

## Thermal Comfort of Buildings Integrated Photovoltaics (BIPV)

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### ABSTRACT

In today's modern world, the extensive use of glass façades in commercial buildings has an impact on the overall thermal comfort and energy consumption of these buildings, especially in regions where there is an energy shortage like Palestinian territories. The author is of the opinion that the use of BIPV systems will not only bring about the thermal comfort but also contribute to the overall energy efficiency of the commercial buildings. The work further cites the integration of photovoltaic cells in building skins and the related factors like heat transfer, thermal conductivity, and indoor thermal conditions are considered. The research signals the capabilities of double-skin and solar-integrated façades in cutting down the solar heat gain, cooling and heating load demands, and simultaneously providing on-site renewable energy. The emphasis is on Palestine, where the high solarradiation levels are in stark contrast to the political, economic, and infrastructural challenges in the energy sector. The paper integrates recent research on thermal comfort solutions, façade technologies, and photovoltaic integration, and shows that BIPV façades are a good option for energy consumption mediations and indoor environmental quality enhancement in commercial buildings. The results also clearly show that the installation of solar systems in the building envelop can be a great help in sustainable building design, energy security, and increased tenant comfort which in turn would support the transition to low and zero-energy buildings in Palestine and other similar climates.

## الراحة الحرارية للمباني التي تعمل بتقنية الخلايا الكهروضوئية المدمجة

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الكلمات المفتاحية	الملخص
الواجهات مزدوجة الواجه الخلايا الكهروضوئية شبه الشفافة الراحة الحرارية المباني الزجاجية الخلايا الكهروضوئية المدمجة في المباني	في ظل الانتشار المتزايد للواجهات الزجاجية في المباني التجارية المعاصرة، برزت تحديات جوهرية تتعلق بتحقيق الراحة الحرارية وارتفاع معدلات استهلاك الطاقة. وتتفاقم هذه الإشكالية في المناطق التي تعاني من أزمات طاقة مزمنة، كما هو الحال في فلسطين. ومن هذا المنطلق، يقترح هذا البحث حلاً مبتكراً يتمثل في دمج أنظمة الخلايا الكهروضوئية ضمن أغلفة المباني (BUILDING INTEGRATED PHOTOVOLTAICS – BIPV)، بما يسهم في تعزيز الراحة الحرارية وتحسين كفاءة الطاقة على مستوى المبنى ككل. يركز البحث على دراسة التكامل الفيزيائي للخلايا الكهروضوئية مع عناصر غلاف المبنى، من خلال تحليل العوامل المؤثرة في الأداء الحراري، مثل انتقال الحرارة، والتوصيل الحراري، والظروف البيئية الداخلية. وتُظهر النتائج أن أنظمة الواجهات المزدوجة المدمجة بالخلايا الشمسية تمتلك إمكانات كبيرة في الحد من اكتساب الحرارة الشمسية، الأمر الذي يؤدي إلى تقليل أحمال التبريد والتدفئة، إلى جانب إنتاج طاقة نظيفة في موقع المبنى ذاته. ويتناول البحث فلسطين كدراسة حالة، حيث تتقاطع وفرة الإشعاع الشمسي مع تحديات سياسية واقتصادية وبنوية تؤثر بشكل مباشر في قطاع الطاقة. وتعتمد الدراسة على مراجعة وتحليل أحدث الأبحاث في مجالات الراحة الحرارية، وتقنيات الواجهات المعمارية، وتكامل الأنظمة الكهروضوئية، مؤكدة أن واجهات BIPV تمثل خياراً فعالاً لتحقيق ترشيد استهلاك الطاقة وتحسين جودة البيئات الداخلية. وتخلص الدراسة إلى أن دمج الأنظمة الشمسية ضمن غلاف المبنى يسهم بشكل ملموس في تحقيق أهداف الاستدامة وتعزيز أمن الطاقة، فضلاً عن رفع مستوى راحة المستخدمين. كما يدعم هذا التوجه التحول نحو مباني منخفضة أو شبه معدومة استهلاك الطاقة، ليس في فلسطين فحسب، بل في جميع المناطق التي تتشابه في ظروفها المناخية.

### Introduction

Sunlight, wind, rain, tides, and geothermal heat are the main sources of renewable energy, which are always naturally renewed during the human timescale [1]. Such resources are considered to be infinite and environmentally friendly and, thus, a long-term substitute for fossil fuels [2]. The main

sources of energy due to which the renewal, mainly solar, wind, hydropower, and geothermal continue to be used for various purposes such as transportation, heating, and electricity generation in remote areas [3]. Besides these, the battle against climate change, along with sustainable development, is another major driving force among the

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numerous benefits the adoption of renewable energy brings, such as lower greenhouse gas emissions. To achieve the Sustainable Development Goals (SDGs), which are set up by the international climate agreements, such as the Paris Agreement that aims to limit global heating to 2°C, renewable energy deployment is paramount [4]. The mentioned technologies are of utmost significance in remote and agricultural areas as they may bring the energy needed to these regions and the necessary energy services as well [3]. On the economic side, renewable energy has its benefits and drawbacks. The huge investment on installation in the beginning may be one of the disadvantages but the operating costs are often very small compared to those of traditional power sources. Government support in the form of grants and tax credits greatly contributes to the economic feasibility of such projects [4]. Along with the developments in the field of technology, the reliability and efficiency of renewable energy systems have also been improved thus making them more competitive in the energy market [5]. In conclusion, renewable energy sources are the most significant elements of the global strategy to achieve energy sustainability, reduce carbon emissions, and enhance the environment and economies' resilience. To combat the urgent climate crisis and to guarantee energy security, these technologies will have to be further developed and integrated.

Various research investigations pointed to the listing of the major types of renewable energy sources, such as biomass, geothermal, hydropower, solar, and wind energy [6]. These organic processes that produce energy are necessary for the transition from fossil fuels to renewable energy sources. Of all the renewable energy sources, one of the most widely used is solar energy, which is the energy obtained from the sun. It is often mentioned as the primary renewable energy source, and its capabilities in significantly reducing carbon emissions have also gained its wide recognition [7].

Wind power is, indeed, a mighty renewable energy source which can be exploited through the wind turbines. Many studies have indicated it as a very good option because of its effectiveness and very small environmental impact during the whole operation [8]. The energy derived from the movement of water is referred to as hydropower or hydroelectric energy. This renewable energy source accounts for a substantial percentage of the total energy resources in the world and, thus, it is one of the largest contributors to the renewable energy supply globally [9]. Geothermal energy, another prominent renewable source, is derived from the Earth's internal heat. The limited geographical coverage of this technology is a disadvantage, yet its low emissions and high reliability still make it a very valuable option in the market [10]. The process of converting organic matter into power is referred to as biomass energy, which is an additional major renewable energy source. Its contributions to the energy supply and diversity are by means of biofuels and biogas, among others [11].

Wave and tidal energy, which are capable of harnessing the power of ocean movements, are among the alternative renewable energy sources that some studies, though infrequently, still point out [10]. However, in the end, these renewable energy sources remain indispensable for the reduction of fossil fuel dependence and the environmental

impact. Each source has its advantages and challenges that determine the pace of its use and integration into the global energy systems. Transitioning to these renewable sources is essential for attaining the objectives set in terms of energy security and the environment [6].

Numerous scientific studies have indicated that solar energy provides different pros and cons. One of the key reasons for the support of solar energy is its big potential in contributing to the sustainable agricultural development goals [12]. In alleviating the reliance on fossil fuels, increasing the greenhouse gas emissions, and being a part of the climate change solution, solar energy might, by helping the positive development of clean energy, sustainable economic growth, and global warming mitigation, actually become less of a menace for fossil fuels. Thus, solar energy is a very reliable alternative for fossil fuels as it is versatile, cost-effective in the long run, and friendly to the environment [13]. Solar power systems are going through a metamorphosis in terms of efficiency and performance due to the never-ending innovations in technology; we can have around 34.1% efficiency with the multi-junction photovoltaic (PV) cells [14]. Besides, solar energy is not only the solution for electricity generation but also it can be utilized for irrigation, water purification, and the domestic sphere such as cooking and space heating. Moreover, the versatility of solar power and its potential for the future are further demonstrated by the fact that it can be used to fuel vehicles and even transfer power from outer space to the planet through satellite power plants [14]. Nonetheless, there are a number of challenges that make solar energy adoption not that easy. The first and foremost barrier is the initial cost which is very high, and the second is the need for power storage systems that are very efficient [13]. The efficiency of solar energy applications, which has been improved recently, still ranges from 18% to 30% and this is below the level of other renewable energy sources [15]. Moreover, there is a problem of intermittent supply from solar power plants which is subject to the sun shining and also the lack of raw materials for making photovoltaic (PV) cells. The changeover from fossil fuels to solar power has also been impeded by the infrastructure that is already in place and geared for conventional power sources, thus making it hard for manufacturers to participate in the transition [13].

