solar Energy Systems (BI-SES), including photovoltaic, solar thermal, and hybrid BIPV/T systems. The building envelope is framed as an active interface for both energy efficiency and on-site renewable energy generation. Through a structured state-of-the-art review, the study compares these systems in terms of energy performance, environmental benefits, costs, maintenance, lifecycle implications, and adaptability across climatic contexts. Results show that NBS provide consistent benefits in thermal regulation and cooling-load reduction, while solar façades are strongly influenced by orientation, geometry, and urban shading. To complement the qualitative analysis, a preliminary energy–environmental assessment is conducted for three façade configurations (conventional wall, green façade, and combined green–PV façade) across three Italian climates (Milan, Rome, and Palermo). Results indicate that vegetation reduces heat losses and CO_2 emissions, with further improvements in integrated systems. Overall, NBS and solar façades emerge as complementary strategies whose integration can enhance building performance and support the transition towards net-zero carbon environments.

Keywords: green building façades; nature-based solutions (NBS); solar-integrated façades; photovoltaics (PV); energy efficiency; urban greening; renewable energy

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1. Introduction

The building sector is now at the center of global strategies for environmental sustainability due to growing awareness of the depletion of natural resources and climate change. This sector is responsible for both energy consumption and greenhouse gas (GHG) emissions globally. Therefore, to reduce the environmental impact and promote the decarbonization of the built environment, the adoption of innovative solutions for building design and renovation has become a priority. Furthermore, the growth of the urban population has led to changes in land use, contributing to the emergence of the urban heat island (UHI) phenomenon, i.e., a significant temperature difference between the urban environment and the surrounding environment due to the reflection and absorption properties of solar radiation typical of construction materials (concrete, asphalt, bitumen, and steel). Given the compact nature of urban areas and the often-limited space available for plants and trees, green infrastructures represent a solution to reintroduce vegetation and biodiversity, improve stormwater drainage, reduce pollutant concentrations, reduce heat losses through the envelope and mitigate temperatures in the summer season. The integration of façades with solar energy production technologies helps to improve the energy efficiency of buildings, making them independent from fossil fuels with technologies with very low environmental impact. Green façades and integrated solar façades represent two distinct but complementary approaches. The former integrates plants and vegetation on the external surfaces of buildings, offering benefits such as thermal insulation, reduction in the urban heat island and CO_2 absorption. Integrated solar façades allow the integration of photovoltaic (PV) or thermal technologies inside the building, which allows the direct production of renewable energy and helps to reduce dependence on fossil fuels. Many studies have examined green façades for their numerous environmental and practical benefits. Perini et al. [1] examined the effects of vertical greening systems on airflow and building envelope temperature, highlighting how these systems can increase the energy efficiency of buildings [2] by insulating heat and lowering surface temperatures. Ottelé et al. [3] demonstrated that climbing plants can capture particulate matter, thus improving urban air quality. Biodiversity is another important aspect: Elek and Lövei [4] studied communities of carabid beetles along an urbanization gradient in Denmark, highlighting that areas with more urban vegetation have richer biodiversity.

These results suggest that integrating green façades can contribute to biodiversity conservation in urban environments by providing habitats for diverse species. An important strategy for in situ renewable energy production is the integration of solar technologies into building façades. Sailor [5] created a model to incorporate green roofs into building energy simulation programs, highlighting how such solutions can improve the energy balance by producing energy and reducing the heating load. Berardi et al. [6] conducted a state-of-the-art analysis of the environmental benefits of green roofs, highlighting how important the integration of PV systems is to maximize energy efficiency and reduce GHG emissions. Although the adoption of integrated green and solar façades presents numerous advantages, there are also significant challenges, including the need for proper maintenance, cost–benefit analysis and the adaptability of the solutions to different urban and climatic environments. The literature highlights the importance of using an integrated design approach that takes into account technical, environmental and social factors to ensure that the solutions are effective and sustainable over time. This paper presents a state-of-the-art review of nature-based and solar-integrated façade systems, focusing on their comparative performance, environmental implications, and potential synergies within decarbonization-oriented building design. The aim of the proposed work is to examine the role of these two solutions in the context of the decarbonization of the building sector, responsible for around 40% of energy consumption and 36% of GHG emissions, carefully reviewing the existing scientific literature. Studies that have assessed the effectiveness, benefits and challenges associated with the implementation of integrated green and solar façades were analyzed with the aim of providing a comprehensive and evidence-based overview. The strategic role of the building sector in achieving decarbonization targets is further reinforced by European regulatory frameworks such as the Energy Performance of Buildings Directive (EPBD) [2], which promotes the transition towards nearly Zero Energy Buildings (nZEB). In this context, recent studies have emphasized the importance of high-performance envelopes and cost-optimal retrofit strategies, particularly in public buildings [7,8].

Several review studies have investigated façade technologies, including double-skin façades [9], solar façades [10], and building-integrated photovoltaic (BIPV) systems from different perspectives [11–14]. However, these contributions typically focus on individual technologies, while a comprehensive comparative assessment integrating nature-based and solar façade systems remains limited.

2. Review Methodology

To ensure a transparent and structured overview of current knowledge on nature-based and solar-integrated façade systems, a targeted literature review was conducted. The objective of the review was to identify and synthesize the most relevant scientific contributions addressing green façades and solar-integrated façades and their potential role in building decarbonization strategies.

2.1. Information Sources

The literature search was primarily conducted using two major scientific databases: Scopus and Web of Science. These databases were selected due to their broad coverage of peer-reviewed publications in the fields of building engineering, sustainable architecture, renewable energy systems, and environmental technologies. Additional relevant publications were identified through Google Scholar to capture recently published articles and citation-linked studies.

2.2. Search Strategy

The search strategy was based on combinations of keywords related to façade-integrated vegetation systems, solar façade technologies, and building decarbonization. The following keyword groups were used:

- "green façade" OR "living wall" OR "vertical greenery system";
- "building-integrated photovoltaics" OR "BIPV façade" OR "solar façade";
- "green façade AND photovoltaic";
- "façade decarbonization" OR "net-zero building envelope".

Search queries were performed using combinations of these terms in order to identify studies addressing the performance, environmental impact, and technological integration of façade-based sustainability solutions.

2.3. Timeframe

The search focused on publications published between 2005 and 2025, capturing the most recent technological developments in façade-integrated vegetation systems and building-integrated solar technologies.

2.4. Inclusion and Exclusion Criteria

Studies were included in the review if they met the following criteria:

- Peer-reviewed journal articles or review papers;
- Studies addressing façade-integrated vegetation systems, solar façades, or hybrid configurations;
- Publications reporting energy, environmental, or performance-related analysis.

Studies were excluded if they:

- Focused exclusively on roof-based systems with no relevance to façade applications;
- Lacked technical or performance-related analysis;
- Were purely descriptive without analytical or quantitative content.

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2.5. Study Selection and Synthesis

The initial database search returned a large number of publications. After removing duplicates, titles and abstracts were screened to identify studies relevant to façade-integrated nature-based and solar technologies. The remaining publications were assessed through full-text review to ensure relevance to the scope of this study.

For each selected publication, relevant information was extracted regarding the façade technology type, climatic context, energy performance indicators, environmental co-benefits, maintenance requirements, and reported limitations. The collected information was then synthesized to identify common trends, advantages, and challenges associated with the analyzed façade technologies. The following provides a schematic overview of the literature review framework and study selection process. In Figure 1 is reported a schematic flowchart of the structured literature review methodology.

