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Review

Energetic Valorization of the Innovative Building Envelope: An Overview of Electric Production System Optimization

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Abstract: The world population increased from 1 billion in 1800 to around 8 billion today. The Population Division of the United Nations predicts a global population of approximately 10.4 billion people by the end of the century. That represents over 2 billion more people. Moreover, the global community is currently experiencing a precarious state due to the enduring repercussions of the COVID-19 pandemic across all sectors, including energy. Given the rising global population and the limited availability of primary energy resources, we must reach a balance between the demands of a growing human population and the planet's carrying capacity. The dreadful conflict in Ukraine has precipitated an enormous energy crisis. This crisis has served as a warning to the world population of how much it depends on this resource to survive. In France, the building sectors, specifically residential and tertiary, account for 45% of the total final energy consumption. It is the first energy consumer of the country and one of the most polluting (i.e., about 34% of CO₂ emitted by France). Consequently, we must consider alternative energy resource forms (i.e., substitution energy forms). Harvesting energy from the building envelope may be a viable technique for partially satisfying the electricity demands of building users. In this context, scientific research offers considerable potential for developing more innovative and efficient systems. This article aims to review the state-of-the-art of advances on the subject to orient and further optimize energy production systems, particularly electricity. This work addresses several points of view: it discusses the overall backdrop of the present study and introduces the subject; details the research strategy and procedures used to produce this paper; develops the state-of-the-art on the potential for generating or recovering power from the building envelope; presents the SWOT analysis of the earlier-described systems. Finally, it concludes by offering findings and viewpoints.

Keywords: systems; power; building envelope; innovation; assembly



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1. Introduction

In the face of a rapidly expanding global population and the finite nature of primary energy resources, it is imperative to reconcile burgeoning human demands with the Earth's energy production capacity. Principal concerns arise from the inadequacy of energy supplies to meet the escalating global demand and the accompanying environmental ramifications associated with fossil fuel utilization. The data from the Agence de la Transition Écologique (ADEME) and the Ministère de la Transition Écologique in FRANCE reveal that the building sector, encompassing residential and tertiary structures, singularly accounts for 45% of final energy consumption in France [1,2]. Furthermore, the United Nations Environment Programme (UNEP) reports that this sector contributes 38% of carbon dioxide (CO₂) emissions, positioning it as the primary energy consumer and one of the most environmentally harmful sectors in the country. In light of contemporary environmental expectations and objectives for sustainable development, concrete

measures are imperative to curtail energy consumption within the building sector. These measures necessitate a dual approach to reducing energy consumption and incorporating more renewable and sustainable energy sources. Given its prominent position among the most polluting and energy-intensive sectors, the building sector represents a focal point for potential improvements. Addressing the need for enhanced energy efficiency in buildings and the obligation to meet the energy demands of a burgeoning global populace underscores the relevance of bolstering our infrastructures and innovations. Central to this endeavour is integrating energy production systems, particularly those generating electricity, into the building envelope. Within this context, scientific research emerges as a formidable avenue for developing innovative and efficient systems.

The broader context in sustainable building practices involves examining the larger framework and global trends that contribute to understanding and implementing environmentally friendly construction methods. The idea of the broader context of the topic can be enumerated by some aspect illustrations such as:

Environmental Challenges:

- **Climate Change:** The growing awareness of climate change has led to an increased focus on sustainable practices in various industries, including construction. Rising global temperatures, extreme weather events, and the depletion of natural resources highlight the urgent need for sustainable building solutions.
- **Resource Scarcity:** The depletion of traditional construction materials and the environmental impact of their extraction has prompted a shift towards more sustainable alternatives. Exploring recycled materials, renewable resources, and innovative construction techniques can respond to this challenge.

Regulatory Framework:

- **International Standards:** Organizations and governments worldwide are establishing and updating standards for sustainable construction. The Leadership in Energy and Environmental Design (LEED) certification and similar global standards provide guidelines for eco-friendly building practices, influencing the construction industry worldwide.
- **Government Policies:** Many countries are implementing policies that incentivize or mandate sustainable building practices. For example, some countries include tax incentives for green buildings, stricter environmental regulations, and government-backed initiatives to promote energy-efficient construction.

Technological Advancements:

- **Innovative Materials:** Advancements in material science have introduced new, sustainable construction materials. These materials, from bamboo and recycled steel to high-performance concrete, offer environmental benefits and improved structural performance.
- **Smart Technologies:** Integrating innovative technologies in building design and management helps optimize energy use, monitor environmental impact, and enhance overall sustainability. Notably, we have the case of buildings using sensors and tools for automation and data analytics to create more efficient and eco-friendly buildings.

Social Awareness and Responsibility:

- **Consumer Demand:** Increasing consumer environmental awareness has created a demand for sustainable and eco-friendly buildings. Developers and builders respond to this demand by incorporating green features and certifications.
- **Corporate Social Responsibility (CSR):** Many corporations are adopting sustainable building practices as part of their CSR initiatives. The concept proposed by each country aligns with societal expectations and contributes to long-term cost savings and a positive brand image.

Global Collaborations:

- **Knowledge Sharing:** With the global nature of environmental challenges, there is a significant emphasis on international collaboration and knowledge sharing. Re-

search institutions, industry experts, and governments collaborate to exchange ideas, technologies, and best practices in sustainable construction.

Economic Considerations:

- **Cost-Effectiveness:** Initially, there might be a perception that sustainable building practices are more expensive than conventional construction. However, many sustainable initiatives are cost-effective over the long term due to reduced energy consumption, lower maintenance costs, and potential government incentives.
- **Job Creation:** The shift towards sustainable building practices also contributes to creating jobs in sectors related to renewable energy, green construction, and the development of eco-friendly technologies.

Understanding this broader context is essential for researchers, policymakers, and industry professionals to make informed decisions and advancements in sustainable building practices that address global challenges while considering economic, social, and environmental dimensions.

Numerous studies have been conducted on the integration of thermal systems into the envelope of a building and their capability to heat or refresh an indoor ambience. For example, Bigot et al. [3] demonstrated that building indoor temperature is considerably influenced by the BAPV. Very few of them deal with the electrical capacity that these walls, roofs, and floors that constitute the building envelope can produce. The scientific issue addressed in this bibliography revolves around identifying the components that form integral parts of the building's architecture and possess the ability to generate electricity directly. The case studies will enable the analysis of the most efficient systems currently available on the market and the scientific challenges that need to be addressed to comprehend and enhance their functioning. Additionally, the evaluation will encompass the financial, technical, and environmental impacts of these integrated components within the building envelope in a socioeconomic, technological, and climatic context.

This article comprehensively reviews state-of-the-art advancements in this domain to guide funders and designers in optimizing electrical production systems integrated into the building envelope. An exhaustive search and selection process was undertaken to conduct this review, encompassing all scientific articles about the study of direct electricity generation systems within buildings and any form of energy potentially convertible into electricity. The inquiry spanned prominent publication platforms, including Elsevier, ResearchGate, Google Scholar, MDPI, and Taylor & Francis. Additionally, a scrutiny of patents filed for relevant technologies was conducted through Google Patents.

2. State-of-the-Art

The literature search was conducted focusing only on the three components forming a building envelope: glazing, walls, and roofing. The ground component was not considered in the bibliography due to the absence of any electricity-generating system utilizing it. The technologies, according to consideration, can generate electricity through either direct or indirect means (e.g., with the conversion of thermal energy to electrical energy). As a result, we exclude technologies that generate energy other than electricity from the bibliography.