Regardless of these challenges, renewable energy sources, mainly solar energy, have numerous advantages that make THEM growth and incorporation into the global energy systems more or less certain thus, public acceptability, cost-efficiency, and political trustworthiness [16]. Finally, the environmental and economic potential of solar energy are great but its Turmoil through Technology and Law have to be resolved first before it could open up a wider market and meet global energy needs [17].

Figure 1 illustrates the methodological framework of the review study. The review begins with stating its focus on traditional insulation materials such as EPS, XPS, etc., and Phase Change Materials (PCMs) used in Mediterranean climates. After that, the study indicates the key criteria for evaluation consisting of thermal characteristics (conductivity, heat capacity), the best thickness (through LCA, simulation methods), the most suitable position (outside, inside, core),

and the effects on energy consumption & thermal comfort. The methodology comprises two parallel ways one for the traditional materials and the other one for the PCMs, with both being assessed through the same criteria. Then, the comparative analysis and results from both sources are taken

up to decide on the material suitability, thickness, placement, and possible energy-saving. To sum up, the study offers practical advice for builders and regulators, and it also puts forward the topics for further research (e.g., dynamic PCM systems, numerical validation).

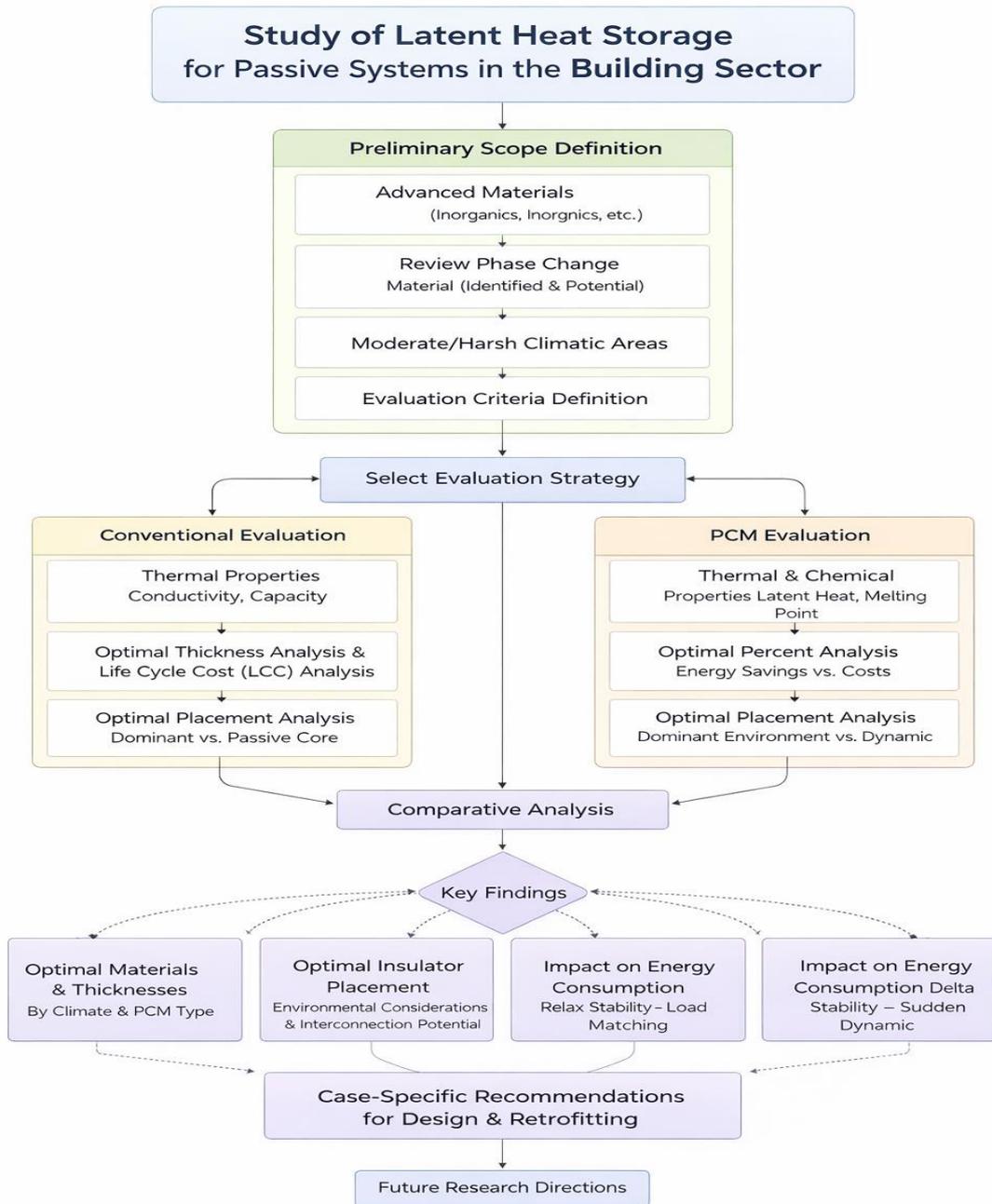


Figure 1: The methodological approach of the review study

### Energy Crisis in Palestine

Palestine's energy crisis is the outcome of a difficult i.e. the geopolitical, economical, and infrastructural factors. Palestine, in addition, is characterized by high population and thus heavy reliance on foreign energy sources due to the lack of natural resources, political instability, and financial difficulties. The country gets 87% of its electricity and all its fossil fuels, mainly from Israel [18]. The reliance on electricity imports and natural gas is made worse by the increasing demands from the industries in addition to the rapid growth of the population which results in a huge energy

deficit. Though Palestine has the lowest per capita energy consumption in the region, it still has to pay the highest energy costs among the Middle Eastern countries [19]. The present situation strongly emphasizes the pressing requirement of alternative energy solutions. The shift to renewable energy sources, especially solar energy, appears to be the most promising way ahead. With solar radiation levels of 5.4 to 8.27 kWh/m<sup>2</sup>/day and about 3,000 hours of sunshine per year, Palestine is in a good position to use solar energy for power generation so as to not be totally dependent on imported energy [20]. Nevertheless, the political and

infrastructural challenges continue to make the crisis worse [21]. Although solar energy technology is not affected by Moreover, the process of switching to solar energy is lagging due to insufficient regulations and public awareness. Among the various technologies available, anaerobic digestion and incineration can extract energy from municipal solid waste, although they come with certain logistical and environmental challenges [22]. Additionally, the electrification of rural areas is considerably affected by political and financial obstacles, thus, making it hard to link these areas with the main power grid. This situation brings to light the necessity for off-grid energy solutions, for instance, the deployment of micro-grid solar energy systems for the provision of electricity to such disadvantaged regions [23]. The combination of renewable energy sources like solar and wind could bring about a major reduction in energy crisis by lowering the reliance on imported energy and helping to achieve sustainable development [19]. In summary, dealing with Palestine's energy crisis means dealing with the problems that lie behind it: political instability, economic limitations, foreign dependence, and the non-use of renewable resources. To conquer these difficulties, immense legislative reforms, the investment in renewable energy infrastructure, and more public education on sustainable practices are the necessary things to do.

### **Solar Energy**

Solar cells, also known as photovoltaic cells, are crucial semiconductor devices that directly change light into electric power and thus are an integral part of solar energy technology [24]. The very first step of this process occurs when semiconductor materials absorb sunlight, thus commencing a photovoltaic reaction. The reaction promotes electrons to move to a higher energy level making it possible for them to go through an external circuit, producing electricity and at the same time coming back to the semiconductor [25].

Crystalline silicon is the most common semiconductor material used in solar cells and it comes in both single-crystalline and polycrystalline forms [26]. Additionally, the other semiconductor materials comprise inorganic compounds such as gallium arsenide, cadmium sulfide, and copper indium selenium, as well as organic and nanocrystalline materials like perovskite [27].