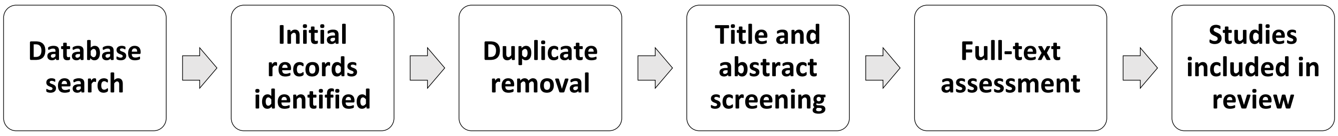

Figure 1. Schematic flowchart of the structured literature review methodology detailing the sequential phases of study identification, duplicate removal, screening (title and abstract), full-text assessment, and final inclusion of relevant studies.

3. Green Walls: Types and Solutions

Green walls are systems for greening vertical surfaces of buildings, with widely demonstrated environmental and energy benefits: first of all, their use allows for reducing overheating of internal environments, especially during the day and during the summer season, thus helping to contain energy consumption for cooling; furthermore, green walls are able to sequester CO_2 through their biomass and in the cultivation substrate of plants, helping to reduce its concentration in the atmosphere.

The European Union (EU) regulatory system recognizes and promotes green walls as nature-based solutions (NBS) for reducing the urban heat island phenomenon and improving the energy efficiency of buildings [15].

Vertical Greenery Systems (VGS), including green façades and living walls, are now classified into well-established construction typologies, with quantified benefits primarily in the thermal domain: reduced cooling loads, lower façade surface temperatures, and mitigation of the urban heat island (UHI) effect. Scientific review studies indicate that thermal performance is the most consistently documented outcome, whereas impacts on air quality, acoustics, urban hydrology, and social co-benefits are still supported by limited empirical evidence. Recent field-based investigations report indoor temperature reductions of up to 2.5–4.5 °C, decreased indoor CO_2 concentrations, and ventilation-related energy savings of around 20% associated with living walls in workplace environments. At the urban scale, green walls are recognized as effective nature-based solutions (NBS) for reducing cooling demand and UHI intensity, with potential reductions in cooling loads exceeding 50% under certain European climate conditions [16].

From a technological point of view, green walls are divided into two categories [17]:

1. Green Façades: these incorporate climbing or hanging plants, in the ground or in pots, leaning against the external wall of a building; they are classified into two subcategories:
    a. Direct: the plants adhere directly to the wall through their tendrils or discoid suckers, depending on the species (e.g., *Parthenocissus cuspidata* or *Hedera helix*);

b. Indirect: the plants rest on special structures anchored to the wall (e.g., cables, ropes, gratings, metal mesh), creating a gap between the plant and the wall (Figure 2); some plants, requiring supports to attach themselves to the wall, are optimal for this typology (e.g., bougainvillea, jasmine, climbing rose, wisteria).

Figure 2. Example of green walls with climbing plants on metal mesh.

Indirect Green Façade is a vertical greening system in which vegetation is not directly attached to the building envelope but is supported by a secondary structure installed at a defined offset from the façade surface. Typical support systems include modular grids, rigid metal meshes, or tensioned cable systems. This configuration reduces the direct interaction between vegetation and the building envelope, improving durability, inspectability, and maintenance management. From a structural perspective, the load implications significantly differ depending on the selected support typology.

For instance, rigid metal meshes or grid systems are characterized by higher self-weight and a more continuous load distribution. They introduce greater permanent loads (dead loads) due to the mass of the supporting frame but allow for more uniform transfer of the vegetation weight and variable actions such as wind pressure and water retention. These systems are generally more suitable for climbers with substantial biomass development, since they provide enhanced stiffness and stability. However, they require careful structural evaluation of the points of anchorage and façade substrate resistance, particularly in retrofit applications.

In contrast, tensioned cable systems exhibit lower self-weight and reduced initial structural impact. Nevertheless, they concentrate loads at discrete anchorage points and are more sensitive to dynamic effects induced by wind loading and vegetative growth. Their higher flexibility may amplify the oscillatory behavior under wind action, requiring a detailed assessment of anchorage stress and long-term performance under cyclic loading conditions.

In both cases, a professional structural evaluation must consider the combined effects of mature vegetation weight, water saturation, wind-induced suction and pressure (which increase due to leaf surface area), accidental loads, and long-term durability of fastening systems. Load combinations should be assessed in accordance with relevant structural design standards, particularly in dense urban contexts where wind acceleration and façade turbulence could intensify stress conditions.

2. Living Walls: these incorporate plant-housing structures attached to the wall. They have the advantage of allowing application to larger and higher surfaces, enabling more uniform plant growth and wall coverage, and allowing a greater variety of plants, even if it is good practice to adopt essences suited to the reference climatic context. They are divided into two subcategories:
    a. Continuous: these use light and absorbent fabric panels, commonly made of felt, with pockets to house the plants; there is no soil substrate; instead, a permeable layer for the uniform distribution of water and fertilizers and an anti-root layer are applied, both supported by a base panel attached to the frame fixed to the wall (Figure 3). Continuous living walls generally use hydroponic fertigation via a system installed in the upper part of the structure;
    b. Modular: these use pre-cultivated modular panels with specific support elements (pots, trays, flexible bags, and tiles for planters) to house the plants, which allows for greater sowing depth than continuous walls (Figure 4). The irrigation system is usually installed between the panels, and water is drained through the panels along the entire façade and collected in a channel at the base (Figure 5).

Figure 3. Example of a continuous living wall in Singapore.

The system is completed by a drainage and recirculation mechanism, typically supported by a hydraulic pump. In general, living walls use a fertigation system at the top that distributes nutrients by gravity with a drip system, equipped with a collection tank at the base, with an automated system with a pump.

The drainage system can be created in various ways: in consecutive layers (drainage, filtering, plant growth), by means of a perimeter ring that collects water and conveys it to a collection system below, or by means of a grid placed under the growth substrate to collect and convey water to the drainage.

Figure 4. Example of a modular living wall with pots.

Figure 5. Green Habitat Wall Green Hydro execution phases (Green Habitat srl).

Finally, it is worth mentioning two other vertical greening solutions that can lead to a slight improvement in energy performance and indoor comfort [18]: the presence of a significant amount of vegetation on condominium balconies and terraces, especially small shrubs, which, if appropriately designed, can represent a real shielding barrier from solar radiation (Figure 6); and stabilized greenery, created with panels containing grassy carpets of small plants (e.g., mosses, lichens) treated with specific substances to reduce maintenance, with the advantage of reducing indoor noise pollution (Figure 7).

Figure 6. The green shield in the "Bosco verticale" in Milan (Italy) designed by arch. Stefano Boeri.

Figure 7. Example of indoor greenery using both real plants and stabilized mosses.

4. Integrated Solar Façades: Types and Solutions

Building-integrated photovoltaic (BIPV) systems have been extensively studied as a key technology for on-site renewable energy generation. Several comprehensive reviews have analyzed their design, performance, and application potential in different building typologies [12–14]. These systems can be integrated into façades, roofs, and glazing elements, contributing to both energy production and architectural functionality.

Walls integrated with solar energy production technologies have the advantage of making the façade an active system capable of contributing to the energy needs of a building. In this regard, we speak of building-integrated photovoltaics (BIPV), which refers to all photovoltaic systems that are not simply installed and juxtaposed to the building envelope but are designed as an integral part of the building with the aim of also taking care of its aesthetic appearance and reducing its landscape/urban impact, especially in protected architectural cases.

In parallel, Building-Integrated Solar Energy Systems (BI-SES) applied to façades—including solar thermal collectors, building-integrated photovoltaics (BIPV), and hybrid BIPV/T systems—have been extensively addressed in numerous systematic reviews [13]. Façade-integrated BIPV/T systems enable the simultaneous production of heat and electricity, thereby reducing heating and cooling loads while significantly increasing overall solar efficiency [19,20]. Reviews focusing on BIPV in urban retrofit contexts highlight the strategic role of façades, particularly in high-density areas where roof surfaces are insufficient, emphasizing the potential of multi-skin systems and ventilated PV façades as an energy-active "second skin" [21–23]. More recently, the development of kinetic solar façades, adaptive systems inspired by plant morphology, and modular agrivoltaics envelopes (PV combined with vertical agriculture) has expanded opportunities for both functional and aesthetic integration [24–26]. Reviews dedicated to solar façades further underline the need for climate-specific optimization strategies, such as orientation, tilt, folded geometries, and semi-transparent modules, as well as integrated evaluations that jointly consider energy yield, architectural constraints, and economic feasibility [27,28].