2.1. Roof Technologies

2.1.1. Photovoltaic and Thermal Panels Integrated with the Roof

Solar thermal systems (STs) have significantly improved efficiency compared to their earlier versions. The driving force behind the advancement of STs lies in the expanding research on alternative energy sources, recognized as an integral component of low-carbon energy systems essential for generating affordable and reliable electricity [4]. This section delves into the latest developments in STS applications, mainly focusing on PVT (i.e., photovoltaic thermal collectors) or "photovoltaic/thermal" systems—currently the most widely employed green energy technology for power production. This hybrid system seamlessly integrates the output of both thermal and electrical energy. The PVT system capitalizes on the photovoltaic (PV) effect, which generates electric energy through solar

irradiation [5]. It finds applications in BIPVs (building-integrated photovoltaic), replacing traditional construction materials [5,6]. PVs can be incorporated as BIPV or building-attached photovoltaic (BAPV) systems. Although BAPV systems yield more electricity, BIPV systems excel in overall building performance due to better control over solar gain. The standard definition for available roof space in BIPV deployment is 40% of the ground-level size. Most solar cells are suitable for BIPV roof applications [7]. Beyond photovoltaic (PV) energy, which directly converts solar radiation into electrical energy, thermal energy can also be harnessed for electricity generation. One promising method involves using thermoelectric generators (TEGs) [8]. Utilizing the Seebeck effect, thermoelectric generators (TEGs) demonstrate their capability to convert thermal energy directly into electrical energy. Consequently, combining PV and TE to enhance electricity production becomes a viable option [9]. This hybrid system incorporates thermoelectric generators attached to a solar panel. Notably, the photovoltaic panels absorb heat and store thermal energy during operation. Applying this technique to the opposite face of the thermoelectric generators on solar panels efficiently recovers the underutilized thermal energy in conventional panels [8]. It constitutes a hybrid photovoltaic and thermoelectric (PV-TE) module that concurrently leverages the photovoltaic and Seebeck effects.

2.1.2. Photobioreactor Roofs

In the pursuit of advancing renewable and sustainable energy sources, the cultivation of algae presents intriguing possibilities. Due to their rapid growth compared to most other plants, algae can yield substantial biomass. Two primary facilities for algae cultivation exist: open ponds and photobioreactors. Open ponds, which do not apply to buildings, are excluded from this study. Photobioreactors, though more costly, boast superior yields and consist of transparent closed tanks filled with water. Microalgae within these reactors can thrive in various water sources, including seawater, wastewater, and harsh water. The cultivation process involves harnessing daylight, carbon dioxide, and organic carbon simultaneously for energy production [10]. A pump circulates water by introducing CO₂-enriched air bubbles into the system, and whereas laboratory studies typically enrich the air with CO₂ using gas canisters, real-world applications aim to capture CO₂ from the surrounding air or recover on-site combustion gases, as demonstrated by the BIQ building and its cogenerator [11]. Regular stirring is essential for proper distribution [12]. An automated anaerobic digestion (AD) unit meets nutrient requirements [13]. The resulting microalgae biomass can be valorized as biomass and/or oil. Microalgae strains also hold potential as a source of H₂ energy, as they can split water into H₂ and O₂ using solar energy [14]. In the AD unit, algae biomass is converted into biogas, such as methane, which powers a biogas generator for electricity and heat production [12]. This biomass can alternatively be transformed into pellets, generating power through combustion [10], or processed to extract lipids for biofuel production, subsequently used in a biofuel generator for electricity [10,15]. Building rooftops can be effectively utilized by integrating these photobioreactors. The choice between tubular and flat photobioreactor (i.e., PBR) panels within both horizontally and vertically oriented buildings presents options. Vertical tubular PBRs, due to their geometry, do not require a specific orientation for optimal solar exposure, whereas flat panels slightly outperform vertical tubular PBRs [12]. Innovative designs like I. Berzin's triangular airlift PBR blend bubble column principles with built-in static mixers [16]. Despite the technical viability of such systems, the economic aspect raises concerns. A. Bender's findings suggest that producing electricity from algae biomass on a building's roof may not be economically feasible [12], and whereas the energy production potential from microalgae remains promising, efficiency improvements are essential, given the myriad factors influencing performance [17]. S. Wilkinson and colleagues delve into the various challenges associated with algae-building technology, offering perspectives for enhancement [18,19].

2.1.3. Building-Integrated Wind Turbines

The development of photovoltaics and wind fields has become evident in recent years. Although the feasibility of integrating photovoltaic (PV) panels into building envelopes is well-established, the same cannot be said for wind turbines. Public acceptance of wind turbines is hindered, primarily due to concerns about visual and auditory disturbances they may cause. Unlike rural areas where wind energy systems are commonplace, harnessing wind as an energy source in urban settings is challenging. Studies have revealed that urban wind flows are predominantly characterized by low speeds, particularly in city centres [20]. Nevertheless, specific urban locations, such as rooftops of large buildings less susceptible to turbulence, exhibit significant potential for wind energy production [21]. Integrating wind turbines with the aerodynamic designs typical of rural areas is often impractical or impossible. Two main types of wind turbines exist: classic horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs). A study by M. Casini delves into various VAWTs, exploring their advantages, disadvantages, and potential applications in urban building contexts [22]. In the context of building integration, wind turbines can be strategically placed on rooftops, between buildings, within through-building openings, or incorporated into the building skin [23]. Rooftop installations are standard, capitalizing on unused space where wind speeds are often optimal at higher elevations. Installing turbines between two buildings requires careful planning during the design phase, ensuring structure compatibility. Integration within building openings and envelopes represents relatively unexplored territory. Noteworthy advancements in building-integrated wind turbines have emerged. In 2015, Park et al. proposed a wind wall turbine system integrated into facades, incorporating guide panels and small rotors for electricity generation. Computational fluid dynamics (CFD) analyses were conducted to optimize rotor shapes and the system demonstrated the capability to meet 6.3% of a residential structure's electricity demands [24]. Subsequently, in 2017, Hassanli et al. introduced a double skin facade (DSF) wind turbine system, proving its feasibility through CFD simulations [23]. Although research in this area is limited, recent studies present promising prospects for advancing building-integrated wind turbine technology.

2.1.4. Hybrid Solar-Wind Systems

This section proposes a distinctive hybrid system that synergizes thermoelectric materials, wind turbines, and solar collectors. Initially, solar heat is absorbed by the collector's absorber plate above the thermoelectric generators. The temperature difference between the hot absorber plate and a stream of fresh air is harnessed to produce energy. The thermoelectric generators heat the fresh air, causing it to ascend due to buoyancy force and the chimney effect, passing through the vertical chimney and slanted collector. Upon reaching the turbine blades, the rising air induces rotation, generating electricity generation [25]. This system encompasses a solar air collector, solar chimney, thermoelectric generators, and a Savonius wind turbine. Its integration occurs in a near-zero energy building in St. Petersburg, Russia [26]. Another employed hybrid system involves a combination of a wind turbine, PV solar panels, a tank, a compressor, a PEMEC (Proton Exchange Membrane Electrolyzer Cell) for hydrogen production with excess electricity, and a PEMFC (Proton Exchange Membrane Fuel Cell) for converting produced hydrogen into power during production deficiencies [27]. In the PEMEC, the consumption of power facilitates the conversion of water into hydrogen and oxygen. The hydrogen and oxygen generated undergo a reaction, producing water and electricity, yet another hybrid system utilizes both photovoltaic (PV) and wind technologies. This system automatically switches between photovoltaic and wind production modes based on weather conditions. It functions as a 2-in-1 wind system, featuring a device with two flexible photovoltaic panels managed by a bending mechanism. This mechanism enables the device to have two profiles [28]. In its flat and extended rectangular shape, the device maximizes sunlight absorption during the sun's dominance, producing clean electricity in PV mode. Conversely, in a half-cylindrical shape (concave and convex), it emulates the Savonius wind turbine blades' structure during

wind dominance, continuing electricity production in wind mode. The device operates autonomously through an embedded electronic and artificial intelligence system. When the wind is favourable, the electro-mechanical system flexes the PV panels to transition to a semi-cylindrical mode. The PV panels extend to a flat shape in the presence of sunlight. This invention pertains to a renewable energy bi-converter system that enhances electricity generation.