Typically, the solar cell structure contains a p-n junction that is very important for the generation of current in an unbiased state [28]. The efficiency of solar cells is determined in part by the materials used, the cell structure, and the light absorption and electron movement management. The introduction of advanced technologies, such as multi-junction cells that consist of several semiconductor layers, has allowed capturing a wider spectrum of sunlight, and thus higher efficiency [28].

Not only has the solar cell technology undergone significant changes, but it also has turned from expensive energy generation source into a low-cost one and thus making solar energy a viable option for the both off-grid and mainstream applications [29]. Among the most significant innovations that have contributed to this, are the application of nanostructures and advanced materials which are still being developed and the efficiency of solar cells has therefore been

political boundaries, the growth and production of energy projects still fall prey to geopolitical restrictions [20]. pushed to more and more applications [30]. Solar cells are the heart of solar energy systems of which the miniature electric generating panels, made up of enormous arrays of the cells, are the largest line of installations capable of producing significant electricity. These installations consist of various components from domestic rooftop solar systems to bigger solar parks [31]. The flexibility of solar cells is demonstrated also by their incorporation into daily use products like mobile phones and electric cars, which actually in turn reveals their capacity for substitution of fossil fuels in energy supply [32]. Not only has the solar cell technology undergone significant changes, but it also has turned from expensive energy generation source into a low-cost one and thus making solar energy a viable option for the both off-grid and mainstream applications [29]. Among the most significant innovations that have contributed to this, are the application of nanostructures and advanced materials which are still being developed and the efficiency of solar cells has therefore been pushed to more and more applications [30]. Solar cells are the heart of solar energy systems of which the miniature electric generating panels, made up of enormous arrays of the cells, are the largest line of installations capable of producing significant electricity. These installations consist of various components from domestic rooftop solar systems to bigger solar parks [31]. The flexibility of solar cells is demonstrated also by their incorporation into daily use products like mobile phones and electric cars, which actually in turn reveals their capacity for substitution of fossil fuels in energy supply [32]. Summarizing, solar cells are primary elements that constitute renewable energy technology, converting sunlight into electric power via sophisticated semiconductor processes. Persistent advancements in material and design development keep on making them more efficient, thus, they are no longer equipment in the new areas of power generation and usage, but their presence is more prominent in the global transition to renewable energy sources. The continuity of research and development in this sector is not only to satisfy the demand for energy but also to accompany it with a reduced negative impact on the environment [33].

Solar cells, which are also known as photovoltaic cells, are machines that through the photovoltaic effect convert sun's light into electricity. The progress of solar cells has produced a sequence of generations, each marked by the use of different materials and that resulted in various kinds of solar cells. The first generation basically consists of crystalline silicon cells, which are further classified into single-crystalline and polycrystalline silicon cells. Single-crystalline silicon cells are characterized by their high efficiency but also their high price due to the energy-consuming purification process of silicon, whereas polycrystalline silicon cells are less efficient but inexpensive, thereby, with their price being the main factor, they are widely adopted [34].

The second generation involves thin-film technologies, which are more affordable to produce than crystalline silicon cells. This category includes amorphous silicon, cadmium telluride, and copper indium gallium selenide (CIGS) cells. Amorphous silicon cells, though less efficient, are inexpensive and flexible, making them ideal for applications

where cost and flexibility outweigh efficiency. Cadmium telluride stands out among thin-film materials for its relatively high efficiency and low production cost [35].

The third generation of solar technology and the new wave of innovations consist of new technologies to make the solar cells better, i.e. more efficient, and cheaper than before. This included solar cells that are dye-sensitized, organic photovoltaic cells, and perovskite solar cells. Dye-sensitized and organic cells are lightweight and flexible, but in general, their efficiency is lower than that of the silicon-based cells. Perovskite solar cells have become a very hot topic due to their high efficiency and likelihood of economical production. However, they are not free from hurdles regarding stability and scalability [36]. Furthermore, there are also specialized solar cells, such as solar concentrating cells that focus sunlight through lenses or mirrors onto high-efficiency cells, and multi-junction cells, which are composed of layers of different materials specifically to catch a wider band of sunlight for more efficient production. Gallium arsenide is a high-efficiency cell material that is mainly used in space applications because of its unique performance, even though it is costly [37]. The latest breakthroughs in technology have also given rise to hybrid solar cells that use a combination of organic and inorganic materials to enhance both performance and stability. The main advantage of these hybrid cells is that they take the best properties of each material type and use them for better charge separation and collection that leads to increased efficiency [38].

In conclusion, solar cells are categorized into first-generation crystalline silicon cells, second-generation thin-film cells, and third-generation emerging technologies, each with unique benefits and challenges. Ongoing research and development in this area aim to enhance efficiency, reduce costs, and overcome stability and scalability issues, contributing to the broader adoption of solar energy [39].

### **The reality of investing in solar energy in Palestine**

The investments in solar energy are largely ruled by the market trends which, in turn, are influenced by a combination of economic, policy, and technological factors. Central Europe has had changing electricity prices that have made the solar energy investment less efficient and less attractive. The Capacity Payment Scheme (CPS) and Capacity Remuneration Scheme (CRS) have been the important factors that support the evaluation of solar energy's market integration, but they have shown a different pattern among the countries owing to these price fluctuations. A reduction in CRS in 2024 points towards the possible difficulties in market integration as a result of market saturation or changing dynamics, therefore influencing the investment decisions in solar energy projects [40].

The solar energy market is not only changing but also greatly impacted by the introduction of new business models and the establishment of new policy frameworks. The advancements in technology and organizational solutions are opening up doors for companies to be flexible and thrive, on condition that they pick the right business models [41]. To make the matter more complex, the global policy landscape is undergoing a transformation with the EU scaling down the

support for solar installations and China shifting its focus more towards installations rather than production. The consequences of such changes could be the consolidation of the market and an increase in the prices of the products, which would, in turn, be a disadvantage for the investors [42]. The market value of solar energy in the U.S. has been quite different from one region to the other. Solar deployment, especially in California, has increased but the market value has gone down due to the variations in energy pricing and the reduction in the capacity credits. Notwithstanding, solar energy still holds the ground because of the dropping costs; as a result, the levelized power purchase agreement (PPA) prices have been in line with the market values in different areas [43].

This competitiveness gets a boost from the support of policies and the introduction of fresh financing methods, such as third-party lease programs, all of which contribute to the Solar's attractiveness to investors. The global solar market is also affected by the changes in the economics of the industry, such as the falling prices of modules and carbon pricing that have accelerated the process of solar reaching price parity with fossil fuels [44]. In spite of this, the sector has to deal with difficulties like cuts in subsidies and barriers to entry which lead to uncertain conditions; however, such an environment is also marked by the possibility of the sector's growth in the emerging markets with a high solar potential like Brazil, India, and South Africa [45]. In the case of Europe, the transition from subsidies such as feed-in tariffs to self-consumption models not only provides an investment opportunity but also specializes the small-scale investors who are attracted by it. The whole process is to see the development of new business models which will reduce dependency on the grid and add to potential savings. However, there are still problems like legal complications and the requirement for effective management to be resolved [46].

Political, economic, and technical aspects constantly generate solar energy investments in the Palestinian context. The import of electric power from Israel is responsible for 90% of the energy demand of the Palestinian Territories and, consequently, frequent electricity outages. The situation has encouraged the move to renewables, particularly solar, as a means to gain energy security and independence [18].

The allure of photovoltaic (PV) systems in Palestine is directly linked to the area's ample solar radiation, with daily average ranging from 5.4 to 6.0 kWh/m<sup>2</sup>, and about 3000 hours of sunshine per year. The great conditions for solar energy generation are making the energy crisis easier to tackle in both urban and rural areas. Gaza and the southern West Bank are already identified as the best spots for IT system deployment [20]. However, there is a positive side to the story; on the other hand, there are still many factors holding back full investments in solar energy in Palestine. Factors such as the lack of technical standards, insufficient training for the staff, and weak energy policies have had a negative impact on the electricity distribution network, thus leading to a high failure rate (47%) of the installed PV systems. Moreover, the lowists in awareness and of non-

technical information are among the behavioral barriers that slow down the penetration of solar technologies [47].