The most widespread PV module technologies are those in monocrystalline silicon (c-Si) and polycrystalline silicon, which represent over 90% of the current market and are characterized by efficiencies in the order of 16–24% and 14–18%, respectively. Among the most advanced technologies, we can mention thin-film cells in amorphous silicon (a-Si), which have efficiencies of 4–10% but are able to guarantee greater versatility in terms of shapes and colors; cadmium telluride (CdTe) cells; PERC (Passivated Emitter and Rear Contact) cells, with efficiencies around 23%; and CIGS (copper-indium-gallium-selenium) and CIS (copper-indium-selenium) structures, which perform better and are more expensive [29]. The curtain walls, that is, the external walls totally or partially glazed and made up of prefabricated panels supported by metal frames, can be integrated with PV modules, thus optimizing the production surface. In this case, however, it is necessary to use semi-transparent modules, with a reduction in performance and an increase in costs. In any case, the efficiency of PV systems depends on the type, temperature and materials of the PV cells; the type of inverter, i.e., the device that transforms direct current into alternating current; the inclination of the module; the presence of shading elements and reflections from the surrounding environment; local climate parameters (atmospheric temperature, wind, radiation); the degree of cleanliness; and the frequency of maintenance.

Summarizing, it is possible to distinguish the following typologies:

1. Continuous façades with crystalline silicon;
2. Continuous façades with amorphous silicon modules;
3. Ventilated façades with c-Si, a-Si, CIGS;
4. Camouflage prints, etc.

Recent studies have explored the integration of photovoltaic façades in urban buildings and high-rise structures, highlighting their potential for improving energy performance, self-consumption rates, and overall system efficiency [30–34]. In particular, semi-transparent and advanced glazing-integrated PV systems have been shown to provide a balance between daylighting and electricity generation [35–38].

An application example is the multifunctional center of Pregassona, Switzerland, with a 170 kWp vertical PV system integrated into the ventilated façade. For the photovoltaic panels, a surface treatment was carried out to obtain a monochrome satin effect and the printing of a modular texture to camouflage the cells [39].

To provide a clearer comparison of the main photovoltaic technologies discussed, Table 1 summarizes their typical efficiency ranges and indicative installation costs per square meter, supporting a more practical assessment for façade integration.

Table 1. Typical efficiency and indicative cost ranges of photovoltaic technologies for building-integrated façade applications.

PV Technology	Typical Efficiency (%)	Indicative Cost (€/m^2)	Key Advantages	Main Limitations
Monocrystalline Silicon	18–22%	250–400	High efficiency; mature technology; long lifespan	Higher cost
Polycrystalline Silicon	15–18%	200–350	Lower cost than monocrystalline; reliable performance	Slightly lower efficiency
Amorphous Silicon (a-Si)	6–10%	150–250	Flexible; better performance under low irradiance	Low efficiency; degradation over time
Cadmium Telluride (CdTe)	10–14%	180–300	Good performance in high temperatures; lower cost	Toxicity concerns; lower efficiency
CIGS/CIS Thin-Film	12–16%	200–350	Flexible; good aesthetic integration	Less mature; higher variability
PERC (Passivated Emitter and Rear Cell)	20–24%	300–450	Higher efficiency than standard silicon; improved performance	Higher cost; thermal sensitivity

5. Comparative Analysis of the Benefits Obtained by the Two Solutions

Green façades and integrated solar façades are two distinct approaches to improving the sustainability of buildings. Each of these solutions has specific limitations and advantages in terms of energy performance, environmental benefits, costs, maintenance and adaptability to various urban and climatic environments.

5.1. Improved Energy Performance

Green envelopes (vegetated roofs and walls) contribute significantly to the energy efficiency of the buildings on which they are placed. Some studies conducted on this topic have shown that green roofs are able to reduce the cooling load by up to 70%, contributing significantly to the reduction in energy consumption for the summer cooling of buildings [39–41]. Furthermore, these solutions improve annual energy efficiency, leading to energy savings ranging between 10 and 60%, depending on the specific climatic and design conditions [42,43]. This occurs thanks to the shading and transpiration of plants, which lower the surface and internal temperature of the building. Green walls can act as additional thermal buffering layers, potentially reducing heating demand in winter and cooling demand in summer. However, the magnitude of these effects depends on climatic conditions, façade configuration, vegetation characteristics, and building design parameters. Vegetation helps to keep internal temperatures more stable and reduces the use of energy for climate control by absorbing and retaining humidity. However, the type of vegetation chosen, its maintenance and local climate conditions determine the effectiveness of these solutions [44–46]. Photovoltaic and solar thermal systems are examples of integrated solar façades that contribute directly to the production of renewable energy [37,38,47,48]. The application of photovoltaics within an architecture allows the generation of energy directly from within the building, reducing dependence on non-renewable energy sources and decreasing the GHG associated with the energy consumed. According to studies [49–51], the efficiency of solar cells has slowly increased over the last two decades, offering significant opportunities for architectural integration and energy production. The integration of PV in architectural design requires careful design to optimize the orientation, inclination and aesthetic integration of solar panels. In fact, careful design can maximize energy production and improve the overall efficiency of the building. Furthermore, the adoption of high-efficiency PV technologies and the selection of appropriate materials are essential to ensure optimal performance over time [52]. Green façades mainly improve thermal insulation and comfort in the home, while integrated solar façades contribute directly to the production of renewable energy. The combination of both solutions can allow for an optimization of the energy efficiency and environmental sustainability of buildings. For example, the installation of PV systems on south-facing façades can be particularly effective during the cold season since the low inclination angle of the sun can be fully exploited.

The potential lower effectiveness of green façades in extremely cold or dry climates is influenced by the species selection and the system design: in cold environments, winter dormancy and leaf loss in deciduous species reduce shading and evapotranspirative cooling; however, the use of frost-resistant evergreen species (e.g., *Hedera* spp. or other cold-hardy evergreens) can ensure year-round foliage coverage, enhancing wind shielding, particulate interception, and façade surface protection even when transpiration is limited. In arid and semi-arid climates, high vapor pressure deficit and water scarcity constrain evapotranspiration, yet drought-tolerant evergreen sclerophyllous and succulent species (e.g., Mediterranean shrubs or *Sedum* spp.) can maintain stable canopy cover with reduced irrigation demand, still contributing to solar shading, surface temperature mitigation, and biodiversity support. The performance of façade systems is strongly influenced by solar control strategies, building orientation, and the integration of advanced glazing and shading technologies, which can significantly affect both thermal behavior and energy demand [53,54]. Therefore, climate-adapted evergreen species, combined with optimized substrate and irrigation strategies, can significantly mitigate the performance limitations of green façades under extreme climatic conditions.

5.2. Environmental Benefits

Green façades and integrated solar façades offer a number of significant environmental benefits, contributing to the sustainability of buildings and the improvement of urban environmental quality.

As for green façades, consisting of plants and vegetation installed on the walls of buildings, the main environmental benefits they bring are:

- Air purification, as the plants present on green façades act as natural filters, absorbing air pollutants such as ozone (O_3), nitrogen dioxide (NO_2) and Sulphur dioxide (SO_2), improving the quality of urban air [55,56].
- Mitigation of the heat island effect, as the vegetal surfaces reduce surface temperatures through evapotranspiration and shading, helping to reduce the heat island effect of cities. Studies show that installing green roofs can reduce the average urban temperature by more than 1 °C [57].
- Rainwater management, as the green façades reduce surface runoff and improve water quality, contributing to the sustainable management of rainwater [58].
- Mental health benefits, as the presence of green spaces is associated with a reduction in stress and an improvement in psychological well-being [59,60].