2.2. Facade Technologies

2.2.1. Solar Paint Wall

Hydrogen presents a compelling solution to the current energy crisis and environmental challenges due to its high energy density and eco-friendly nature as a carbon-free energy source [29]. One promising method for hydrogen production is photocatalytic hydrogen evolution (PHE), a process that utilizes solar energy to split water molecules [30–32]. In this light-assisted catalysis, a newly developed solar paint exhibits the capability to split and absorb water vapour, producing hydrogen [31]. The innovative substance within the paint, synthetic molybdenum-sulfide, functions akin to silica gel but with added benefits. Unlike traditional silica gel, this novel substance acts as a semiconductor, catalyzing the separation of water molecules into hydrogen and oxygen. The subsequent step involves converting hydrogen into electricity using hydrogen fuel cells, which generate electrical energy through the combination of hydrogen and oxygen atoms [30]. The emerging class of inorganic coordination polymers, sulfur-rich molybdenum sulfides MoS_x ($x = 3^2/3$), holds significant promise for catalytic applications [30], particularly in hydrogen production. Researchers have explored the material's potential as an electrocatalyst, leveraging its quick moisture uptake and high conductivity. A catalytic ink was developed for electrolyte-free hydrogen production, avoiding the need for external power sources or complex fluid-handling machinery. To enhance water splitting efficiency, MoS_x 's was combined with TiO_2 (P25) due to the former's small band gap [30]. Additionally, well-defined photocatalysts, including Al-doped SrTiO_3 ($\text{SrTiO}_3:\text{Al}$) loaded with a RhCrO_x and CoO_y co-catalyst, were employed in a batch phase reactor using actual air samples or water vapour dosed into N_2 gas [31]. Zinc indium sulfide (ZnIn_2S_4) has garnered attention in PHE applications [32] owing to its outstanding semiconductor features, such as non-toxicity, a reasonable band gap, and high stability. Through electrochemical processes, fuel cells facilitate the conversion of hydrogen and oxygen's chemical energy into direct current electrical energy.

2.2.2. Photobioreactor Facade Panels

Previously, we discussed the utilization of PBRs employing microalgae for electricity production. This technology can be seamlessly integrated into building facades and even windows, as outlined in [19]. The technology resembles rooftop PBRs and can manifest in various forms, as indicated in [33]. Numerous studies have highlighted the additional benefits of incorporating PBRs into facades, serving purposes such as glazing panels [17], thermal insulation, sun-shading [11], and significantly contributing to air purification by converting CO_2 into O_2 . The vertical flat panels serve as a double skin facade and facilitate natural ventilation, as noted in [33]. Despite theoretical models and simulations, the practical application of this technology is challenging due to inherent problems described in [11,34]. However, there is a noteworthy real-scale application—the BIQ (bio-intelligent quotient) Building, constructed in 2013, stands as the first microalgae-powered building [18,33]. By installing vertical flat panels on two facades, the BIQ Building partially meets its energy needs [19]. Additionally, research by G. M. Elrayies et al. indicates that the Process Zero project covers 9% of the GSA office building's requirements by installing tubular PBR front panels [11]. Furthermore, integrating PBRs on both roofs and facades presents an opportunity to enhance energy production [11]. Hybrid PBRs, combining the strengths of different types, offer another avenue for maximizing benefits, as discussed in [14].

2.2.3. Microbial Biophotovoltaic Wall Technology

Microalgae have demonstrated significant potential in biotechnologies, yet they are not the sole contributors to electricity generation. Cyanobacteria, a type of bacteria, have proven to possess the ability to generate power. A specific type of microbial fuel cell, a biophotovoltaic (BPV) cell, harnesses this capability. Using water as an electron source, BPVs can convert light energy into electrical output. Unlike traditional photovoltaic (PV) systems, BPV devices can produce electricity in light and darkness, making them more sustainable. Typically, the production of BPVs involves collecting cells in a liquid culture and then applying them to an electrode. However, this approach has drawbacks, primarily associated with the liquid phase. Some cyanobacterial and microalgal species, as indicated in previous studies [35], have demonstrated the ability to grow on a conducting anode without needing any organic substrate for electron transfer. The work of M. Sawa et al. highlights a breakthrough in the field by showcasing the feasibility of fully printing a bioelectrode using a conventional inkjet printer [36]. The prototype featured a thin-film paper-based biophotovoltaic cell composed of a layer of cyanobacterial cells on a carbon nanotube conducting surface. A unit of nine BPVs successfully powered a digital commercial clock, cycling between 30-min “ON” periods and 30-min “OFF” intervals to recover BPV devices. Additionally, the prototype demonstrated the ability to power an LED for 60 s with one pulse every 2.5 s, providing sufficient electricity to illuminate the LED. This innovative technology is promising as a bio-solar panel during daylight hours and transforms into a bio-battery at night. The potential applications could be expanded through large-scale printing, such as creating wallpapers that generate electricity by harnessing solar energy captured during the day.

2.3. Window Technologies

2.3.1. Photovoltaic Glasses

The potential of fenestration systems can be significantly heightened by integrating photovoltaic (PV) technology into windows. Modern technologies utilize semi-transparent thin-film solar cells on windows, a recently developed technique that enhances daylight and thermal performance while augmenting energy generation capacity [7]. A new type of photovoltaic shutter system, known as the louvred photovoltaic window, has been introduced. This system allows for adjusting inclination angle and spacing based on solar altitude angle and weather conditions in different months [37]. Building-integrated photovoltaics (BIPVs) can also be implemented on Windows, offering the advantage of electricity generation [6]. Another potential strategy for enhancing the power output of solar cells incorporated into building windows is the Building-Integrated Concentrating Photovoltaic (BICPV) window. An innovative concept, the BICPV smart window generates energy and regulates the entry of solar heat and visible light into buildings. It features an optically switchable thermotropic layer with integrated PV cells [38]. A novel Concentrating Photovoltaic/Thermal Glazing system (CoPVTG), developed at the University of Ulster’s Center for Sustainable Technologies in Belfast, UK, presents cutting-edge technology. This system consists of two glazed panels, one externally shaped to create lenses that focus solar energy onto photovoltaic cell lines. The unique characteristics of these lenses allow solar radiation to enter interior spaces during winter and be directed onto photovoltaic cells during summer, reducing solar gains while providing electricity to the building. The double-glazed panel structure of CoPVTG and CoPEG devices makes them versatile components for building glazing. The external glass panel is designed to create concentrating lenses that focus solar energy onto PV cell stripes built into the windows. Notably, the CoPVTG system facilitates heat recovery through air flowing through the air cavity, simultaneously cooling down the PV temperature and enhancing its electrical performance. Additionally, the thermal energy produced by PVs can be converted into electrical energy, with thermoelectric generators (TEGs) being one possible strategy [8].

