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Analysis of Building-Integrated Photovoltaic Systems: A Case Study of Commercial Buildings under Mediterranean Climate

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Abstract

In the last decades, due to the significant increase in energy consumption in the building sector, many engineering strategies were developed to benefit from the use of renewable energy, particularly the solar energy. Today, building-integrated photovoltaic (BIPV) is being considered by building designers as an innovative technique for clean energy production and reduction of green house gases. Integration of PV cells in the building envelope can help in overcoming many economical and social barriers that are preventing a wider dissemination of the technology in the Mediterranean area. The BIPV components are multifunctional elements that can be used not only as energy converters, but also as shading devices, cladding, façade or roofing elements, etc. The Mediterranean countries are located in a relatively sunny area with a global horizontal radiation of 7.5–8 kWh/m^2 in summer. However, the temperature in these countries can reach high levels for the same period. This can affect the performance of the BIPV cells. In this paper, BIPV systems are analyzed through a literature review where the BIPV systems that are most suitable for Mediterranean climate are investigated according to architectural constraints. The case of commercial buildings is considered where different integration scenarios are compared and analyzed. The energy performance of BIPV systems is assessed through modeling and simulations by a simplified approach taking into account various parameters such as the climate, tilt angle, azimuth angle, and types of cells. Prospects for the development of this sector are discussed at the end of this paper.

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Keywords: BIPV, Photovoltaic System, Solar Energy, Building Architectural Integration, Mediterranean Climate

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1. Introduction

The Mediterranean buildings are responsible in average for 40% of the region's total energy consumption and more than 20% of its CO_2 emissions. The use of renewable energy sources has been recently receiving considerable attention as a viable source of energy supply in buildings through the funding of many initiatives to create awareness and building capacity throughout the region, especially in the solar energy sector [1]. Most of the countries in the Mediterranean region benefit from an abundant solar radiation, yet the exploitation of this renewable source of energy is still limited. Considering that the solar thermal technology has reached a certain maturity, the PV still lacks its place, although it has a great potential mainly on commercial buildings where electricity is the first need. One often-mentioned alternative to conventional PV systems is building-integrated photovoltaic systems (BIPV), which could be an especially attractive source of energy. Today, BIPV is being considered by building designers and engineers as an innovative technique for clean energy production and reduction of green house gases.

The solar PV cells have been subject to many enhancements in the last decade; however their use in buildings is still restrained due to many constraints:

- Aesthetical: When installing the PV modules on the existing structure of a building, they often form a strange element to its architecture, since they are not an integral part of it. The perception of the system within the building is a major element of reserve towards their implementation by the building stakeholders.
- Technical: Under optimal conditions, the solar PV modules require a large space for installation which is not always available on the building's roof. Furthermore, the roofs are not always suitable and optimal orientation is not always easy to achieve.
- Economical: The cost of the PV system and its implementation is still significantly high in comparison to solar thermal systems. For example, it is estimated that a typical solar PV system would have a payback period ranging from 7 to 10 years in Lebanon, while a solar domestic hot water system would have less than 5 years.
- Social: People in the Mediterranean region (mainly the South and East parts of the Mediterranean basin) are still not familiar with the technology, and are not ready yet to accept it as a reliable source of energy. Many awareness campaigns and training paths on BIPV design are being currently conducted in these countries.

BIPV could help in avoiding the aesthetical problems by being an integrated part of the building envelope as any other regular building component. The needed BIPV area can also expand to cover most of the envelope and generate the required energy. Being part of the building envelope and replacing some of its conventional components, a BIPV system will not relatively have a significant extra cost to the existing structure, and these components may also provide other functions to the building, such as shading, cladding, and insulation, in addition to being energy converters.

There are several types of integration but we can generally classify them in two categories: roof integration, and façade integration. The integration in the building façade should be prioritized particularly because of the available exposed area to the solar radiations which is usually larger than the roof. And the vertical mounting of collectors in mid-latitudes helps preventing overheating risks in summer, and thus a better performance of the system. This can be explained by a better distribution of the solar radiation over the year in comparison to solar radiation on tilted collectors (Fig.1).