The Palestinian Authority has what it takes to foster the use of renewable energy in the future through a variety of legal measures and incentives, such as national subsidies and grants aimed at persuading the private sector to invest in the renewable energy sources (RES) and energy efficiency (EE) sectors. Nevertheless, they are still not viewed as strong enough to entirely wipe out the major impediments to investment [48]. Additionally, the government has set a target to include a certain percentage of renewable energy in the electricity generation from the measured use, thus indicating that it is determined to change the game and lessen the dependency on energy from outside [49]. The regulatory environment in the Palestinian territories is in state of transition, with the government coming up with new laws and regulations that have been aimed at the support of the development of renewable energy sources and the issue of energy efficiency. However, the actual affect of these policies is very much to a degree determined by the larger political situation, including the continuous presence of the Israeli military, which imposes a number of restrictions on the electricity sector's development [49].

According to market trends, the installation of grid-connected PV systems has been on the rise especially for the residential sector and is mainly attributed to the drop in prices of PVs and the favorable government regulations. These systems have proven to be economically viable with a payback period of around 4.9 years and an IRR of 25%. Moreover, the installation of PV systems has also benefited the electric grid positively in that it has led to loss reduction and improvement of voltage levels [50].

To sum up, the solar energy market of Palestine is growing, however, it has to overcome some obstacles that need unified actions to tackle the technical, regulatory, and political barriers. The potential of solar energy in the area will be completely tapped only if there is the continued development of supportive policies, and there are also greater awareness and training.

## **Building-integrated Solar System**

### **The concept of solar cell integration in glass**

The usage of solar cells in glass facades, otherwise called Building Integrated Photovoltaics (BIPVs), is a major step forward in the direction of sustainable architecture that not only provides for the production of energy but also aesthetic and functional building design. It is the incorporation of photovoltaic (PV) technology directly into a building's external surfaces, like windows and facades, that leads to solar energy capture without detracting from the building's visual appeal.

The major upside of BIPVs is their dual character. The systems not only generate power, but also serve as a barrier to solar radiation, thus enhancing indoor thermal comfort and cutting down on the use of artificial lighting and cooling systems. For instance, a study has found that BIPV facades can bring about a reduction in total electricity consumption by up to 79.3% in comparison with conventional glass walls, and this is one of the factors that test their efficiency in energy conservation [51]. Different kinds of solar cells

applied in BIPVs give various advantages. Organic photovoltaic (OPV) technology, known for its lightness, flexibility, and semi-transparency, is well-suited for use in windows and facades. OPVs show good performance even in low-light, which is a plus for cities that do not get consistent sunlight [52]. Likewise, third-generation solar cells, which include dye-sensitized and perovskite cells, not only offer transparency but also provide color customization, thus pertaining to the modern aligned architectural needs [53].

BIPV systems are now considered to be the most effective way of getting the most out of a building besides energy generation. For example, bifacial photovoltaic modules are capable of generating electricity from both sides and thus they can output about 5% more than the former and at the same time cooling demand can be reduced as a result of their operation as a passive system [54]. Moreover, new technologies incorporating phase changing materials are able to serve the dual purpose of producing hot water for domestic needs, thus enlarging the wide-range of applications of these integrated systems [55]. Along with the theoretical part, the benefits of these developments are supported by numerous case studies. One of them is the use of polycrystalline photovoltaic windows instead of traditional glass in a building situated in Latakia, which not only produced enough electricity for the lighting and office equipment but gradually made it a zero energy building [56]. Besides that, the new lightweight, colored photovoltaic modules offer the possibility of setting up facades that would not only be visually appealing but also economic [57].

Even though there have been significant breakthroughs, challenges still exist, such as the necessity for further studies on durability and adapting these technologies to the existing building regulations and standards. Nonetheless, BIPVs can still play a major role in the path towards Nearly Zero-Energy Buildings (nZEBs) and reducing greenhouse gas emissions, thus contributing to the global sustainability goals [58].

In summary, integrating solar cells into glass facades represents a promising strategy for sustainable building design, providing energy efficiency, aesthetic versatility, and functional advantages. As technology progresses and becomes more affordable, BIPVs are expected to play an increasingly significant role in future urban architecture.

### **Techniques and materials used in solar cell integration with facades**

The use of solar cells in building facades is an application of different techniques and materials that not only improve the look of the buildings but also their performance and energy efficiency. This application is a major part of the modern-day architectural practices that are focused on the proper utilization of renewable energy sources. A major method practiced is the incorporation of multilayer optical interference filters prepared by RF magnetron sputtering. These filters solve the problem of aesthetics by making the solar system's black color and its parts less visible, thus enhancing facade aesthetics through high color reflection at certain visible wavelengths, and acting as an anti-reflective coating in the near-infrared region which increases solar system efficiency [59]. Another way is to use photovoltaic (PV) materials in place of traditional building materials in

facades. Do not only convert solar energy into electricity and thus increase the energy efficiency but also support environment-friendly living by cutting down on emissions [60].

Integrating passive cooling methods like phase change materials (PCM) and evaporative porous clay into solar systems can further boost their effectiveness. The PV system operation temperature is reduced and consequently, their efficiency is enhanced and electricity production costs are lower [61]. Glass is likewise an indispensable material in the solar facades where the cast glass structure is employed as the solar concentrators that obliterate the light to the certain areas. This approach not only improves the quality of the indoor environment but also produces electricity, which in turn, cancels the costs incurred by cooling [62]. In the same vein, ceramic materials are being investigated for incorporation into solar thermal collectors. Ceramics, while offering a wide range of finishes and integration possibilities within the building envelope, could be less energy-efficient compared to traditional metallic collectors [63].

The creation of lightweight, glass-free, and colored PV modules is one more groundbreaking concept. Consisting of crystalline silicon, these modules exude architectural beauty and a wide spectrum of colors making them apt for building integration. Also, they performed well and proved their practicality for use in real-life scenarios [57]. On the contrary, the cadmium telluride, organic and polymer cells, hybrid cells, and thin-film technology advancements in the PV technology area are also considered to be the BIPV future (Building-Integrated Photovoltaics). These technologies not only present diverse options for installation, maintenance, and aesthetic flexibility but also promote more seamless assimilation into architectural designs [64].

In the end, the process of combining solar cells with building facades is a complex but promising area that combines the use of state-of-the-art materials together with the application of modern techniques, namely, multilayer optical filters, PV materials, passive cooling systems, and light PV modules. Every method has its own pros and cons, but all of them work towards the same aim of enhancing building energy efficiency and at the same time keeping aesthetic values. The new techniques just developed and the constant collaboration of the different experts required in this area are already propelling the possibilities in solar architecture even further, thus making it very easy to envision the day when building designs will be not only more sustainable but also more attractive.

### **Solar cell technology analysis**

In-depth solar cell technology analysis truly needs to be based on comprehensive methods, which allow to evaluate not only the performance but also the efficiency and future potential. Such an analysis can be performed using diverse techniques that can be classified into four categories: experimental, diagnostic, modeling, and comparative studies. Experimental analysis is usually concerned with the research of electrical characteristics of solar cells in varying environmental and operational conditions. A case in point is [65], who studies the solar cells' current-voltage behavior with changing light intensities and temperatures; thus, he

sheds light on performance optimization via thermal management and light modulation strategies that are already in place. Another example is [66], who points out the necessity of evaluating photovoltaic (PV) technologies in different light spectra for the purpose of not only getting the optimal installation conditions but also reducing performance losses to a minimum. Diagnostic methods, among which is the photo-scanning method, stress the significance of measuring solar cell efficiency with Levchenko's techniques, to mention just one. This method acts as a detector of areas that are cold and hot and gives out data that can be quantified thus allowing for exact diagnostics of solar cells that have different surface sensitivities [67]. On the other hand, developers' techniques like numeric models and machine learning algorithms are the backbone of solar cell performance simulation. For instance, Ali et al. use a model that combines numeric simulation with an Emotional Artificial Neural Network to predict the electrical behaviors of solar cells, counting on the energy and exergy aspects. This methodology leads to a better prediction of energy, exergy, and power, while at the same time being less costly in terms of computations compared to conventional numerical models [68]. Moreover, [69] apply differential equations for the investigation of the performance of solar cells with sensitizer molecules, thus reviewing the influence of the photon absorption and the electron emission on cell efficiency.