2.3.2. Triboelectric Nanogenerator Glasses

Solar energy is commonly harnessed for electricity generation through renewable sources. Yet, an alternative approach involves tapping into mechanical energy generated by rain, mainly through utilizing triboelectric nanogenerators (TENGs). The research on TENGs, incredibly transparent ones that can be integrated into Windows, has gained significant traction. In the single-electrode mode, the friction between positively charged raindrops and the negatively charged TENG surface creates an electric current by establishing a potential difference between the system's two electrodes [39]. This technology can be coupled with a contact-mode TENG, assembled with elastic springs, to convert wind energy into electricity. This innovative approach results in a dual-mode TENG comprising a raindrop-TENG and a wind-powered-TENG, enhancing efficiency in terms of operating conditions and electrical output [40]. Two interfaces are considered: solid/solid or solid/liquid. Water (positive charge) directly contacts the SLIPS surface (negative charge) in the solid–liquid structure. On the other hand, the solid–solid system involves a triboelectric material (positive charge) obtaining the SLIPS (negative charge) when waterdrops interface with it. The liquid–solid TENG boasts a simple structure but tends to have a lower friction coefficient than the solid–solid system, which uses water as the friction material [41]. Z. Chen et al.'s work [42] demonstrates that incorporating a slippery lubricant-infused porous surface (SLIPS) into the system enhances its resilience, allowing the TENG to withstand humidity and extreme temperatures better, contributing to prolonged durability. Although the power generated by this system remains relatively low, Q. Zhou et al.'s study revealed that it can produce enough energy to light eight LEDs in series. Furthermore, after tapping on the translucent TENGs for 2.5 h, a 1000 μF capacitor was charged with a working voltage of 3 V—sufficient to power an electronic transducer for a single temperature/humidity test [43]. This transparent TENG could be a self-powered raindrop-detection sensor, automatically controlling window closure during inclement weather.

3. Discussion: SWOT Analysis Systems Coupling in the Building Envelope

To summarize the outcomes of this extensive literature review, we conducted a meticulous analysis employing SWOT analyses for each system under investigation. This strategic methodology offers an insightful view of the existing research landscape and enables a nuanced representation of both progress and obstacles. As a result, it yields valuable perspectives on the complexities essential for future studies, be they related to internal dynamics or external factors impacting the system. Table 1 shows that Multi-purpose BIPV, BAPV, or PVT systems integrated into the building offer several advantages over traditional PV systems. They generate dual energy output, exhibit higher efficiency, are flexible and efficient, and contribute to reducing fossil fuel consumption. These systems have a wide application range, are cost-effective, maintain architectural uniformity, and require less installation costs. They also require less space and help regulate indoor building temperature, utilizing excess heat. Multi-purpose photovoltaic-thermal systems offer a comprehensive solution that addresses energy production, cost-effectiveness, space efficiency, and environmental sustainability. However, these systems have the same weaknesses as conventional PV systems: the need for energy storage batteries during cloudy periods or to provide electricity in the evening. These additional components can increase the investment cost of the system as well as maintenance requirements. Indeed, the high installation costs, intermittent energy production due to weather conditions, and the necessity for energy storage to address intermittency and meet local energy demands can stop the development of these systems. Additionally, the impact of accumulated dust on reducing power output and system efficiency can be added to the difficulty of managing this system. The prospects for improving the system would involve finding solutions to electrical overproduction (via more eco-friendly storage techniques) and addressing losses due to site meteorology, orientation, and system positioning angles. Models for system deterioration or ageing should also be developed.

Table 1. SWOT analysis of the photovoltaic and thermic panels.

Strengths	Weaknesses	Opportunities	Threats
<p>Multi-purpose: both the electricity and heat energy can be obtained from the same system [44]</p> <p>PVT (see line 68) system has better efficiency than the PV system [9]</p> <p>Flexible and efficient [44]</p> <p>Can help reduce fossil fuel consumption [4]</p> <p>Has wide application area [44]</p> <p>Inexpensive and convenient [44]</p> <p>Keeps the architectural uniformity on roofs [45]</p> <p>Installation cost may be reduced for the need of only one system to be installed instead of two systems [45]</p> <p>Lower space utilization than the two systems alone [45]</p> <p>Reduce the temperature of the photovoltaic panels and take advantage of the excess heat [9]</p> <p>Abundance of raw materials [46]</p>	<p>The cost of installation can be relatively high [44]</p> <p>The absence of the sun at night and cloudy days [47]</p> <p>PVT systems intermittently produce energy depending on weather [4]</p> <p>Need for an energy storage system to address the issues of intermittency and meet local energy needs [5]</p> <p>Accumulated dust can reduce power output and therefore system efficiency [5]</p>	<p>Improving the optical properties of the working fluid can improve efficiency [9]</p> <p>The better the performance of the PVT system, the higher the transmittance of visible light and solar infrared rays absorbed [9]</p> <p>The thermal energy generated by the system can be converted to electrical energy by the Peltier effect [33]</p> <p>It can be integrated into a building and forms a part of the building (BIPVT) [48]</p> <p>PVT systems integrated into the building envelope avoid additional land use [6]</p> <p>Can be integrated with other energy sources for enhanced efficiency [4]</p> <p>Can be coupled with another electricity production system [33]</p> <p>Applying PV systems to the roof can markedly decrease the heat flux through the roof [7]</p>	<p>Planning of site and orientation [5]</p> <p>Exposure to the elements and risk of premature deterioration [46]</p> <p>The efficiency of the modules varies significantly depending on weather conditions, climate, and the presence of shading effects [7,46]</p> <p>Thermal losses within the photovoltaic panel [33]</p> <p>Overproduction of electricity [46]</p>

Algae (i.e., through photobioreactor facade panel systems and PBRs in Table 2) offer a promising energy source. Photobioreactors, unlike open ponds, require less space, consume less water, and are less weather-dependent. Additionally, they prevent culture evaporation, offer effective light distribution, and demonstrate climate change resistance. These factors, coupled with their ability to work at night and avoid contamination, make photobioreactors a more efficient and environmentally friendly option for energy production than traditional methods such as solar panels. The optimal conditions for algae cultivation include temperature range (16 to 27 °C), indirect middle-intensity light, necessary nutrients (salinity, CO₂, ammonia, phosphate), ideal pH (7–9), and the need for air circulation to harvest CO₂. Habibi et al. [49] shows that the initial investment required compared to an open pond is higher. Additionally, the scientific literature shows the necessity to control algae cultivation and highlights the lack of experience in building applications and the negative net present (observed) values from such photobioreactor facade panels after 15 years. Algae production presents multifaceted solutions with diverse applications outside of electricity production:

- It serves as a versatile tool for wastewater treatment, effectively cleansing water sources.
- Algae cultivation facilitates oxygen production and boasts an impressive CO₂ capture capacity, absorbing up to 85% of CO₂ content, thus aiding in carbon sequestration efforts.
- The yield of oil production from algae surpasses that of traditional sources such as soybeans by 60 times and palm by five times, promising a sustainable alternative to biofuel production.
- Algae production contributes to heat generation through innovative methods like biogas-to-electricity conversion in generators and recovering waste heat for steam supply, enhancing building energy efficiency. This algae cultivation also enables the production of food, ensuring a high-quality nutrient source compared to conventional

open pond methods. These numerous applications demonstrate that the process yields valuable by-products and offers the potential for light energy production, further diversifying its utility.

- Algae cultivation provides an unexpected benefit by offering thermal insulation, showcasing its potential as a comprehensive and sustainable solution across various domains.

However, it is imperative to adjust algae species to match specific climates and locations and to have stringent regulations in the construction domain. Indeed, it is essential to study the system's lifespan, maintenance, and cleaning requirements. We also note that the higher investment and production costs compared to open ponds render photobioreactors economically unviable. Factors like oxygen levels in water directly impact algae cultivation, whereas excessive light intensity can hinder photosynthesis. There are risks of poor or non-performance, and other renewable sources typically outperform algae in energy production. Certain algae species also pose human health risks.