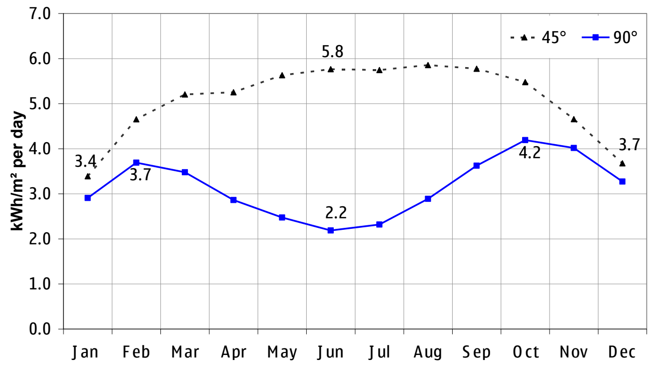


Fig. 1. Yearly Distribution of the Average Daily Irradiation on Vertical versus 45° Tilted Area in Beirut (33.9° lat.)

The adoption of BIPV in buildings varies significantly from country to another due to many factors: built environment, electricity infrastructure, regional and governmental policies, consumer demand, tariff scheme for grid connected BIPV systems, and the climate. This paper tries to investigate the technical feasibility of this integration in Mediterranean climate. For this purpose, a simulation tool is used to calculate the energy performance of a small scale PV system embedded in a public commercial building for different integration strategies and several Mediterranean climates. A comparative study will help decision makers (architects and building owners) in understanding better the behavior and the productivity of this system and will make it easier for them to accept and adopt BIPV in their projects.

2. Literature Review on BIPV

BIPV are photovoltaic materials replacing usual building materials by their integration to different parts of the building envelope (roof, skylights, or facades) [2] and thus reducing the heat transmission through it [3]. The different configurations of BIPV include BIPV roofing consisting of incorporating solar cells into roof elements (tiles, metal...), Glass based BIPV (semi-transparent glazing, sunspaces…), BIPV incorporated to Curtain walls, facades and many other methods of implementation [4].

The BIPV cells are classified as silicon based solar modules and non-silicon based. Silicon-based modules are the most commonly used in the Mediterranean solar market. They consist of 3 types; mono-crystalline, polycrystalline and amorphous. The mono-crystalline modules are normally of a black or gray colour and have the highest efficiency, but also high prices. The polycrystalline modules have a blue colour deriving from small crystals and are cheaper but yield lower efficiencies. The amorphous cells (known also as thin-film cells) have a reddish brown colour and consist of an extremely thin layer of silicon that is un-crystallized and placed on a substrate. The non-silicon based solar modules are either Cadmium Telluride (CdTe) or Copper Indium Gallium Selenide (CIGS), which are classified under the thin-films category. Recently, BIPV technology is widely implemented to the new and retrofitted building construction constituting one of the primary sources of electricity. For instance, a BIPV system is able to decrease the cooling load and electric consumption of a building by 33–50% [5]. In addition to be clean, available, safe and renewable from solar energy [2], one of the main advantages of the BIPV technique is the reduction of the primary cost of the construction material which quantity is significantly reduced due to integration of the PV material in it [6]. Furthermore, the BIPV technology is more economic than the PV one as it requires less space and electric cables [2] hence decreasing transmission and distribution losses [4]. BIPV is a multi-functional strategy including thermal insulation, shading, electricity generation, and contributing to innovations in the architectural design [4-7].

Different parameters should be taken into consideration for the proper function of the BIPV cells. A primary factor affecting the BIPV effectiveness is the temperature of the PV cells [8-9] which depends on the thermal characteristics of the material composing the PV cells, their type, their mode of encapsulation and installation, in addition to the weather conditions [10-11]. The operating temperature of the PV cells should be controlled to avoid the deterioration of performance resulting from exceed of temperature [8]. One proposed method to avoid excessive heating temperatures from unabsorbed irradiations is to implement a ventilation method through forced or natural convection along the PV panels. Different models have been studied to predict the temperature at the panels at a precision of 50% [12]. On the other hand, the orientation of the PV cells largely affects their performance influencing the incident solar radiation and thus their electrical power output. Yang et al developed a mathematical model to optimize the tilt and azimuth angles as a function of Hong Kong weather conditions in order to increase the efficiency of the installed system [13].