As regards integrated solar façades, which incorporate PV technologies into the building envelope, the environmental benefits offered are:

- Reduction in GHG emissions, as PV façades produce energy from renewable sources and contribute to the reduction in CO_2 and other GHG emissions, supporting decarbonization objectives [61].
- Efficiency in land use, as solar panels can be integrated directly into building structures, allowing for the optimization of the use of urban space and reducing the need for additional land for energy production.
- Greater thermal insulation, as PV façades can reduce the need for heating and cooling and, consequently, overall energy consumption [62].

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Both green and integrated solar façades offer distinct but complementary environmental benefits, and the adoption of these solutions contributes to urban sustainability, improving air quality, reducing GHG emissions and promoting the well-being of inhabitants.

5.3. Costs and Maintenance

Although they are innovative solutions to improve the sustainability of buildings, green façades and integrated solar façades require specific considerations in terms of initial costs, maintenance and durability. The implementation of green façades involves initial costs related to design, installation and selection of appropriate plant species. Maintenance can be significant, including irrigation, pruning and phytosanitary control [12]. However, the durability of roofs can increase by up to 50 years or more if protected by a green layer. Integrated solar façades, on the other hand, require a high initial investment for the purchase and installation of panels, but maintenance costs are generally lower, limited to periodic cleaning and performance monitoring [63].

A professional long-term feasibility assessment of façade-integrated systems must account for lifecycle-critical components and risk profiles beyond routine maintenance considerations. In photovoltaic (PV) systems, while modules typically guarantee performance over 25–30 years, inverters represent a major lifecycle constraint. String and central inverters, in particular, generally require replacement after 10–15 years due to thermal stress, electrical loading, and environmental exposure. This replacement cycle entails additional embodied energy, capital expenditure, and potential system downtime. From a lifecycle cost and carbon perspective, inverter substitution constitutes a non-negligible intervention that directly affects long-term sustainability metrics and operational reliability.

Similarly, nature-based solutions (NBS) such as green façades involve biological processes that introduce distinct long-term risks. These may include plant mortality, moisture accumulation, root-system interactions with building envelopes, pest colonization, fungal growth, and allergenic exposure. If not properly designed and managed, the vegetative system can generate structural, hygienic, or microclimatic vulnerabilities. However, these risks are largely controllable through species selection, controlled irrigation strategies, and structured maintenance protocols.

Therefore, both photovoltaic and biophilic façade systems present lifecycle-specific constraints: technological obsolescence in the case of PV (notably inverter replacement), and ecological–biological variability in the case of NBS. A rigorous professional evaluation of long-term feasibility must integrate these factors within a comprehensive lifecycle and risk-based framework, rather than relying solely on simplified comparisons of routine maintenance intensity.

The choice between green façades and integrated solar façades depends on many factors, such as the specific energy needs of the building, the local climate, the building exposure to sun radiation, the expected aesthetics and the availability of resources. To find the best solution and design buildings that are both energy efficient and sustainable, a thorough assessment of these elements is necessary.

5.4. Adaptability to Different Urban and Climatic Contexts

Green and solar façades must be suitable for different urban and climatic environments. Their effectiveness varies depending on environmental, climatic and urban circumstances. Green façades, or vegetal walls, as previously seen, reduce the UHI effect, improve air quality and improve the thermal insulation of buildings, but their effectiveness depends on the climate and the environment in which they are used. Through shading and evapotranspiration, green façades can significantly contribute to the reduction in surface temperatures in hot and arid climates. Research conducted by Hasanaj [64] highlights how the addition of vegetal elements to building façades can help reduce high temperatures in densely populated urban areas. Green façades can improve the thermal insulation of buildings in temperate and humid climates, reducing the need for heating during the cold months and cooling during the hot months. The Handbook of Good Practices for Adaptation to Climate Change [65] highlights how essential nature-based solutions, such as green façades, increase the resilience of buildings to climate change. However, low temperatures, which affect plant growth and their ability to insulate heat, can reduce the effectiveness of green façades in cold climates. In situations like these, it is essential to choose cold-resistant plants and create structures that protect plants from negative climate changes. In addition, green barriers can improve the climate in the cold months by blocking north winds [66]. Integrated solar façades, on the other hand, offer significant advantages in terms of renewable energy production, and their adaptability to different climate contexts depends on the availability of solar radiation and local environmental conditions. The integration of solar panels in façades can maximize energy production in areas with strong insolation, contributing significantly to the energy needs of the building. However, the efficiency of these systems may be reduced in areas with less solar exposure or with adverse weather conditions. According to some studies [67,68], to optimize the performance of integrated solar systems, careful design is needed, taking into account building orientation, shading and local climate conditions. In densely populated urban contexts, shading caused by adjacent buildings can negatively affect the efficiency of integrated solar façades. Therefore, it is essential to carry out a detailed analysis of the surrounding environment during the design phase to ensure that solar systems receive a sufficient amount of solar radiation [69,70]. The choice between green façades and integrated solar façades must therefore be guided by a thorough analysis of the climate and the specific urban conditions of the project site. In fact, although green façades are very useful for insulating heat and improving the microclimate in cities, they can only work in extremely cold or dry climates. Integrated solar façades, on the other hand, can significantly contribute to the production of renewable energy. However, their efficiency depends on the availability of solar radiation and the characteristics of the urban environment surrounding them. To maximize the benefits of both solutions, an integrated and context-sensitive design is required.

6. The Role of the Two Solutions in Decarbonization

The decarbonization of the building sector represents one of the most urgent challenges to combat climate change. According to the IEA 2020 report [71], buildings are responsible for approximately 40% of global energy consumption and a third of GHG emissions. In this context, green façades and solar façades emerge as innovative solutions to reduce the carbon footprint of buildings, improve energy efficiency and promote urban sustainability; in fact, both solutions contribute through a series of mechanisms to the reduction in greenhouse gas emissions, playing an important role in the decarbonization of the built environment [72] and offering a series of significant benefits, including the reduction in energy consumption, the improvement of the urban microclimate and the mitigation of the heat island effect [73].

Green façades contribute to decarbonization through direct and indirect mechanisms; in fact, from a decarbonization perspective, façade-integrated solar technologies can significantly reduce operational greenhouse gas emissions by replacing conventional energy sources, while nature-based solutions primarily contribute by reducing energy demand and improving microclimatic conditions. The integration of these approaches represents a promising pathway towards low-carbon buildings [74,75]. One of the many direct benefits that green façades provide to the environment is the absorption of carbon dioxide (CO_2) during photosynthesis, thus contributing to a reduction in atmospheric concentrations of greenhouse gases. According to a study by Perini et al. [1], green façades can reduce CO_2

emissions from buildings by up to 20% through direct absorption and thermal insulation provided by vegetation. Furthermore, a study by Chen et al. [76] showed that a 100 m^2 green wall can sequester up to 2.3 tons of CO_2 per year. In addition to CO_2 absorption, green façades improve the energy efficiency of buildings. Vegetation acts as an insulating layer, reducing the amount of heat that enters the building during the summer and limiting heat loss during the winter. This results in a decrease in the use of heating and cooling systems, resulting in lower energy consumption and related emissions. Some studies [1,49,50] have observed that the use of green façades can lead to a reduction in energy consumption for cooling of up to 50% in temperate climates, with a consequent reduction in CO_2 emissions associated with energy consumption. Furthermore, green façades mitigate the UHI effect, a phenomenon that increases energy consumption and GHG emissions in cities. A study by Alexandri and Jones [77] highlighted that the surface temperatures of green walls can be up to 10 °C lower than those of conventional walls, contributing to reducing urban temperatures and improving thermal comfort. An additional benefit of green façades is their ability to improve urban air quality; in fact, plants can absorb air pollutants such as particulate matter and nitrogen oxides, contributing to a healthier environment. A study by Ottelé et al. [3] showed that green façades can reduce particulate matter concentrations in the air by up to 30%, thereby improving air quality in densely populated urban areas. Integrated solar façades, which enable on-site renewable energy generation, directly contribute to decarbonization by reducing dependence on fossil fuels and decreasing CO_2 emissions associated with energy production. According to a systematic review by Shukla et al. [78], BIPV systems can cover up to 50% of a building's energy needs, with a potential to reduce CO_2 emissions by up to 150 kg/m^2 per year. According to an analysis by Peng et al. [13], integrating PV systems into buildings can reduce CO_2 emissions by up to 1.5 kg per kWh of energy produced.