The performance comparison of solar cell technologies is a significant part of studies. Nayak et al. [70] carry out a deep analysis of the different solar cell technologies like single-crystalline and multicrystalline silicon, thin films, and the newest perovskite technologies. Their analysis reveals how power conversion efficiencies have been improved and the possibilities for future advances through intermixing different PV technologies. In the same way, Abbott et al. [71] do a simulation to give a forecast of the yearly energy output of the various texturing methods, thus, implicitly indicating the role of thoroughness in modeling as a factor determining the ultimate worth of solar cell technologies. Also, not only it is necessary but also it is always going to be so to comprehend what is at the core of the solar cell function. For example, the conditions necessary for solar cell operations, like the diffusion and drift processes responsible for the functionality of the junctions, are next to the work of [72], who talk about these phenomena in the context of PN junctions. Papadopoulos' method of mapping the racemization process with the generation-decay time maps facilitates estimating the racemization behavior which is pivotal to solar cell efficiency.

In summary, a thorough analysis of solar cell technology integrates experimental data, diagnostic techniques, modeling, and comparative studies. This multifaceted approach optimizes solar cell performance, enhances efficiency, and guides future technological advancements, contributing to the broader goal of sustainable energy utilization. The integration of these methods is crucial for advancing solar cell technology and addressing the challenges associated with renewable energy systems.

### **Engineering and design challenges in applying solar cells to facades**

The main problem, when it comes to the integration of photovoltaic (PV) systems into the building envelope, is the thermal management of the systems. This integration can in a big way alter the thermal characteristics of a building. The use of phase change materials (PCM) together with BIPV systems, for instance, can manage the peak operational temperatures and, in effect, the energy efficiency through altering the heat and mass transfer in the facade. However, this entails having very complex simulation models, which can predict and optimise the performance very accurately, as in the case of comparative studies that utilized tools such as Energy Plus and Ansys for BiPV/PCM systems [73]. The thermal reaction of these systems is very much dependent on the weather conditions; therefore, precise modelling and validation are very important in order to bring the theoretical predictions close to the experimental data.

Aesthetic integration is another challenge that photovoltaic systems present to building designers. Very often, architects and engineers find themselves in a dilemma that involves energy performance as opposed to aesthetic dimension. For instance, coloured BIPV modules may not only make the solar facade more attractive but also lead to reduced efficiency as a result of shading from the color filters or the painting techniques used [74]. The aesthetic and performance issue is a very critical aspect of BIPV design and hence there is a strong need for customization to clear up the conflicts between architectural aspirations and energy performance [75].

In addition, the interdisciplinary character of BIPV projects calls for efficient cooperation of diverse parties, such as architects, facade consultants, and suppliers of systems. The analysis of barriers to market entry of BIPV systems has revealed that the overlapping responsibilities of these professionals can lead to complications during the stages of design and implementation. The challenges are made considerably worse by the high expenses required for the initial investment and the limited public knowledge of BIPV technologies, which, consequently, prevent such technologies from being adopted on a large scale despite their ability to produce significant amounts of energy through installations on facades [76]. Furthermore, the installation of photovoltaic systems within facades must take into account the whole energy consumption of the building. While PV systems are mainly seen as electric power suppliers, their installation within the building envelope can impact both the building's thermal characteristics and its energy efficiency, which, in return, poses extra design challenges in the context of Nearly Zero Energy Building (ZEB) concepts [77].

Finally, the integration of solar cells into building facades involves overcoming technical challenges related to thermal management and energy performance, addressing aesthetic integration issues, and ensuring effective interdisciplinary collaboration. Meeting these challenges requires advanced simulation tools, innovative design solutions, and coordinated stakeholder efforts to fully harness the potential of BIPV systems in sustainable building design [74].

### **The impact of solar cells on architectural formation**

In addition, the interdisciplinary character of BIPV projects calls for efficient cooperation of diverse parties, such as architects, facade consultants, and suppliers of systems. The analysis of barriers to market entry of BIPV systems has revealed that the overlapping responsibilities of these professionals can lead to complications during the stages of design and implementation. The challenges are made considerably worse by the high expenses required for the initial investment and the limited public knowledge of BIPV technologies, which, consequently, prevent such technologies from being adopted on a large scale despite their ability to produce significant amounts of energy through installations on facades [76]. Furthermore, the installation of photovoltaic systems within facades must take into account the whole energy consumption of the building. While PV systems are mainly seen as electric power suppliers, their installation within the building envelope can impact both the building's thermal characteristics and its energy efficiency, which, in return, poses extra design challenges in the context of Nearly Zero Energy Building (ZEB) concepts [77].

The incorporation of solar cells in buildings has been made possible through a combination of different technologies and materials, such as cadmium telluride, organic and polymer cells, and thin-film technology. These materials offer a wide range of aesthetic and functional characteristics, thus providing great flexibility in design regarding the dimensions, form, and color of solar cells. Besides the above, PV systems can introduce a more pleasing look to the buildings, besides their practical benefits like on-site electricity generation, thus saving costs and energy losses traditionally incurred during retrofitting [64]. Integration of solar cells into architectural design depicts a difficult scenario. Aesthetic premise is a major factor since, in the hands of poor integration, PV systems might actually destroy the aesthetic of the building. Careful positioning and angling are a requirement for soaking up the maximum sunlight for the least deterioration of the visual aspect. The use of several functions for the PV modules and the types of their installation also play a big role in coining the building's visual design [78].

Moreover, the installation of solar cells in buildings is already mentioned or considered as a part of a bigger debate about the energy transition with justice. Though solar energy gives an extraction less alternative, it still rolls over some of the extractive practices associated with fossil fuels such as the mining of rare earth materials. Solar panels manufacturing may cause emissions, and their rapid turnover might cause resource dependencies. Hence, the problems above point out the need for solar energy to have a just distribution of its benefits and a possible resource management change in the building design [79]. One of the projects that break the mold is the interactive canopies, which are a testimony to the potential of solar energy to penetrate the architectural form and change it dynamically. These canopies are so smart that they change with the environment and control the solar radiation levels to keep on the light side and at the same time use less power. This method not only shows how solar technology can be smoothly integrated into

architectural design but also the acquisition of building efficiency and occupant comfort [80].

In summary, the integration of solar cells into architectural design has a profound impact on both the aesthetic and functional elements of buildings. While offering significant advantages in sustainability and energy efficiency, the successful incorporation of solar technology into architecture requires careful consideration of aesthetic, technical, and social factors to ensure a balanced and equitable approach to building design.

### **Environmental and economic benefits of integrating solar cells with the building**

Integrating solar cells into buildings, particularly through Building-Integrated Photovoltaics (BIPV), provides significant environmental and economic advantages, making it a key strategy for sustainable urban development and energy efficiency.

#### **Environmental Benefits**

1- Reduction in Carbon Emissions: BIPV systems play a significant role in carbon emissions reduction by replacing traditional building components with solar panels that produce clean energy. Such changes correspond with the targets of decarbonization, as seen in the EU's dual-purpose roofing systems that not only prevent leakage but also lower CO<sub>2</sub> emissions [81]. In addition, the installation of solar cells in building façades and rooftops could profoundly reduce the electricity demand in cities, thus helping to combat global warming [53].

2-Optimized Resource Utilization: Among the various benefits of solar technology in buildings, resource efficiency is one of the major ones. Solar thermal applications combined with other renewable resources, such as wind or biomass, in a hybrid setup can lead to improved efficiency of energy use and lower carbon footprints [82]. In addition, eco-designs of BIPV products, which are targeted at 30% efficiency by 2030, are mitigating urban heat island effect thus bringing greater environmental benefits [83].

3-Support for Circular Economy: Building integrated photovoltaics (BIPV) systems are frequently created with the entire lifespan of the parts in mind, encouraging at the end of their life disassembly and recycling. This method is in line with the circular economy, energy usage during the life of the building component is reduced and among the sustainable construction practices, BIPV is one [81].

#### **Economic Benefits**

1-Energy Cost Savings: The BIPV systems of the future will be the ones that cut the energy cost a great deal by their ability to produce electricity that the building consumes, thus being less dependent on the power grid. Just to illustrate, one of the proposed designs for a BIPV-installation on the rooftop, could supply almost 50% of the energy required for the whole building and thus save considerably during the lifetime of the system [84].

2-Local Economic Development: The BIPV systems' deployment brings about the local economy's revival as it the BIPV systems not only will be creating jobs in the areas of manufacturing, installing, and maintaining these systems but also the local market will have the benefit of having cheaper electricity brought by the BIPV systems. The studies have

pointed out that the use of rapid impact assessment matrix methodology has not only identified but also quantified the economic impact of solar instalment [85].

3-Incentives and ROI: The government incentives like net energy metering (NEM) have made BIPV systems much more attractive from a financial point of view. These incentives together with improved ROI are the main driving forces behind the wider acceptance of solar technologies in residential and commercial buildings [84].