Table 2. SWOT analysis of photobioreactor facade panels.

Strengths	Weaknesses	Opportunities	Threats
<p>Generate energy [10]</p> <p>Algae can grow in seawater, wastewater, or harsh water [10]</p> <p>Algae have a high rate of growth (higher than most other productive crops) [10]</p> <p>More microalgae species can be developed (compared to an open pond) [10]</p> <p>Can produce 5 to 10 times higher yields per aerial footprint (than open pond) [10]</p> <p>Biogas production [10,33]</p> <p>Significantly decrease the building's energy demands [33]</p> <p>Biomass production high-efficiency (compared to open ponds) [10,33]</p> <p>Preventing culture evaporation [33]</p> <p>Effective light distribution [33]</p> <p>Climate change resistance [33]</p> <p>Tubular PBRs do not need a specific orientation for good exposure to solar light [11]</p> <p>Lower environmental impact than solar panel [10]</p> <p>Need less area (compared to an open pond)</p> <p>Lower water consumption (compared to an open pond)</p> <p>Less weather dependent (compared to an open pond)</p> <p>Work also during the night</p> <p>Avoid bacterial and dirt contamination [50]</p> <p>PBR design permits more effective use of light (compared to open ponds) [50]</p>	<p>An ideal temperature range is required for algae to bloom (being 16 to 27 °C) [10]</p> <p>Required indirect, middle-intensity light levels [10]</p> <p>Nutrients required (salinity, CO₂, ammonia, phosphate) [10]</p> <p>Specific pH required (7–9 is ideal) [10]</p> <p>Air circulation needed (harvest CO₂) [10]</p> <p>Initially require a higher investment (compared to an open pond) [50]</p> <p>Require a high control of algae cultivation [50]</p> <p>Lack of experience in building applications [19]</p> <p>Negative net present values (NPVs) after 15 years [12]</p>	<p>Algae production can be used for wastewater treatment [51]</p> <p>Oxygen production [51]</p> <p>CO₂-capture capacity (absorbing as much as 85% of CO₂ content) [51]</p> <p>The yield of oil production far exceeds that of soybeans (by 60 times) or palm (by 5 times) [51]</p> <p>Heat production (biogas-to-electricity conversion in the generator) [12]</p> <p>Recovering waste heat as steam supply [12]</p> <p>Able to produce food grade biomass (compared to open ponds) [10]</p> <p>Able to produce by-products [33]</p> <p>Can produce light energy [33]</p> <p>Provide thermal insulation [33]</p>	<p>A necessity to adapt algae species according to climate and location [19]</p> <p>Specific and tight regulations for real-life building [19]</p> <p>Need to study the lifetime of the system [19]</p> <p>Need to study the maintenance and cleaning requirements [19]</p> <p>Higher investment and production costs (compared to an open pond) [19]</p> <p>Not economically viable for the moment [19]</p> <p>Oxygen in the water directly affects the cultivation [10]</p> <p>Excessive light intensity can inhibit the photosynthesis process [33]</p> <p>A lack of natural light during the night causes biomass losses (25%) [33]</p> <p>Risks of poor or non-performance [18]</p> <p>Other renewables produce more energy [18]</p> <p>Human health risks with some algae species [18]</p>

Table 3 shows the building-integrated wind turbine systems. The significant advantages of integrating vertical axis wind turbine (VAWT) wind walls within off-grid systems

encompass several vital points, including reducing wind farm needs, particularly in off-grid settings, resulting in decreased infrastructure requirements. This reduction minimizes the necessity for cables and associated infrastructure for electricity delivery and mitigates costs and logistical challenges. Moreover, VAWT wind walls contribute to a notable decrease in energy losses, especially within off-grid systems, thereby enhancing overall efficiency. The flexibility of these wind walls, facilitated by demountable wind-harvesting panels, ensures adaptability to diverse environments. Unlike horizontal axis wind turbines (HAWTs), VAWT wind walls can capture wind from any direction without necessitating orientation. Additionally, they effectively harness turbulences, further optimizing energy capture. VAWTs exhibit minimal noise production, even under low or high wind conditions, offering a quieter alternative for energy generation. The elimination of yaw mechanisms in VAWT wind walls simplifies their design and maintenance and contributes to their operational efficiency. Furthermore, compared to typical HAWTs, their lower wind startup speeds enable them to operate efficiently across varying wind conditions, solidifying their viability within off-grid systems. The inconveniences in building-integrated wind turbines are vibration and noise related to wind turbines, depending on the typology of the system. HAWTs require constant alignment with the wind direction for optimal performance. Conversely, VAWTs exhibit reduced efficiency compared to traditional HAWTs and are positioned closer to the ground where wind speeds are typically lower, thus unable to harness higher wind speeds aloft. Consequently, VAWTs experience intermittent energy production influenced by varying weather conditions. Small wind turbine systems can be integrated into various structures in the building. They contribute to aesthetic design, such as in double-skin facades. Vertical axis wind turbines (VAWTs) can be positioned closer to the ground and in areas where taller structures are prohibited. Additionally, wind walls serve multiple purposes, including minimizing glare, controlling radiation, providing insulation, collecting heat, sequestering carbon emissions, and enhancing the aesthetic appeal of the building. Particular avenues of research should be carried out to improve the integration of wind energy systems into the architecture of the building. Indeed, the public perceives wind turbines negatively due to visual pollution. In urban areas, turbulent and low-velocity wind conditions prevail, compounded by wind shadows caused by adjacent buildings and high urban terrain roughness. Turbines between buildings may cause discomfort for pedestrians due to high wind speeds near the ground. Additionally, buoyancy and heat effects on turbines should be considered. Early urban planning is essential in designing neighbouring buildings for turbines between them.

Hybrid solar-wind systems (see Table 4) do not rely on fossil fuels, making them more environmentally friendly and significantly reducing carbon dioxide emissions. Additionally, they require less space, have lower climate dependency, and offer better cost-effectiveness. Furthermore, they are more efficient and have a shorter payback than conventional systems. Moreover, the system includes a wind turbine that can operate during nighttime, further enhancing electricity generation and economic viability. However, hybrid technology necessitates a more significant initial investment than a singular system, such as solar panels, wind turbines, and energy storage. Combining a solar chimney with mirrors enhances the heat gain of the system. Incorporating a wind turbine and solar chimney into a PVT (photovoltaic thermal) panel system reduces the payback period and increases the potential for reducing CO₂ emissions. This configuration offers low operation and maintenance costs, generates minimal noise, and allows for integration with a storage system for both electricity and heat. Additionally, surplus power can be sold. These hybrid devices may not address all scenarios, especially in highly constrained building spaces, making installation impossible.

Table 3. SWOT analysis of the building-integrated wind turbines.