Planning to install a PV panel as part of a BIPV project includes study and optimization of the parameters mentioned above. Implementation of the project in a certain urban or rural location requires a sensitivity analysis study along with its validation. Thus Cheng et al. [14] have studied the parameters affecting performance of the panels using the program PVsyst in 20 different locations all situated in the northern hemisphere. Along with this simulation program the authors compared the irradiation values to NASA Surface Meteorology and solar energy database, the Solar Energy database of University of Massachusetts and the Taiwan Central Weather Bureau. The values were parallel and with little differences between the simulator and the data collected from three separate databases. To calculate the optimal tilt angle, the simulations for the 20 different sites was repeated at each 10 degrees. The following variables were used in the simulation an area of one square meter, a module type of a standard 180 Watts, the façade was chosen as the mounting disposition, a southern orientation, a mono-crystalline technology and a ventilated property. The optimal tilt angle was concluded to be equal to the latitude angle specific for each site studied. It was mentioned that in the 20 sites the simulator was able to obtain almost 98.61% of the PV performance.

3. Simulation of Integration Strategies

3.1. Building Description

An existing office building located in Beirut (latitude angle of 34° north) was selected for the simulations to study the performance of BIPV systems in the Mediterranean region. The building has an area of 2000 m^2 and is characterized by a special circular architectural south-oriented glazed façade (see Fig. 2). The windows are double pane and the external walls and floors are made of concrete, masonry and steel. The total yearly energy consumption of the building is around 1460 MWh and it has an existing PV plant installed on the roof. The objective is to expand the existing conventional PV system by a complementary BIPV system.

Fig. 2. South-façade of the building.

3.2. Integration Strategies

Several scenarios were considered, roof mounted, replacing the glazing, or even replacing the existing steel overhangs used for shading (see Fig. 3). These entire scenarios were studied in the simulation phase to decide on the best integration strategy regarding the energy performance and the aesthetics of the solution.

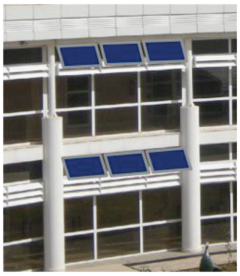


Fig. 3. One of the integration scenarios: Substituting the overhangs by BIPV.

3.3. Simulation Software

PVsyst is a simulation program developed by the University of EPFL in Switzerland, providing options for various design permutations for the consumption of solar energy. As part of this study a grid-connected BIPV was modeled. This design is preferred to that of off-grid BIPV since it will have better economical and environmental impacts by avoiding the use of storage batteries.

4. Discussion of Results

Simulations were carried out for a system of 17.6 kW_p due to area constraints for a yearly period, and several parameters were manipulated in the simulation software, providing options for various design permutations to reach the best integration option.

4.1. Tilt Angle

Knowing that the plane tilt angle of the photovoltaic panels is of high importance, iterations covering different tilt angles of the panels' plane were implemented for a range of 0 to 90 degrees with increments of 10 degrees. Standard polycrystalline cells and the climate of Beirut city were selected. The results obtained are shown in Fig. 4.

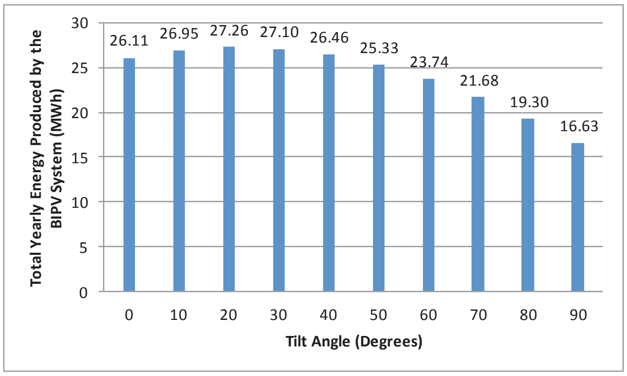


Fig. 4. One of the integration scenarios: Substituting the overhangs by BIPV.

The results show that the best tilt angle must be between 20 and 30 degrees with an energy production of more than 27 MWh per year. Therefore the vertical mounted BIPV glazing solution, in addition to being the most expensive, will be neglected since it will produce only 61% of the optimum energy production possible.

4.2. Type of Cells

Three types of cells to be used in the integration solution were evaluated: Monocrystalline, polycrystalline, and amorphous thin-films were compared. Following the building special form, the BIPV plant was distributed to cover three orientations (South, East and West). The tilt angle was fixed to 30 degrees, and an energy production 27 MWh per year was set as a target. The results of simulations show that the total area required in the building will change from 111 m^2 if the monocrystalline cells are used, to 176 m^2 if the thin-films technology is adopted.

Table 1. The results of simulations according to cell type.