The initial costs and the requirement for the development of infrastructure, however, are among the issues that have to be dealt with before these benefits can be enjoyed. On the other hand, the solar cell efficiency improvements and the declining production costs are slowly but surely knocking down these barriers one by one [86]. Moreover, the incorporation of third-generation solar cells, e.g., dye-sensitized and perovskite cells, not only brings the issue of aesthetics but also that of energy performance which can consequently contribute to the wider adoption [53].

In summary, integrating solar cells into buildings offers considerable environmental and economic benefits, contributing to sustainable urban development and energy efficiency. Continued research, development, and supportive policies are essential to maximize these benefits and overcome existing challenges.

## **Commercial Buildings and Energy Consumption**

The energy consumption in both residential and commercial buildings is highly affected by the factors of economic growth and urbanization. Measuring the energy consumed in buildings is not easy and thus calls for a good building energy management system. This system is vital for the assessment of the energy efficiencies of different building structures [86].

### **Commercial buildings in Palestine**

The energy consumption, sustainability, and environmental impact of commercial buildings in Palestine present a variety of challenges and opportunities. On the one hand, the commercial sector is the largest energy consumer in the region, consuming about 40% of the total energy, mainly because of the use of fossil fuels and imported electricity, which are the major contributors to lighting and heating-related greenhouse gas emissions [87]. The operational phase, which is the main contributor over the entire life cycle of the buildings, takes up 73% of energy and emits 82% of the total greenhouse gases [88]. The situation reveals the necessity of energy efficiency measures as a priority.

The National Energy Efficient Action Plan (NEEAP) 2019 intends to overcome these problems by introducing the energy efficiency technologies and decreasing the energy footprints of buildings [87]. Nonetheless, the initiatives for sustainable construction are still facing certain barriers, such as the absence of energy efficiency policies in traditional and commercial building sectors and the difficulties in conserving the numerous heritage buildings in the region [89]. The lack of well-defined energy efficiency standards makes it hard to reduce power use and emissions. Different aspects of energy retrofitting programs and energy efficiency measures reveal that the potentials for energy saving are quite large. A case in

point is simulations that show comprehensive retrofitting may reduce the energy input for heating, cooling, and lighting by as much as 80% in domestic buildings [92]. Even if these studies are concentrated on residential buildings, their insights are applicable to commercial buildings too, signifying that energy conservation through similar measures might be even more substantial.

The use of renewable energy sources, such as solar energy, is also seen as a practical solution to cut down on imported energy and facilitate the transition to nearly zero-energy buildings (ZEB) [87]. This not only helps with energy consumption but also aligns with the sustainability agenda by reducing the carbon footprint and improving energy security. On the other hand, the deployment of these strategies is hindered by several issues, such as the lack of funds, low public knowledge, and the existence of obsolete laws [89]. Furthermore, the seismic risk of buildings in places like Nablus complicates the issue, requiring that the local seismic situation be taken into account when building design and retrofitting [91].

As a result, even though the commercial buildings in Palestine are highly energy-consuming and unsustainable, there exist some measures to rectify the situation through the use of energy-efficient technologies, retrofitting programs, and renewable energy. In addition to overcoming barriers related to regulations and economics, raising people's awareness and considering seismic aspects will be critical for the commercial building sector to become more sustainable in the region.

#### **Thermal comfort in commercial buildings**

Commercial buildings' thermal comfort is an intricate matter that focuses on the preservation of indoor atmosphere in which no one feels excessively hot or cold, thus enhancing the overall satisfaction and productivity of the employees. It is a crucial factor in the workplace because it not only brings about contentment and productivity but also influences the quantity of energy used and the sustainability of the building design and operation [92]. The adaptive thermal comfort model suggests that instead of limiting indoor temperature ranges, the occupants should be allowed to adapt to a wide variety of temperatures, thereby giving more preference to natural and mixed-mode systems of ventilation. The aim of these systems is to make the use of energy in mechanical cooling less dependent by maintaining comfort and thus resulting in the use of less energy [93]. Thermal comfort improvement by using PCMs (phase change materials) together with insulation and natural ventilation has been validated for warm and humid climate areas. Buildings in Chennai, India, for instance, with PCM and insulation system design stayed at comfortable temperature even during extreme summer heat [94]. A study in Guangzhou, China, suggested that the thermal comfort level in green-certified office buildings is higher than that of conventional buildings. The advantageous temperatures of these green buildings support a wide spectrum of temperatures which may result in the adoption of less energy for air conditioning [95]. Nigeria has the situation in such a way that in the commercial space, building orientation and design considering natural ventilation and thermal inertia become necessary for the

thermal comfort to prevail [96]. The application of energy retrofitting measures such as the installation of shading devices will considerably decrease solar heat gain and consequently improve thermal comfort. In Surabaya, Indonesia, the installation of horizontal shading devices has been remarkably effective in reducing indoor temperatures as well as saving on the energy used for cooling [97]. Moreover, the use of PCM as part of the building envelope has proved to be a very effective passive method for increasing thermal mass thereby reducing temperature fluctuations and consequently improving thermal comfort [98]. Assessment of thermal comfort mostly relies on the use of indices such as the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) which are based on the consideration of air temperature, radiant temperature, air velocity, and level of clothing [99]. There have been some advancements, yet the offer of thermal comfort still on the condition of energy efficiency is a tough nut to crack. Smart building technologies and local thermal standards are among the options for getting rid of these challenges [100]. The construction industry is steadily recognizing the significance of thermal comfort which in turn, is the mother of innovations in materials and design practices that have the two-sided nature of health and energy efficiency [101].

In summary, achieving thermal comfort in commercial buildings requires a blend of adaptive design strategies, advanced materials, and energy-efficient technologies. By addressing varying climatic conditions and occupant needs, designers can create environments that improve comfort while advancing sustainability objectives. This holistic approach is crucial for future building design, meeting both human and environmental requirements.

#### **The relationship of integrated solar cells in building facades to the thermal conductivity of the building**

Integrating solar cells into building facades offers a transformative strategy for improving thermal and energy performance. These systems not only capture solar energy but also help manage thermal light, which is vital for decreasing energy use in heating and cooling. By optimizing heat distribution and light management, solar-integrated facades enhance overall energy efficiency and improve indoor air quality by reducing reliance on artificial climate control systems, thus promoting sustainable building practices and healthier environments. The impact of solar cells on thermal conductivity significantly affects energy efficiency and indoor comfort, influenced by factors such as the type of solar technology, facade design, and environmental conditions. For instance, building-integrated photovoltaic (BIPV) systems can bolster thermal insulation by minimizing heat transfer through the building envelope; semi-transparent photovoltaic windows with advanced glazing can significantly enhance energy efficiency [102]. Facades incorporating photovoltaic technology can achieve substantial energy savings, cutting total electricity consumption by up to 79.3% compared to conventional glass walls, showcasing their effectiveness in reducing thermal loads [49]. Heat-pipe-ringing (HPR) embedded facades show impressive thermal efficiency, with annual performance ranging from 62.6% to

73.5%, which is critical for minimizing energy losses across various climates [103].

The design of solar-integrated facades, such as those utilizing crossed compound parabolic concentrator photovoltaic windows, directly impacts thermal conductance and optical transmittance, essential for assessing energy efficiency and indoor comfort [103]. Additionally, the performance of these systems is sensitive to environmental factors like solar irradiance and air temperature; for example, semi-transparent photovoltaic windows exhibit varying efficiency based on weather conditions, influencing both thermal insulation and electrical output [102]. The dynamic thermal performance of photovoltaic double-skin facades is also affected by glass transmittance and natural ventilation, with the latter becoming more significant during night time [104].

Building-integrated photovoltaic/thermal (BIPV/T) systems provide multifaceted advantages by simultaneously generating electrical and thermal energy, thereby enhancing overall energy performance. These systems can lower the surface temperatures of photovoltaic panels, improving their electrical efficiency [105]. However, despite their potential, the broader adoption of solar-integrated facades is hindered by technological challenges and the necessity for innovative solutions to enhance performance and reduce costs [106]. Thus, while integrated solar cells in building facades present significant benefits for thermal conductivity and energy efficiency, their effectiveness can vary based on design and environmental conditions, highlighting the need for customized solutions tailored to specific building types and climates.