Bakhshoodeh et al. [79] evaluated the impact of irrigation regimes of green façades on evapotranspiration rates and evapotranspirative cooling effects over the course of a day and verified that the west-facing green façade was able to recover from a visibly stressed condition with a water content lower than 8%; furthermore, during the warmest periods, evapotranspirative cooling of green façades occurred with adequate irrigation. The authors also suggest using alternative and sustainable water sources for urban irrigation, such as greywater (wastewater not discharged from sinks, washing machines, showers or toilets). Going deeper, Sharbafian et al. [80,81] also studied the impact of some characteristics of the green façade (density and distance from the structure) on indicators of natural light, visual comfort, and heating and cooling load and its characteristics for 30 different green façade projects on various building fronts. The results show that increasing the density of green façades affects the indices of natural light and thermal load. Increasing the density of green façades decreases the natural brightness and cooling load, and there is a weak correlation between low densities and thermal loads. Energy performance is closely related to environmental performance. Using the LCA method, Blanco et al. [82] evaluated the environmental performance of an indirect green façade system compared to other conventional non-vegetated building solutions integrated with different materials for thermal insulation. The study highlighted that indigenous plants reduce environmental impacts through the reduction of fertilizers and irrigation because they adapt to the local climate and that the only component on which it is possible to intervene in order to reduce the environmental impact substantially is the steel frame, which is replaceable with a wooden one.

Vassiliades et al. [21] analyzed the effects on thermal comfort in public spaces caused by the integration of active solar energy systems on existing façades in two coastal cities, Naples and Thessaloniki. The simulation results showed that the negative effects on the temperature of the adjacent public space are limited. Furthermore, the use of active solar systems as vertical shading devices in the Thessaloniki configuration may have a slight positive effect on the urban microclimate in cities with this climate, except along the north and west axis during winter.

The efficiency of integrated solar systems, as seen, depends on various factors, including the orientation of the building, the inclination angle of the panels and the local climate conditions. A study by Aste et al. [83] highlighted that the optimization of these parameters can significantly increase energy production, contributing more effectively to the reduction of emissions. In addition to energy production, integrated solar façades can improve the overall energy efficiency of the building. For example, PV systems can act as solar shading, reducing solar heat gain and decreasing the need for internal cooling. Jelle et al. [29] observed that the use of integrated solar façades can lead to a reduction in cooling energy consumption of up to 30%. Furthermore, solar thermal façades, which convert solar energy into heat, can complement heating and domestic hot water systems, further reducing fossil energy consumption [84]. A study by Biyik et al. [14] demonstrated that integrating solar thermal collectors into façades can improve the energy efficiency of buildings by up to 60%, with a significant impact on decarbonization.

The combination of green and solar façades represents a synergistic strategy to maximize environmental and energy benefits. For example, hybrid façades, integrating vegetation and photovoltaic modules, can improve the efficiency of solar panels thanks to the cooling effect of vegetation, which reduces the operating temperatures of the modules and increases their performance. In addition, hybrid façades can enhance urban biodiversity, reduce noise pollution and improve air quality, contributing to more sustainable and resilient urban environments [85]. Recent research has also focused on advanced and hybrid façade systems integrating phase change materials (PCM), photovoltaic-thermal (BIPV/T) technologies, and dynamic control strategies. These approaches aim to enhance thermal storage capacity, improve energy efficiency, and optimize system performance under varying climatic conditions [86–88].

Despite the many benefits, large-scale implementation of green and solar façades requires careful consideration of technical, economic and regulatory factors. Initial installation and maintenance costs can be a significant barrier, especially in high-density urban contexts [1]. However, lifecycle assessment (LCA) studies demonstrate that long-term benefits, in terms of energy savings and emissions reduction, often outweigh the initial costs [3]. Furthermore, public policies and economic incentives can play a crucial role in promoting the adoption of these technologies. For example, energy certification and financing programs, such as LEED and BREEAM, have helped to spread the use of green and solar façades in many countries.

It can therefore be stated that green and solar façades represent promising solutions for the decarbonization of the building sector. By reducing CO_2 emissions, improving energy efficiency and promoting urban sustainability, these technologies can significantly contribute to the transition to a low-carbon future. However, to maximize their potential, an integrated approach is needed that combines technological innovation, public policies and active participation of all stakeholders.

The choice between green and integrated solar façades must in fact be guided by a thorough assessment of the specific climatic and urban conditions of the project site. While green façades offer significant benefits in terms of thermal insulation and improvement of the urban microclimate, their effectiveness may be limited in extremely cold or dry climates. On the other hand, integrated solar façades can provide a substantial contribution to renewable energy production, but their efficiency depends on the availability of solar radiation and the characteristics of the surrounding urban environment. An integrated and context-sensitive design is essential to maximize the benefits of both solutions.

7. Synergies Between Solutions, Implications and Future Challenges

In this study the main characteristics of the green and solar façades, which are schematized in Table 2, were assessed.

Table 2. Comparative analysis of conventional, nature-based, and solar-integrated façade systems in terms of energy, environmental, economic, and technical performance.

Criteria	Conventional Façade	Nature-Based Façade (Green Wall)	Solar Façade (BIPV/PV-Integrated)	Hybrid Green–Solar Façade
Energy Performance	Standard thermal insulation depending on materials	Improved thermal insulation due to vegetation layer and shading	On-site electricity generation; limited direct insulation effect	Combined effect: reduced thermal losses + potential electricity generation
Heating Demand Reduction	Baseline performance	Moderate reduction (especially in winter)	Indirect impact	Higher reduction due to combined insulation and buffering effects
Cooling Demand Reduction	Limited passive cooling	Significant reduction due to evapotranspiration and shading	Reduction through solar shading (depending on configuration)	Enhanced cooling reduction due to synergy between shading and vegetation
Renewable Energy Generation	None	None	High (electricity generation from PV modules)	Moderate–high (depending on PV integration and system design)
Environmental Impact (CO_2 Emissions)	Higher emissions due to higher energy demand	Reduced emissions through lower heating/cooling demand	Reduced emissions via renewable electricity production	Lowest emissions due to combined energy savings and renewable generation
Urban Heat Island Mitigation	No contribution	High contribution (vegetation cooling effect)	Limited contribution	Moderate–high (vegetation + partial shading effects)
Biodiversity Support	None	High (habitat creation for flora and fauna)	None	Moderate (depends on vegetation design)
Land Use Efficiency	Neutral	High (vertical greening reduces need for horizontal land)	Neutral	High (multifunctional façade use)
Initial Cost	Low	Medium–high	High	High
Maintenance Requirements	Low	High (irrigation, pruning, plant care)	Low–medium (cleaning, inverter replacement)	Medium–high (combined maintenance needs)
Operational Complexity	Low	Medium	Medium	High
Durability and Lifecycle Issues	High durability (well-known systems)	Dependent on plant species and maintenance quality	Dependent on PV lifespan (20–30 years; inverter replacement needed)	More complex lifecycle management
Technological Maturity	High (fully established)	Medium–high	High (mature PV technologies)	Medium (emerging integrated solutions)
Integration Complexity	Low	Medium	Medium–high	High (multi-system integration required)
Overall Performance Potential	Baseline reference	Good environmental and passive energy performance	Strong energy production capability	Highest potential but with higher complexity and uncertainty