Type of Cells	Area Required for South Oriented PV (m^2)	Area Required for East Oriented PV (m^2)	Area Required for West Oriented PV (m^2)	Total Area Required for the Building (m^2)
Mono-Si	55	28	28	111
Poly-Si	59	29	29	117
Thin-Films	88	44	44	176

This means that for the last technology, the needed area will be larger by 50%, a luxury that cannot always be available in buildings (see Fig. 5)

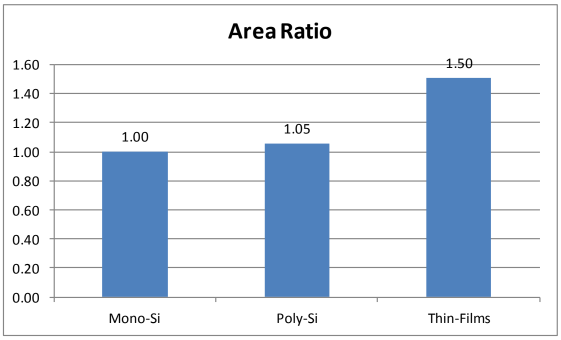


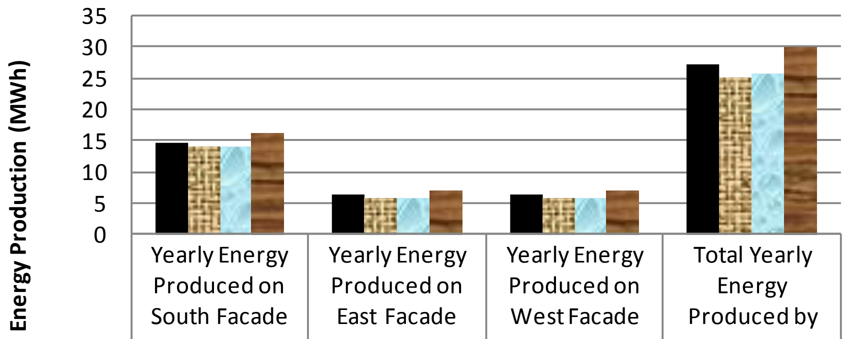
Fig. 5. PV Area ratio compared to the benchmark of using Mono-Si.

The area ratios for the monocrystalline and polycrystalline are relatively the same (only 5% more area will be needed in the case of poly-Si). Since the average cost of the polycrystalline is cheaper than the monocrystalline technology, it would be logical to consider the Poly-Si as the most convenient solution for the integration in the building.

4.3. Climate

To study the impact of different Mediterranean climates on the performance of the solar system, it was assumed that the selected building has been located in three other representative Mediterranean cities: Rome (Latitude 41.90 N), Barcelona (Latitude 30.05 N) and Cairo (Latitude 41.38 N). The polycrystalline technology is chosen, the tilt angle is considered to be 30 degrees, and the PV is integrated as overhangs in the façade of the building. The results show that the energy productions ranges between 25 and 30 MWh for all selected regions, with a variation of the order of

19 % with is considered to be an acceptable range since it will be very easy to compensate for the losses (such as in the case of Rome) by increasing slightly the covered PV area to reach the same energy production.



	Yearly Energy Produced on South Facade (MWh)	Yearly Energy Produced on East Facade (MWh)	Yearly Energy Produced on West Facade (MWh)	Total Yearly Energy Produced by BIPV (MWh)
Beirut	14.615	6.227	6.256	27.098
Rome	13.903	5.648	5.656	25.207
Barcelona	14.152	5.721	5.731	25.604
Cairo	16.109	6.981	6.981	30.071

Fig. 6. Energy produced by BIPV as overhangs in several Mediterranean cities.

5. Conclusion

A literature review on BIPV system was conducted to identify the different techniques and strategies that can be used today on buildings located in the Mediterranean region. A sensitivity analysis was conducted in order to determine the optimal design of the BIPV system for an office building. Different configurations were considered and analyzed based on various tilt angles, cell types and Mediterranean climates. Energy production, architectonic integration and space limitation were the criteria used for the proper selection of the proper BIPV system. It was found that BIPV systems can produce an adequate amount of energy while being at the same time part of the building envelope. These integrated elements can also work as regular building components, ensuring the other functions of shading, waterproofing and insulation. The BIPV on commercial buildings, mostly occupied during the day, can contribute directly to the building occupants' electricity demand while also avoiding transmission and distribution losses and reducing capital and maintenance costs for utilities. Integrating the photovoltaic power system into the architectural design, however, offers more than cost benefits. It also allows the designers to create environmentally sound and energy efficient buildings, without sacrificing comfort, aesthetics or economy, and offers a new and versatile building material.

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