#### **The impact of integrated solar cells in building facades on the building's thermal comfort based on heat orientation.**

Solar cells' placement on the facade substantially changes the structure's thermal conductivity and heat transfer characteristics. The energy generation and heat control of photovoltaic (PV) systems shared the main mediating factor of this connection. If buildings are designed with integrated photovoltaic (BIPV) systems, they can reverse the building envelope's thermal resistance. One of the ways to get this done is by limiting the heat transfer through the facade, which in turn helps to maintain the indoor thermal comfort and reduce the energy needed for heating and cooling. For instance, the integration of PV systems with transparent wall configurations has been shown to save substantial amounts of energy by reducing artificial lighting and thermal loads while also generating electricity [51]. This dual functionality highlights the BIPV systems' potential to contribute to energy savings and efficiency. Moreover, the thermal performance of BIPV systems is upgraded by the cooling techniques developed. The researchers have proved that using advanced cooling methods like impingement and film cooling can drastically influence the heat transfer rates in PV cooling ducts. This is especially important because PV panels are likely to lose some of their efficiency due to overheating, mainly because part of the solar energy absorbed is not transformed into electricity, but rather it is dissipated as heat [107]. By improving the heat transfer, these cooling techniques allow the PV cells to operate at lower temperatures, which consequently enhances their electrical

efficiency. In addition, the use of heat-pipe-ring (HPR) embedded facades as solar collectors has been proven to provide very high thermal efficiency and to be a reduction of energy losses especially when optimized for a particular climate condition. These systems can operate with thermal efficiency from 62.6% to 73.5% which is greatly influenced by the design and the local climate, thus providing a very solid alternative for the use of solar energy in building applications [103]. On top of that, the use of phase change materials (PCMs) in BIPV systems can not only be a very advanced form of thermal management but also a method of storing excess heat and releasing it when required, thus controlling indoor temperatures and making the least use of external heating and cooling systems [54].

The thermal efficiency of the building facade is improved by this method and also it is a source for domestic hot water, thus proving the multifunctionality of the contemporary BIPV systems. Furthermore, BIPV systems through the management of solar radiation are able to consume less energy by providing electricity. A case in point is that dynamic PV facades are able to cut down energy consumption by 73% in certain months through the controlling of their transparency and orientation for solar heat gain [108]. Another example of this is the dynamic vertical PV integrated building envelope (dvPVBE) which provides high-rise buildings with not only aesthetic solutions but also energy generation [109]. In the same manner, Building-integrated photovoltaic (BIPV) systems can be a big help in the process of converting residences into net-zero energy consumers. For this reason, solar-rich regions of China can have energy demands met through BIPV systems installed on the roofs and south-facing facades of multi-story residential buildings [110]. Also, in a domestic setting, the return on investment for mini BIPV systems remains around 6 to 7 years, dependent on factors like geography and size of the system [111]. This rather shorter payback period makes BIPV systems a very attractive investment choice for those who wish to reduce their energy costs and their carbon footprints at the same time. The payback period of BIPV systems is quite variable in commercial buildings. In some cases, it can be as short as 12 years, while in others, it can last up to 41 years, depending on factors such as building type, location, and the extent of photovoltaic coverage [112]. The economic assessment of BIPV systems in high-rise office buildings, on the other hand, emphasizes the importance of electricity pricing structures as the main determinant of the payback duration [113]. Nevertheless, it is still difficult to strike the right balance between the two conflicting requirements of thermal resistance and light transmittance, especially in the case of window-integrated PV systems. For instance, including compound parabolic concentrators in PV windows could lead to great thermal resistance but would also lower the light transmittance, which is an important factor for the provision of sufficient natural lighting indoors [114].

To put it briefly, the application of solar cells on building facades can greatly improve the thermal conduction and heat transfer properties of the construction. BIPV systems can use sophisticated cooling methods, design for particular climates, and apply multifunctional materials such as PCMs to bring

about a decrease in energy consumption and an enhancement of building performance. These advancements show the capacity of BIPV systems to play a role in the area of sustainable building practices and energy conservation by being a part of the solution rather than the problem.

**The impact of integrated solar cells in building facades on the building's thermal comfort based on reduce energy consumption.**

Solar energy (BIPV) is the term for the integration of solar cells onto building facades. It is a vital component of BIPV systems that improve thermal comfort while lowering energy usage. BIPV systems affect the thermal performance of the building while producing energy locally. According to studies, these systems may greatly reduce the amount of energy used for lighting, heating, and cooling, which will enhance thermal comfort. For example, PV-integrated louvers on south-facing facades have been found to reduce energy consumption in various U.S. climate zones, particularly in areas with moderate cooling needs [115]. Additionally, facade-integrated PV panels, as opposed to rooftop installations, offer visual comfort benefits by minimizing glare and maintaining optimal indoor lighting conditions, which is particularly advantageous in tall office buildings [115]. Transparent wall configurations integrated with photovoltaics also contribute to energy savings, with some studies reporting up to 79.3% reductions in electricity consumption compared to traditional glass walls, thanks to decreased artificial lighting and thermal loads [47]. BIPV systems also help stabilize indoor temperatures, especially when combined with phase change materials (PCMs), which can reduce peak temperatures and reliance on HVAC systems [116]. In addition, combining mechanical solar ventilation with BIPV can not only result in decreased indoor temperatures but also providing better comfort due to the lower indoor humidity levels [117]. On the other hand, BIPV systems differ in efficiency depending on the climate; in cold areas, the installation of solar panels on the roof might be a better option as it can help to maintain the indoor temperature by providing power and receiving heat from the sun [115]. Moreover, the temperature comfort in the building largely depends on the location and designing of the urban space as well as the BIPV system itself. For example, the summer thermal comfort in northern European cities will be influenced by the use of BIPV systems without low emissivity coatings while in southern areas the effect will be negligible [118].

In summary, integrating solar cells into building facades can significantly enhance thermal comfort and energy efficiency, especially when combined with technologies like PCMs and mechanical ventilation. The effectiveness of these systems depends on factors such as climate, building orientation, and facade design, requiring careful consideration to maximize the benefits of BIPV systems.

**The impact of integrated solar cells in building facades on the building's thermal comfort based on Light distribution.**

significantly affect the thermal comfort of the building inhabitants mainly by light distribution pattern control. The buildings equipped with semi-transparent photovoltaic

(STPV) windows face the situation where the radiation absorbed by solar cells is the reason for creating a non-uniform thermal environment which directly and indirectly influences the thermal comfort of the people living in that space by the 'slightly warm' condition that is shed on them. This is explained through the interaction of thermal and daylight environments, where the illuminance levels have a pronounced effect on the thermal sensation in the different ranges [2]. In the same way, the bifacial PV modules, which are able to take in solar power from both sides, are responsible for creating a thermal gradient, which is especially noticeable at noontime during the summer. This gradient in the indoor temperature profile causes the PMV index to fluctuate indicating discomfort during sunny days with heavy solar radiation. Nonetheless, the addition of a heat insulation reflective layer at the back of these modules can increase indoor comfort by regulating light distribution and thus eliminating some of the thermal discomfort leading to an extension of the annual thermal comfort period by 8% [119]. One more remarkable instance of the distribution of light's effect on thermal comfort is found in the kirigami-inspired building envelopes. These envelopes, The surfaces of glass, with their reflective properties and geometric patterns, play an important role in the climate control of the building by balancing the daylight and the heat coming from the windows, hence, the indoor temperature and light are distributed uniformly which saves energy and makes the people inside more comfortable [120]. Moreover, radiant floor heating in areas with large windows can lead to discomfort in case the heat is unevenly distributed due to the floor being heated by the sun and the people sitting or lying on it. Therefore, the use of ventilation systems and smart controls becomes necessary to cool down areas and make the thermal environment comfortable [121]. All in all, these contributions highlight the importance of patterns of light in determining the thermal comfort in buildings that have solar cells integrated, hence, there is a need for the invention of design and control strategies that could maximize both the energy-saving aspect and the well-being of the occupants. Enhancing Occupants' Thermal Comfort in Buildings by Applying Solar-Powered Techniques [122].

In the same manner, south-facing PV-integrated louvers have the potential to cut down the total energy used in buildings by a large amount [115]. These louvers have such a high efficiency that they control the penetration of sunlight in the most effective way, thereby maintaining a good illuminance level throughout the majority of the indoor area and at the same time making the area glare-free [115].