The analyzed technologies are usually seen as distinct and competing solutions; however, their combination could bring joint benefits (Figure 8). In fact, considering how the efficiency of photovoltaic modules is affected by surface temperatures, the integration of greening technologies with photovoltaic systems can be a valid alternative. On the one hand, the presence of an air gap and foliage between the wall and the PV modules helps to mitigate temperatures by up to 4 °C, reducing overheating of both the wall and the modules themselves, and on the other hand, the support structure of the panels also acts as a support for the plants, and the resulting shielding allows thermal stress on the foliage itself to be reduced [89]. Furthermore, the combination of green surface and PV systems is the basis of agrivoltaics interventions. In the literature, there are cases of tests carried out on vertical walls that combine the two solutions [90]. In the case of the "Öko-Prüfstand" test, carried out at the Technical University of Vienna, an integrated system of indirect green wall and PV façade was created. The system consists of climbing plants (*Wisteria sinensis*, *Campsis radicans*, *Lonicera henryi*) arranged in flower boxes, filled with green roof substrate, and attached to wooden trellises and galvanized steel structures. On the external side, 45 centimeters from the façade, monocrystalline PV modules, both opaque and semi-transparent, were installed. The study demonstrated that the presence of the panels did not affect the growth of the plants, although it was necessary to integrate irrigation in summer with a mechanical system. Furthermore, once the plants had reached maturity and widespread concentration, it was possible to obtain operating temperatures 1–4 °C lower with an external temperature of 20 °C and, in general, a reduction in the surface temperatures of the envelope. In the case of the "GreenPlusSchool@Megalopoli" test, carried out in a school building in Vienna, combined systems of modular living wall and photovoltaic façade were created and studied. In detail, the living wall is made up of 30 × 100 cm modules with 18 plants each, includes a lava-based substrate, is mounted on a steel load-bearing frame, and is spaced from the load-bearing wall by a 5 cm air gap. For the construction of the living wall, eight plant species were tested (*Bergenia cordifolia*, *Festuca gautieri*, *Geranium sanguineum*, *Heuchera cultorum*, *Sagina subulata*, *Sedum floriferum*, *Sedum reflexum* and *Sedum spurium*). The photovoltaic wall is made up of 80 × 160 cm semi-transparent PV modules. The modules were placed at two different distances (25 and 45 cm) from the living wall to evaluate the different behavior.

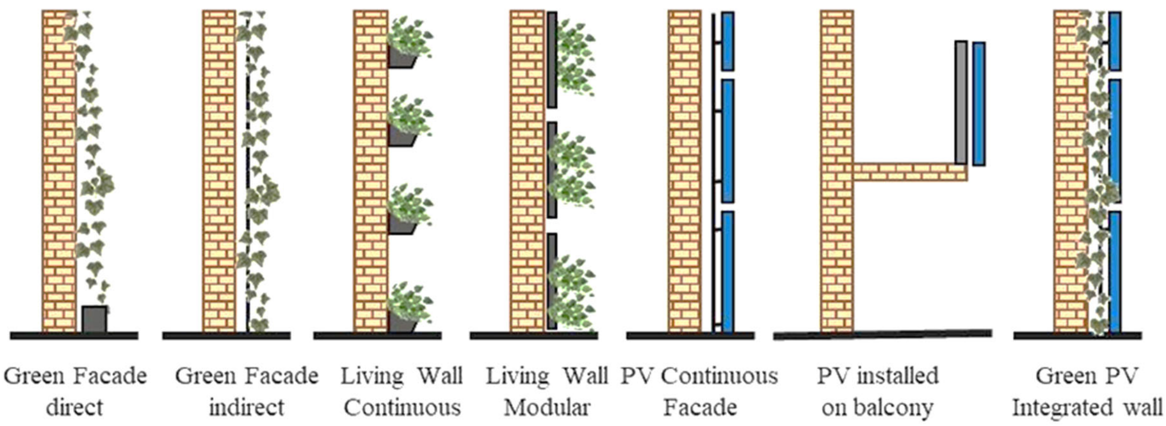

Figure 8. Graphical scheme of the analyzed green façades, solar façades, and combined façades.

The researchers observed, first of all, the better vitality of the essences *Heuchera cultorum*, *Bergenia cordifolia* and *Festuca gautieri*, which suffered less from thermal stress and shading, and, furthermore, the better behavior of the system with a distance of 45 cm between the foliage and the modules. In fact, the presence of a larger air chamber guarantees greater ventilation, which was advantageous both for the plants, in terms of better growth and also greater ease of maintenance operations, and for the panels, in terms of greater performance and electrical energy productivity due to the lower temperatures.

The integration of green façades and solar systems represents a promising strategy to improve [90,91] the energy efficiency of buildings and contribute to environmental sustainability (Figure 8).

This combination offers a series of synergistic benefits that go beyond the individual benefits of each system:

1. Improved Energy Efficiency. Green façades, consisting of plants and vegetation, can positively influence the performance of integrated solar panels. Vegetation helps reduce the surface temperature of the building through shading and evapotranspiration, creating a cooler microclimate. This natural cooling can increase the efficiency of photovoltaic panels, since high temperatures tend to reduce the performance of solar modules. Some studies have highlighted how green façades can be effectively combined with solar panels to address the challenges of global warming [92,93].
2. Environmental Benefits and Reduction in CO_2 Emissions. The integration of green façades and solar systems contributes significantly to the reduction in CO_2 emissions. Plants absorb carbon dioxide during photosynthesis, while solar panels generate clean energy, decreasing dependence on fossil fuels. This dual action not only improves urban air quality but also supports global decarbonization goals.
3. Improved Urban Comfort. Green façades offer additional benefits in terms of urban comfort. Vegetation contributes to the reduction in the heat island effect in urban areas, lowering ambient temperatures and improving the local microclimate. In addition, plants act as a natural barrier against noise, improving the acoustic insulation of buildings. These aspects, combined with the renewable energy production of solar panels, make urban environments more livable and sustainable.
4. The integration of green façades and solar systems represents an innovative strategy in the field of sustainable architecture, with significant implications at both environmental and socio-economic levels.
5. Environmental Implications. Green façades and integrated solar panels have a significant impact on climate change mitigation [52]. Green façades reduce energy demand for heating and cooling while reducing the thermal insulation of buildings. This effect, combined with energy production from renewable sources such as solar panels, reduces greenhouse gas emissions related to the construction sector. Urban vegetation improves the air in densely populated urban areas by reducing air pollution and absorbing CO_2 [94].
6. Socio-Economic Implications. The adoption of these integrated technologies has the potential to promote the green economy, generating new job opportunities in the design, installation and maintenance of sustainable building structures [95,96]. Furthermore, buildings that use energy efficiently and have green areas improve the mental and physical health of employees, increasing productivity and quality of life. Vegetation can also increase the real estate value of a building and make it more attractive on the market.

Despite the many benefits, the integration of green façades and solar systems presents some challenges. The design must carefully consider the interaction between vegetation and solar panels to avoid unwanted shading that could reduce energy production. Furthermore, the combined maintenance of both systems requires careful planning to ensure the longevity and efficiency of the installation. It is essential to evaluate local climate conditions, the selection of appropriate plant species and the orientation of the building to maximize the synergistic benefits. The integration of green façades and solar systems therefore represents an innovative solution for sustainable buildings, offering environmental, energy and urban

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comfort benefits. Careful design and adequate maintenance are essential to overcome the associated challenges and maximize the benefits of this combination.