Strengths	Weaknesses	Opportunities	Threats
<p>Reduced wind farm needs (off-grid system) [10]</p> <p>Limiting cables connection and infrastructure for electricity delivery [10]</p> <p>Decrease energy losses (off-grid system) [10]</p> <p>Wind walls are flexible systems (wind-harvesting panels are demountable) [49]</p> <p>VAWT wind walls are able to capture incoming wind from any direction (unlike HAWTs) [22]</p> <p>VAWT wind walls do not need to be oriented [22]</p> <p>VAWT wind walls can take advantage of turbulences [22]</p> <p>The noise is almost zero for normal winds and even for low winds with VAWTs [22]</p> <p>For VAWTs, no yaw mechanisms are needed [22]</p> <p>VAWTs have lower wind startup speeds than typical HAWTs [22]</p>	<p>Vibration and noise problems [22]</p> <p>Classic HAWTs need to be always aligned to the wind direction [22]</p> <p>VAWTs have decreased efficiency (more than common HAWTs) [22]</p> <p>VAWTs have rotors located close to the ground where wind speeds are lower [22]</p> <p>VAWTs cannot take advantage of higher wind speeds above [22]</p> <p>Intermittent energy production depending on weather [22]</p>	<p>Small wind turbines may be coupled with street lighting systems (smart lighting) [22]</p> <p>Can be paired with a photovoltaic system Can contribute to aesthetic design for the buildings (in double skin facade for instance) [22]</p> <p>VAWTs can be located nearer to the ground [22]</p> <p>VAWTs may be built at locations where taller structures are prohibited [22]</p> <p>Wind walls systems minimize glare and circulate air [49]</p> <p>Wind walls control radiation [49]</p> <p>Wind walls provide insulation [49]</p> <p>Wind walls collect heat [49]</p> <p>Wind walls generate energy [49]</p> <p>Wind walls sequester emissions [49]</p> <p>Wind walls provide aesthetics [49]</p> <p>Wind walls increase property value [49]</p>	<p>Wind turbines have a negative response from the public [52]</p> <p>Visual pollution [52]</p> <p>Turbulent and low-velocity wind conditions in urban areas [52]</p> <p>Adjacent buildings can cause wind shadow [53]</p> <p>Urban terrain roughness is high [53]</p> <p>If close to the ground, turbines between two buildings may cause discomfort for pedestrians (high wind speed) [23]</p> <p>Heat effects may affect the turbine (buoyancy needs to be considered) [23]</p> <p>Turbines between two buildings need early urban planning in the design of neighbouring buildings [23]</p>

Table 4. SWOT analysis of the hybrid solar-wind systems.

Strengths	Weaknesses	Opportunities	Threats
<p>Produce electricity [25–27]</p> <p>Do not require any fossil fuels [25]</p> <p>Have greater potential to reduce carbon dioxide emissions than the two systems alone [25–27]</p> <p>Lower climate condition dependence than the two systems alone [27]</p> <p>Need less area than two separated systems</p> <p>Better LCOE (levelized cost of electricity) [27]</p> <p>More environmentally friendly than the two systems alone [25,26]</p> <p>Better in terms of payback time than the two systems alone [27]</p> <p>More efficient than the two separated systems [27]</p> <p>The wind turbine can also rotate during the nighttime and improve the economics of the system by more electricity generation [25]</p>	<p>Require a larger initial investment than a unique system (solar panels, wind turbines, and energy storage) [27]</p> <p>Climate condition dependence [27]</p> <p>Intermittent production [27]</p> <p>Need more area than a unique solar or wind system [27]</p>	<p>Coupled with a solar chimney, using mirrors can increase the heat gain of the system [25]</p> <p>Adding a wind turbine and a solar chimney to a PVT panel system reduces payback period [25]</p> <p>Adding a wind turbine and a solar chimney to a PVT panel system increases the potential to reduce CO₂ emissions [25]</p> <p>Low operation and maintenance cost [25]</p> <p>Produce low noise [25]</p> <p>Can be equipped with a storage system for electricity and heat [25]</p> <p>Excess power can be sold [26]</p>	<p>May not be sufficient to cover all needs [26]</p> <p>May not fit into areas with limited space [27]</p>

Technological features for high-efficiency, clean energy production through solar paint (see Table 5) are promising. Indeed, the adaptability of solar paint to various surfaces, the aesthetic integration into building envelopes, ease of application using a simple brush, low-cost, adjustable electrochemical performance, and environmental friendliness with no emission of ozone-depleting substances are all advantages of this exceptional paint. More advanced studies should be carried out at the current stage because the technology described needs to exhibit more efficiency, raising doubts about its sustainability. The solar paint technology still has room for improvement regarding its efficiency. Indeed, with a significant moisture adsorption capacity, it efficiently binds water molecules, facilitating its functioning. Moreover, its semiconductor nature ensures excellent conductivity, which is essential for its operation. Its ability to absorb light enhances its performance, whereas its high catalytic activity further contributes to its effectiveness. Additionally, its integration with standard inverter technology, akin to traditional solar cells, enables seamless connection to the electricity grid network, ensuring its compatibility and scalability within existing infrastructure. Future research perspectives would be oriented on the recent solar cell technology, requiring further investigation to determine its viability, especially in light of competition from more efficient and reliable traditional solar cells.

Table 5. SWOT analysis of solar paint.

Strengths	Weaknesses	Opportunities	Threats
High conversion efficiency [54] Produces clean energy [31] Gas phase water splitting is predicted to require less energy [31] Efficient light absorption with minimal light scattering [30] Adaptable to many surfaces [30,55] Provides aesthetic integration into the building envelope [30,55] Easy and quick application with a simple brush [56] Low-cost technology [55] Delivers an adjustable electrochemical performance [57] Environmentally friendly and emits no ozone-depleting substances after use [55]	Very low efficiency [58] Doubt regarding the sustainability of this technology [55]	A large moisture adsorption capacity for binding water molecules [30] It should be a semiconductor with good conductivity [30] Providing light adsorption capabilities [30] Features high catalytic activity [30] Utilizes the standard inverter technology employed by traditional solar cells for connecting to the electricity grid network [55]	Competition with more efficient and reliable traditional solar cells [58] Very recent technology that necessitates additional studies to ascertain its viability [58]

Table 6 underscores the remarkable capabilities of the microbial biophotovoltaic technology system under examination, showcasing its extraordinary growth potential even under limited light conditions for prolonged periods. Moreover, it significantly enhances water-use efficiency with a modest culture volume. By employing a gel as a substitute for the conventional liquid reservoir in bio-photovoltaic (BPV) devices, the system achieves notable improvements in power output compared to its counterparts. Notably, this system demonstrates remarkable endurance, sustaining electrical production for well over 100 h, starkly contrasting with the one-hour operation typically in paper-based microbial fuel cells (MFCs). Its versatility extends to delivering short power while remaining disposable and environmentally friendly, marking a significant advancement in sustainable power solutions. However, there are several critical factors affecting the performance of microbial fuel cells (MFCs):

- The notable limitation in electricity production suggests a need for further optimization.
- The printing process risks damage to cyanobacteria cells, potentially compromising their effectiveness within the MFCs.
- This study observes a decrease in power output in low-light conditions compared to well-lit environments, highlighting the dependency of MFCs on light availability.
- The Therinted Carbon Nanotube (CNT) cathode is identified as a significant bottleneck in MFC performance, indicating the necessity for alternative cathode materials or fabrication methods to enhance overall efficiency.

We underscore the complexity of MFC technology and the importance of addressing various challenges to realize its full potential in sustainable energy production. The feasibility of utilizing a low-cost commercial inkjet printer without significantly impacting the cell viability of the system has been highlighted in the scientific literature. The advantages of paper as an inexpensive and biodegradable material and the potential for miniaturizing cyanobacteria culture are also interesting avenues for improving the process. Additionally, employing high-performance carbon black (CB) could enhance power output, whereas desert CB usage might reduce material and energy expenses for scaling up. This research also proposes the development of bioenergy wallpaper and demonstrates that incorporating a hydrogel between the anode and cathode could improve power output by exposing the cathode to more air. This solar energy is an intermittent source due to its dependence on external factors such as location, weather, time of day, and seasons, resulting in inevitable drops in energy production during low light conditions. The optimization of the cell design is essential for better efficiency of the system.