Talking about thermal comfort, mounting of PV panels on façades might change the building's thermal character in such a way that it is less favorable for indoor temperature regulation. In cold areas, installation of the solar panels on roofs could be more advantageous in terms of the power generation being well-balanced with the solar heat gain; this is important for thermal comfort in the winter months [115]. In contrast to the above, Vassiliades et al. [118] claim that BIPV systems installed in northern urban locations which do not use low-emissivity coatings may lead to a decrease in the thermal comfort level during the warmer months. Facade

areas with large glasses suffer much more from thermal discomfort due to solar radiation. An uncontrolled retail display window can lead to a rise in mean radiant temperature (MRT) to the point where it is no longer pleasant for the occupants. For the thermal comfort in the interior environments through these glass areas, the use of glass with proper solar heat gain coefficients (SHGC) is a necessity [123]. Moreover, adjustment of albedo and distribution of urban thermal inertia may be done to allow for the management of solar paths and the properties of building materials thus leading to the creation of pleasant thermal environment [122]. The integration of solar cells and building facades is not only a step towards energy efficient and thermal comfort but also an area with some challenges. The performance of these systems can vary considerably depending on the combination of climate, building design, and material properties which are the main factors involved. Thus, a deep understanding of these aspects becomes a necessity in order to optimize BIPV systems not only in terms of performance but also in terms of the occupants' comfort level. In addition, the glare and thermal discomfort issue in certain configurations bring once again the importance of careful design and technology integration to the forefront [124].

To sum up, solar cells incorporated in building facades can contribute to thermal comfort through regulating solar heat gain and the distribution of light. BIPV systems' effectiveness is influenced by a variety of factors which include system design, climatic region, and the characteristics of building materials. Even though these systems contribute to lower energy usage and better visual comfort, still great attention on glazing properties and thermal management strategies is necessary for the best thermal comfort. All these findings point to the necessity of integration building design that is based on energy efficiency and occupant comfort as the two main priorities.

#### **The impact of integrated solar cells in building facades on the building's thermal comfort based on improved air quality**

Integrating solar cells into building facades, particularly through Building Integrated Photovoltaics (BIPV), has a notable impact on thermal comfort and air quality within buildings, with outcomes varying based on geographical location, design, and the technologies employed. The inclusion of solar cells can alter the thermal dynamics of the building envelope, influencing thermal comfort. For instance, research in Sweden and Cyprus revealed that PV panels without low emissivity coatings can affect thermal comfort, particularly in northern climates like Sweden, where the impact is more significant during summer months [118]. This indicates that the design and material properties of PV panels play a critical role in their effectiveness. Additionally, the use of heat-pipe-ring (HPR) embedded facades as solar collectors has been found to enhance thermal efficiency, reducing reliance on conventional heating and cooling systems and thereby improving thermal comfort, especially in regions with substantial temperature variations [103].

The integration of phase change materials (PCMs) with BIPV systems further stabilizes indoor temperatures, as shown in

studies where peak temperatures were reduced by up to 4.5°C, leading to a more stable and comfortable indoor environment [116]. Solar ventilation systems, which utilize solar energy for ventilation, can also enhance indoor air quality and thermal comfort by reducing operating temperatures and humidity, contributing to overall energy efficiency [117]. However, limitations exist, such as the insufficient heating capacity of air indirectly heated by PV panels during winter months, highlighting the need for a hybrid approach that combines solar energy with other heating methods to ensure consistent thermal comfort throughout the year [125]. Furthermore, renovation strategies incorporating solar harvesting facades into existing HVAC systems demonstrate potential reductions in greenhouse gas emissions and energy consumption, which are crucial for maintaining indoor air quality and thermal comfort [126]. Lastly, solar ventilation techniques, by harnessing solar energy, improve indoor air quality and reduce reliance on non-renewable energy sources, thus contributing to a healthier indoor environment and better thermal comfort [127].

In summary, integrating solar cells into building facades can significantly improve thermal comfort and air quality, with effectiveness depending on the technologies used, climate conditions, and the inclusion of complementary systems.

#### **The basis and strategies for reducing energy consumption through the use of solar cells in records.**

Reducing energy consumption with solar cells involves leveraging technological innovations and strategic applications. The core of these strategies focuses on enhancing solar cell efficiency and integrating them into conventional energy systems [128]. A key approach is improving the efficiency of solar cells through technological upgrades. For example, applying multilayer antireflection coatings to crystalline silicon solar cells can significantly lower power consumption by reducing energy losses from reflection. This is accomplished by applying numerous layers of silicon nitride (SiN) by plasma-enhanced chemical vapor deposition, which maximizes light absorption and increases cell efficiency [129].

Integrating solar cells into existing systems also contributes to energy savings. For instance, in radio stations, solar cells can act as the primary power source, with a system that monitors and manages power distribution [130]. When solar cell output drops below a certain level, non-essential loads can be temporarily disconnected to lower overall power use without affecting essential functions [131]. This approach reduces both energy consumption and the required capacity of solar cells. Additionally, combining solar cells with other technologies can further decrease energy use. In wireless sensor networks, energy-aware data compression schemes can be employed. These schemes adjust data compression based on the remaining energy from solar cells, balancing energy consumption with data transmission delays [132]. This ensures efficient energy use and extends the network's operational lifespan. Solar cells also help reduce reliance on grid electricity for radio base stations. By aligning photovoltaic system output with daily power consumption patterns, significant cost savings can be achieved. This

requires understanding seasonal solar energy variations and optimizing the photovoltaic system accordingly [133]. Moreover, solar energy can be utilized for cooling applications, which are typically energy-intensive. Using solar-powered absorption refrigeration units can greatly reduce the energy needed for cooling, minimizing dependence on conventional energy sources [134].

Likewise, reducing energy consumption through the use of solar cells involves a variety of strategies and technologies aimed at optimizing the efficiency and effectiveness of solar energy systems. One fundamental approach is the integration of solar collectors and phase change materials (PCMs) to manage energy demand in buildings. This method utilizes PCMs to absorb excess solar radiation during summer, thereby reducing energy consumption by 44% on hot days and 36.6% for solar hot water systems, leading to significant annual energy savings [135]. Another strategy involves the application of multilayer antireflection coatings on crystalline silicon solar cells, which enhance their efficiency by reducing power consumption through improved light absorption [129]. In wireless sensor networks, energy-aware selective compression schemes leverage solar energy to manage data transmission efficiently, using excess energy to minimize delay times and optimize network performance [132]. Additionally, solar cells are employed in low-power consumption devices like meter recorders, which convert solar cell voltage outputs into frequency data for efficient remote monitoring and data storage [136]. For radio stations, power consumption is minimized by stopping power supply to non-essential systems when solar charging decreases, thus maintaining operational efficiency without compromising system quality [137]. Similarly, in the realm of solar cell manufacturing, strategies to reduce the use of silver in metallization processes are explored, such as using copper plating and aluminum layers, which not only cut costs but also improve the environmental footprint of solar cells [138]. Lastly, cognitive strategies in wireless sensor networks, which include the use of game theory and cognitive radio technologies, are employed to optimize energy consumption by adapting transmission parameters based on available spectrum and enhancing collaboration among nodes, leading to significant energy savings [139]. These diverse strategies highlight the multifaceted approach to reducing energy consumption through solar cells, encompassing technological innovations, material optimizations, and strategic energy management across various applications.

In summary, reducing energy consumption with solar cells involves a comprehensive approach that includes enhancing cell efficiency, integrating solar technology with existing systems, and combining solar energy with other technologies. These methods not only save energy but also support sustainability by decreasing the environmental impact of energy use. Effective implementation requires a deep understanding of both solar technology and the specific energy demands of the systems involved.

## Conclusion

The holistic application of solar cell installation on building facades and roofs marks the beginning of a new era of sustainable architecture and energy-efficient city

development. BIPVs not only produce power, but they also give thermal comfort in the rooms and an attractive look through transparent, coloured, and bifacial modules. They contribute to the environment by reducing carbon emissions significantly, using energy and materials efficiently, and adhering to circular economy practices. Economically, the benefits include lower electricity costs, job creation in the area, and higher returns on investments. These pros like precise thermal management, aesthetic versus performance conflict, and different departments' cooperation, along with high initial investment still need to be resolved. Proper government regulations together with ongoing solar technology, simulation tools, and monitoring improve the situation gradually. The literature reviewed has unequivocally established that BIPVs are more than a contender for placing the world of architectural energy consumption and its associated carbon emissions in the Nearly Zero-Energy Buildings (nZEBs) bracket besides contributing to global sustainability goals positively.

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