8. Simplified Preliminary Energy–Environmental Assessment

The following analysis represents a simplified preliminary assessment intended to provide an indicative comparison between different façade configurations. The evaluation is based on a steady-state thermal-loss estimation using monthly climatic data and simplified envelope parameters. Consequently, the results should be interpreted as illustrative trends rather than predictive performance outcomes.

The objective of this preliminary assessment is to provide a first-order estimation of how different façade configurations may influence thermal losses through the building envelope and the associated environmental impact. Three façade configurations were considered:

- Conventional Wall, consisting of a traditional masonry wall assembly;
- Green Wall, corresponding to the conventional wall supplemented with an external vegetation layer;
- Combined Wall, corresponding to the green wall configuration, further complemented by an air cavity and an external vertical photovoltaic (PV) panel.

Although simplified, these configurations enable a preliminary comparison between traditional building envelopes, nature-based façade systems, and hybrid green–solar façade solutions. In the present assessment, the photovoltaic panel was not explicitly modeled as an electricity-generating system. Instead, the PV layer was considered as an additional external façade component influencing the thermal configuration of the building envelope. Consequently, the analysis focuses on differences in thermal losses between façade configurations, while the potential electricity generation of the photovoltaic system is not explicitly quantified.

The main input parameters adopted for the simplified thermal assessment, including layer composition, thicknesses, and representative thermal properties, are summarized in Table 3.

The reported values represent typical configurations derived from technical standards and literature sources and are intended to provide a consistent basis for comparative analysis rather than exact design specifications.

To investigate the influence of climatic conditions, three façade configurations were evaluated in three Italian cities characterized by different heating requirements: Milan (2404 Heating Degree Days—HDD), Rome (1415 HDD), and Palermo (751 HDD). These cities represent three distinct climatic contexts within Italy, ranging from relatively cold northern climates to warmer Mediterranean environments.

The annual thermal losses through the building envelope were estimated using a simplified steady-state approach based on the thermal transmittance of the façade and the temperature difference between indoor and outdoor environments. Monthly average outdoor temperature data were obtained from the National Air Force Meteorological Service [97]. Solar irradiance data were obtained from the National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) [98], while thermal transmittance values for typical wall assemblies were derived from technical documentation provided by the National Association of Thermal Insulation (ANIT) [99].

Although the present study adopts a simplified steady-state approach, this methodology is consistent with first-order energy assessment techniques commonly employed in early-stage building design. Similar approaches are widely used in the literature to provide preliminary comparisons between alternative façade configurations prior to the implementation of detailed dynamic simulations.

Table 3. Simplified façade assemblies and thermal assumptions used in the steady-state model.

Component	Layer Description	Thickness (m)	Thermal Conductivity (W/m·K)	Thermal Transmittance Contribution
Conventional Wall	Internal plaster	0.015	0.70	–
	Brick masonry	0.300	0.60	–
	External plaster	0.015	0.70	–
	Overall U-value	–	–	~1.20 W/m^2K
Green Wall	Conventional wall base	–	–	–
	Vegetation layer (foliage + substrate)	0.100	0.40 (equivalent)	–
	Air gap (non-ventilated)	0.050	–	–
	Adjusted U-value	–	–	~0.80–0.90 W/m^2K
Combined Wall	Green wall configuration	–	–	–
	Ventilated air cavity	0.100	–	–
	External PV panel (opaque layer)	0.050	0.20 (equivalent)	–
	Adjusted U-value	–	–	~0.70–0.80 W/m^2K

Dynamic simulation tools (e.g., EnergyPlus, TRNSYS) have demonstrated that façade-integrated vegetation systems and ventilated photovoltaic layers can significantly influence building energy performance through transient heat-transfer mechanisms, solar gains, and thermal inertia effects. However, such approaches require detailed input data related to material properties, boundary conditions, vegetation dynamics, and system interactions, which are beyond the scope of this early-stage comparative assessment. Therefore, the simplified model adopted in this study should be interpreted as a preliminary analytical framework aimed at identifying relative performance trends rather than providing absolute predictive results.

The heat transfer through the façade was estimated using the steady-state heat-loss relationship:

$$Q = U \times A \times \Delta T$$

where Q represents the heat-transfer rate through the wall (W), U is the thermal transmittance of the façade (W/m^2K), A is the wall surface area (m^2), and ΔT is the temperature difference between indoor and outdoor conditions (K). This formulation provides a first-order approximation of heat losses across different climatic contexts and façade configurations. To ensure transparency and reproducibility of the preliminary assessment, the main thermo-physical properties and stratigraphic configurations of the analyzed façade systems are explicitly reported. Table 4 summarizes the layer composition, thickness, thermal conductivity, and corresponding thermal resistance values adopted for each façade typology.

The reported values are based on standard construction practices and technical references, including data provided by the National Association of Thermal Insulation (ANIT) [99], complemented by typical ranges available in the literature for vegetated systems and ventilated façades. In the case of green and hybrid façade systems, equivalent homogeneous layers are adopted to represent complex components such as vegetation and air cavities within the limits of a steady-state modeling approach.

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Table 4. Stratigraphy, material properties, and thermal assumptions of the façade configurations used in the preliminary assessment.

Façade Type	Layer (From Inside to Outside)	Thickness (m)	Thermal Conductivity λ (W/m·K)	Thermal Resistance R (m^2K/W)
Conventional Wall	Internal plaster	0.015	0.70	0.021
	Hollow brick masonry	0.300	0.40	0.750
	External plaster	0.015	0.70	0.021
	Total (excluding surface resistances)	—	—	0.792
	Global U-value	—	—	1.10–1.20 W/m^2K
Green Wall	Internal plaster	0.015	0.70	0.021
	Hollow brick masonry	0.300	0.40	0.750
	External plaster	0.015	0.70	0.021
	Vegetation layer (foliage + substrate equivalent)	0.050–0.100	0.20–0.30	0.20–0.40
	Total (excluding surface resistances)	—	—	~1.0–1.2
	Effective U-value	—	—	0.70–0.90 W/m^2K
Combined Wall (Green + PV)	Internal plaster	0.015	0.70	0.021
	Hollow brick masonry	0.300	0.40	0.750
	External plaster	0.015	0.70	0.021
	Vegetation layer	0.050–0.100	0.20–0.30	0.20–0.40
	Ventilated air cavity	0.050–0.100	—	0.15–0.25
	External PV panel (glass + cells equivalent)	0.005–0.010	1.00	0.005–0.010
	Total (excluding surface resistances)	—	—	~1.2–1.5
	Effective U-value	—	—	0.50–0.70 W/m^2K

The thermal resistance of the vegetation layer is treated as an equivalent homogeneous layer, representing the combined effect of foliage density, substrate, and air gaps, as commonly adopted in simplified façade modeling approaches.

The thermal resistance of the ventilated air cavity is estimated based on typical values for naturally ventilated façade systems under steady-state assumptions, without explicitly modeling airflow dynamics. Surface thermal resistances (internal and external) were considered according to standard practice but are not explicitly reported in the table for clarity. Material properties and thermal parameters are based on technical documentation provided by ANIT [99] and typical values reported in the literature for green façade systems and ventilated façades.

To estimate the environmental implications of the different façade solutions, the calculated thermal energy demand associated with façade heat losses was converted into equivalent greenhouse gas emissions. The Global Warming Potential (GWP) was expressed in terms of CO_2 equivalent emissions using the coefficient 0.23 kg CO_2/kWh, derived from the National Inventory of Polluting Emissions provided by the Italian Institute for Environmental Protection and Research (ISPRA) [67].