Table 6. SWOT analysis of microbial biophotovoltaic technology.

Strengths	Weaknesses	Opportunities	Threats
<p>Very great capacity for growth [36]</p> <p>Works in the dark (for several hours even if the range is lower) [36]</p> <p>Improves water-use efficiency (considering the minor volume of starting culture) [36]</p> <p>Uses a gel (which replaces the liquid reservoir normally used in conventional BPV devices [36])</p> <p>Great power output compared with conventional liquid culture-based BPV devices [36]</p> <p>Electrical output can be sustained for more than 100 h (paper-based MFCs can only operate for 1 h) [36]</p> <p>Can provide a short burst of power [36]</p> <p>Disposable and environmentally friendly power [36]</p>	<p>Low electricity production [36]</p> <p>Damage possibility of cyanobacteria cells during printing [36]</p> <p>Power output is less in the dark than in the light [36]</p> <p>Printed CNT cathode is a limiting factor in microbial fuel cell performance [36]</p>	<p>Feasibility of using an inexpensive commercial inkjet printer without (really) affecting cell viability [36]</p> <p>Paper is an inexpensive widespread material and biodegradable [36]</p> <p>The potential of miniaturization for cyanobacteria culture [36]</p> <p>Use of high-performance CB could increase the power output [36]</p> <p>Use of desert CB might reduce the material and energy costs of scale-up [36]</p> <p>Could be developed for bioenergy wallpaper [36]</p> <p>Hydrogel between anode and cathode would improve the power output (by exposing the cathode to more air) [36]</p>	<p>Solar energy is an intermittent energy source (inevitably drops in low light) [36]</p> <p>Production depends greatly on external conditions (location, weather, time of the day, and seasons of the year) [36]</p> <p>Optimizing cell design [36]</p>

Integrating photovoltaic glazing and shading devices (PV devices) presents a multi-faceted solution towards achieving sustainable energy practices and enhancing building efficiency (see Table 7). By harnessing clean electric energy, these innovative technologies contribute significantly to active energy conservation for windows, reducing lighting loads

and overall electricity consumption. Moreover, their implementation as part of a sustainable electricity production system fosters environmental responsibility and facilitates long-term energy savings. The CoPVTG (Combined Photovoltaic and Thermal Glazing) device emerges as a standout solution, consistently delivering high energy yields while ensuring a uniform distribution of daylight. Its ability to regulate solar contribution and its economic feasibility render it a compelling option for architectural integration. Notably, CoPVTG devices not only meet the functional requirements of natural lighting but also uphold the aesthetic integrity of buildings, thereby striking a harmonious balance between sustainability and design. Furthermore, compared to alternative technologies like CoPEG (Combined Photovoltaic and Electrochromic Glazing), CoPVTG systems demonstrate superior energy performance, augmented by exploitable hot air. Adopting PV glazing and shading devices represents a pivotal step towards achieving energy efficiency and architectural excellence in contemporary construction practices. However, some negative points should be highlighted. Indeed, the climate and location of the site dramatically influence the effectiveness of photovoltaic windows. Electricity generation from BIPV systems is intermittent due to varying weather conditions. Additionally, the orientation of buildings impacts the performance of these systems. The benefits of building-integrated photovoltaic (BIPV) windows are the ability to provide adequate ventilation, reduce building cooling or heating loads, and serve as both facade windows and exterior elements. BIPV windows are noted for their insulation capabilities, with studies showing superior energy-saving performance compared to conventional insulating glass windows. Additionally, PV insulating glass units are highlighted for their more significant energy-saving potential than PV double-skin facades. The potential of Low-E coatings to minimize heat transfer through radiation is also a positive point of view for improving the system. Coloured modules can result in notable efficiency reductions, varying based on the materials and colours employed. Additionally, the duration required to recoup energy investments and the associated uncertainty regarding greenhouse gas emissions are not clarified in the scientific literature. This uncertainty underscores the challenge of competing with traditional roof PV systems.

Table 8 discusses converting ambient mechanical energy from wind impact and water droplets into electricity. This process can be utilized for a self-powered intelligent window system. The technology involved, known as TENGs (triboelectric nanogenerators), maintains transparency, ensuring that they do not obstruct or reduce the window's surface area. Their system has a high transmittance rate of over 60% and exhibits low water contact angle hysteresis when treated with SLIPs (Slippery Liquid-Infused Porous Surfaces). Additionally, the efficiency of energy conversion is enhanced with the addition of SLIPs, which also provide benefits such as anti-fouling, anti-icing, and drag reduction. This approach aligns with sustainability and renewable energy principles, offering advantages such as affordability, lightweight construction, and the ability to harness both wind and rain. Furthermore, introducing solid–solid/liquid–solid convertible TENGs expands the range of conditions under which energy can be generated. However, Table 8 shows the high limitations of the discussed system, emphasizing its meagre power output compared to conventional systems like photovoltaic (PV) panels and wind turbines. It also underlines the system's dependence on climate conditions, noting that variations in temperature and humidity can significantly impact its performance. In addition, the system can serve as a rain sensor or sensor for a self-powered window-closing system. For example, the component can be integrated with other electricity generation systems like photovoltaic windows. The challenges for improving the systems are increasing the durability and limiting the triboelectric nanogenerators' power. It is also important to make the system more competitive (efficient and reliable) than the existing integrated systems in the building envelope.

Table 9 shows the potential of PVTENG hybrid systems in energy production, particularly on sunny and rainy days. These systems offer advantages such as complementing individual PV and TENG components, good transparency (23.49% visible light transmittance), high colour rendering (CRI of 92), and effective window insulation. They convert

ambient mechanical energy, particularly from water droplets, into electricity. Additionally, integrating SLIPs (Slippery Liquid-Infused Porous Surfaces) leads to benefits such as low water contact angle hysteresis, increased energy conversion efficiency, and properties like anti-fouling, anti-icing, and drag reduction. Overall, these systems offer sustainable, renewable energy solutions at low cost and with lightweight construction. The difficulty observed in the hybrid system is the meagre power output and specific transmittance (i.e., the transmittance phenomenon can only be performed in a particular wavelength range). The difficulty observed in the hybrid system is the meagre power output and the specific transmittance effect of the material used in the system (i.e., the transmittance phenomenon can only be performed in a particular wavelength range). One of the main problems encountered in this hybrid system is the shading effects that impede heat transfer and lead to a decrease in air temperature, particularly in greenhouse applications where there is a high plant growth factor. Further research should be carried out to solve this shading problem. Climatic conditions, including temperature, humidity, and atmospheric pressure, can significantly impact the performance of electrical systems. These factors can influence the durability of components, potentially leading to lower overall reliability and efficiency. Additionally, in situations where short circuits occur, there may be limitations on the amount of output current that can be safely handled, which can further compromise the operational capabilities of the system. Therefore, understanding and mitigating these dependencies are crucial in ensuring the resilience and functionality of electrical infrastructure under various environmental conditions.

Table 7. SWOT analysis of photovoltaic glasses.