The results of the preliminary assessment are illustrated in Figure 8. In all analyzed climatic contexts, the addition of a vegetation layer contributes to improving the overall thermal performance of the façade by increasing the effective insulation capacity of the envelope. As a consequence, lower heat losses through the wall and a corresponding reduction in estimated energy demand and associated emissions can be observed.

The effect appears more pronounced in colder climates, such as Milan, where the heating season is longer and thermal losses play a more significant role in the overall building energy balance. The combined façade configuration, which includes both vegetation and a ventilated cavity with an external photovoltaic panel, shows the lowest thermal losses among the analyzed cases. This configuration may benefit from the additional thermal buffering provided by the vegetation layer and the air cavity (Figure 9).

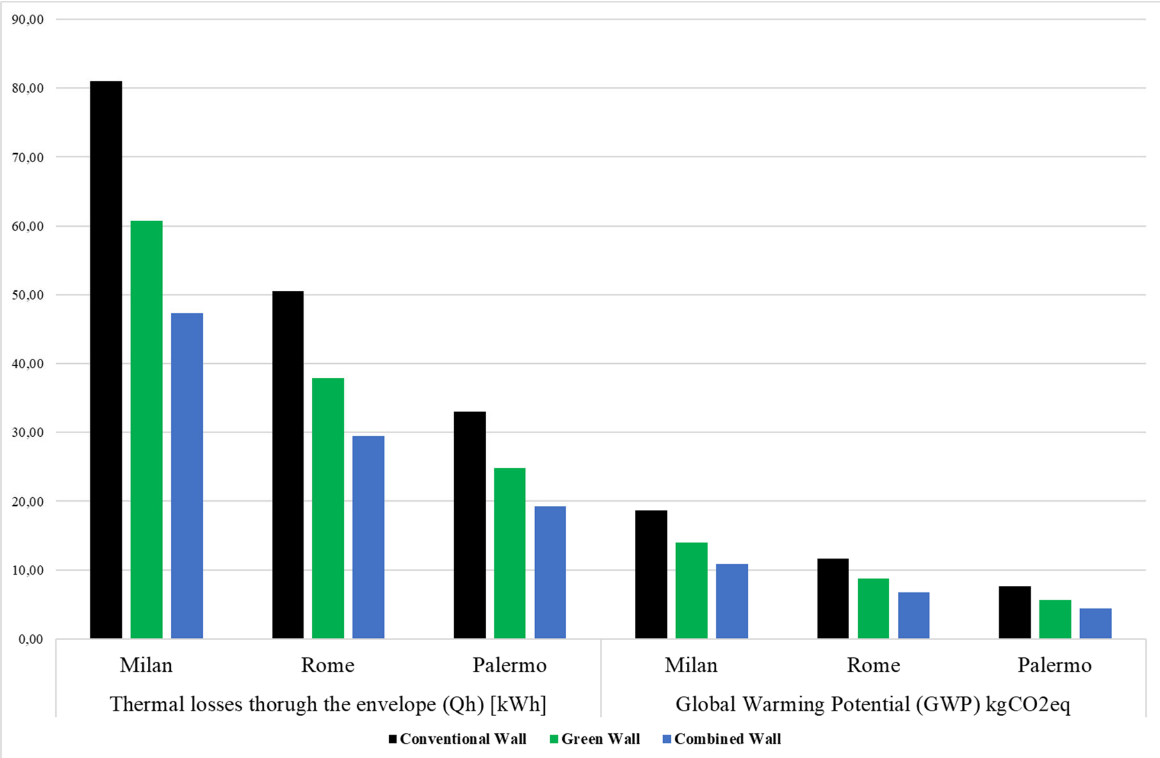

Figure 9. Annual thermal energy losses and equivalent carbon emissions in the assessed cases.

However, it should be emphasized that the present analysis focuses exclusively on steady-state heat-loss mechanisms and does not explicitly simulate dynamic thermal processes. In particular, the simplified model does not account for solar radiation absorption by photovoltaic panels, seasonal variations in solar exposure, or the dynamic thermal behavior of façade systems under summer conditions. These factors may significantly influence the overall energy performance of integrated green–solar façade systems.

Therefore, the results presented in this section should be interpreted as a preliminary comparison highlighting potential trends rather than as a comprehensive performance assessment. Future research should extend this analysis through dynamic simulation approaches and experimental validation to better capture transient effects and system interactions.

Several limitations should be acknowledged when interpreting the results presented in this study.

First, the literature review follows a structured approach but does not constitute a fully systematic review. Although major scientific databases were consulted and a transparent selection strategy was adopted, some relevant studies may not have been captured due to differences in terminology or indexing across databases.

Second, the preliminary assessment presented in Section 7 is intentionally simplified and is based on steady-state thermal calculations. This approach does not account for dynamic thermal behavior, hourly climatic variability, or transient heat-transfer mechanisms that may influence façade performance in real operating conditions.

Third, the photovoltaic layer in the combined façade configuration was not explicitly modeled as an electricity-generating system. The analysis therefore focuses on the influence of façade configurations on thermal losses rather than on the full energy balance of the building envelope.

Finally, the interaction between vegetation systems and photovoltaic components—including shading effects, evapotranspiration processes, seasonal plant growth, and the potential cooling of PV modules—was not explicitly simulated. These aspects may significantly influence the performance of hybrid façade systems and should therefore be investigated in future research through advanced dynamic simulations and experimental investigations.

9. Conclusions

This study has provided a structured overview of nature-based and solar-integrated façade systems, examining their respective roles and potential synergies within decarbonization-oriented building design. The analysis highlights that green façades and solar façades should not be interpreted as competing solutions, but rather as complementary strategies that may jointly contribute to improving the environmental performance of the built environment.

The review of the literature indicates that nature-based façade systems are particularly effective in enhancing thermal regulation, mitigating the urban heat island effect, and providing additional environmental co-benefits such as air quality improvement and biodiversity support. Conversely, solar-integrated façades primarily contribute to on-site renewable energy generation, thereby reducing dependence on fossil fuels and associated greenhouse gas emissions. Their effectiveness, however, is strongly influenced by climatic conditions, façade orientation, and urban context.

The preliminary quantitative assessment carried out in this study suggests that the integration of vegetation layers can contribute to reducing thermal losses across different climatic contexts, with further improvements observed in combined green–solar façade configurations. These findings indicate that hybrid solutions may benefit from synergistic effects, such as thermal buffering and potential microclimatic interactions between vegetation and photovoltaic components.

However, it is important to emphasize that the quantitative analysis is based on a simplified steady-state approach and is intended to provide only a first-order comparison between façade configurations. Therefore, the results should be interpreted as indicative trends rather than predictive performance outcomes. More robust conclusions require detailed dynamic simulations and experimental validation, which are beyond the scope of the present study.

From a scientific perspective, this work contributes to the existing literature by proposing a comparative analytical framework that integrates qualitative review and preliminary quantitative assessment to evaluate façade-based decarbonization strategies. In this context, the findings support the interpretation of green and solar façades as complementary design elements within integrated building systems.

Future research should focus on the development of advanced modeling approaches capable of capturing transient heat-transfer processes, solar radiation effects, and the dynamic interaction between vegetation systems and photovoltaic components. In particular, multiscale modeling frameworks linking material properties, façade configuration, and building energy performance are needed to improve predictive accuracy.

In addition, further investigation is required to better understand the coupled effects of shading, evapotranspiration, and photovoltaic temperature regulation in hybrid façade systems. The integration of dynamic simulation tools with experimental validation and monitoring techniques could provide deeper insights into system behavior under real operating conditions.

Finally, the application of data-driven and machine-learning approaches may support the optimization of hybrid green–solar façade configurations, enabling context-specific design strategies adapted to different climatic and urban scenarios. These research directions are essential to support the large-scale implementation of integrated façade systems in the transition toward net-zero energy buildings.

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