Strengths	Weaknesses	Opportunities	Threats
Obtain clean electric energy [37] Realize active energy saving of windows [59] The implementation of PV glazing and shading devices has the potential to decrease lighting loads and electricity consumption [7] Sustainable electricity production system [7] Integrated glazing reduces the environmental and economic impact of buildings [6] The CoPVTG device always provides the highest energy yield [60] Provide a uniform daylight distribution [7] Provide solar contribution control [7] Economically feasible [7] It can meet the needs of natural lighting while satisfying architectural aesthetics [37] CoPVTG devices provide higher energy yield than CoPEG [60] CoPVTG systems provide exploitable hot air [60]	The performance of BIPV depends highly on the climate and location site [7] Intermittent electricity production depending on weather conditions [7] Building orientation affects performances of the system [7]	Provide adequate ventilation (BIPV windows) [5] Reduce building cooling load or heat load [7,59] Can be installed as a facade window and balustrade or sloped as an exterior element [6] Capable of insulating the building [60] PV windows demonstrated superior energy-saving performance compared to conventional insulating glass windows [61] PV insulating glass units have greater energy-saving potential than PV double skin facades [61] Low-E coatings have the potential to minimize heat transfer through radiation [7]	Coloured modules can lead to significant efficiency losses depending on the materials and colours used [6] The timeframe for recovering energy investment and the associated uncertainty in greenhouse gas emissions remains unclear [6] Competition with traditional roof PV systems

Table 8. SWOT analysis of triboelectric nanogenerators.

Strengths	Weaknesses	Opportunities	Threats
Convert ambient mechanical energy (from wind impact and water droplets) into electricity [39] Can be used for a self-powered smart window system [39] TENGs are transparent (do not cover or sacrifice surface area window) [39] High transmittance of over 60% [39] Low water contact angle hysteresis with SLIPS addition [41] More efficient energy conversion with SLIPS addition [41,42] Anti-fouling, anti-icing, and drag reduction with SLIPS addition [41,42] Sustainable and renewable energy [62] Low cost [62] Lightweight [62] Take advantage of both wind and rain [39] Solid–solid/liquid–solid convertible TENG increases the conditions under which energy can be produced [40]	Very low power output compared to conventional systems such as PV panels and wind turbines [41] Climate conditions dependence [39] Temperature and humidity may affect the performances of this system [39]	Act as a rain-sensor to prevent rainwater from entering the house [41] Integrating an electrochromic device (ECD) (change colour or opacity) [39] Can be paired with other electricity-production system such as PV glasses [63] Can be used as a sensor for self-powered window-closing system [41]	Lower durability [64] Limited short circuit output current [64] Competition with more efficient and reliable systems

Table 10 provides a quantitative comparison of various systems that have been the subject of scientific articles. The comparison is conducted based on three essential criteria:

- The electrical energy production generated by the system;
- The financial cost;
- The CO₂ emission or absorption rate by the device.

It emerges that BIPV or BAPV systems are the least expensive ones (approximately 0.15 euros per kWh). This can be explained by the fact that the technology of these systems has evolved significantly in recent years, contributing to this cost reduction. Regarding PBR systems, it is noted that they are the least polluting. The explanation is that the algae used in the device need to absorb a maximum amount of CO₂ (200 m² of algae absorb approximately 8.5 tons of CO₂ per year) to produce this electrical energy. As for energy production, the wind turbine integrated into the building is the most profitable system (it produces approximately 0.41 kW per m² of habitable area).

Table 9. SWOT analysis of the photovoltaic and triboelectric nanogenerator hybrid system.

Strengths	Weaknesses	Opportunities	Threats
Energy production on sunny days and rainy days [63] PVTENG hybrid systems represent a great potential to complement vulnerable aspects of individual PV and TENG components [63] Good transparency (visible light transmittance (VLT) of 23.49%), colour rendering (CRI of 92), and window insulation [63] Convert ambient mechanical energy (from water droplets) into electricity [39] Low water contact angle hysteresis with SLIPS addition [41] More efficient energy conversion with SLIPS addition [41] Anti-fouling, anti-icing, and drag reduction with SLIPS addition [41] Sustainable and renewable energy [62] Low cost [62] Lightweight [62]	Very low power output [41] Specific transmittance (blue layer) [63]	Shading effects [63] Hampers heat transfer [63] Decreases air temperature [63] Greenhouse applications (high plant growth factor of 25.3%) [63]	Climatic conditions dependence [64] Lower durability [64] Limited short circuit output current [64]

Table 10. Quantitative comparison systems. Complementary information: positive CO₂ is when the system rejects carbon and negative CO₂ is when the system absorbs carbon in the atmosphere.

Systems	Production (in kW · m ⁻²)	Cost (in \$)	CO ₂ (in KgCO ₂ /Year)	References
Photovoltaic (BIPV or BAPV) or Photovoltaic glass	0.16–0.19	0.16 (by kWh)	At + 27 until + 139	[65,66]
PBRs (bioreactor) or Microbial biophotovoltaic technology	0.06–50	1000–1500 (by m ²)	–42.5	[49,67]
Building-integrated wind turbines	0.41	767.3 (by unit)	At + 7.5.10 ⁸ until + 22.10 ⁸	[68,69]
Solar paint wall	0.02–0.5	-	-	[58,70]
Triboelectric nanogenerators glasses	0.0018–0.05	-	-	[71]

4. Conclusions

The building envelope element ensures structural stability, resilience, and protection from external elements. Despite its primary functions, an opportunity exists to enhance the building's energy balance without additional surfaces. Often overlooked, the roof presents untapped potential, offering ample space and optimal exposure to harness various energy sources such as solar, rain, and wind. This makes it ideal for incorporating energy recovery devices like PVT panels, wind turbines, and PBRs for algae cultivation. In specific contexts, hybrid systems prove advantageous, generating more energy, optimizing space, and mitigating the limitations of standalone systems. Beyond energy production, specific systems offer additional functionalities; for example, algae-based systems exhibit prowess in wastewater treatment and carbon dioxide capture. Conversely, facades and windows are susceptible to climatic factors, necessitating modulating and regulating systems. Technologies like PBR facade panels and wind walls generate electricity and provide thermal

and acoustic insulation, shading effects, and ventilation, contributing to reduced energy consumption. However, many of these systems require refinement and further development to validate their viability and effectiveness. Some technologies discussed in this study generate limited electrical currents, pose implementation challenges, or exist only in theoretical or simulated forms. In summary, integrating electricity production systems into the building envelope taps into the potential of existing surfaces and aligns with the imperative of meeting growing energy needs sustainably. The combination of building envelopes and energy production holds promise for creating more resilient, efficient, and environmentally conscious structures. This bibliographic study demonstrates that the evolution of electricity-producing systems integrated into the building envelope and the risks involved, if we move towards these increasingly innovative technologies, have not really been addressed in the scientific literature. Further studies should be conducted to define the economic, technical, environmental, and social implications of these electricity production systems integrated into the building envelope.

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Abbreviations

The following abbreviations are used in this manuscript:

AD	Anaerobic digestion
ADEME	French Environment and Energy Management Agency
BAPV	Building-attached photovoltaic
BIPV	Building-integrated photovoltaic
BIQ	Bio-intelligent quotient
BPV	Biophotovoltaic
CFD	Computational fluid dynamics
CoPEG	Concentrating Photovoltaic Evacuated Glazing
CoPVTG	Concentrating Photovoltaic Thermal Glazing
DSF	Double skin facade
HAWT	Horizontal axis wind turbine
MFC	Microbial fuel cell
PBR	Photobioreactor
PEMEC	Polymer electrolyte membrane electrolyzer
PEMFC	Polymer electrolyte membrane fuel cell
PV	Photovoltaic
PVT	Photovoltaic thermal collector
SLIPS	Slippery lubricant-infused porous surface
ST-PSC	Semitransparent polymer solar cell
STPV	Photovoltaic Semi-Transparent
STS	Solar thermal system
TE	Thermoelectric
TEG	Thermoelectric generator
TENG	Triboelectric nanogenerator
UNEP	United Nations Environment Programme
VAWT	Vertical axis wind turbine

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