PERFORMANCE OF OFFICE BUILDING INTEGRATED PHOTOVOLTAIC FOR WINDOWS UNDER SEMI-ARID CLIMATE IN ALGERIA

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DEDECATION

To my beloved parents, wife, my daughter Leen, sisters and friends

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ABSTRACT

Building integrated photovoltaic (BIPV) has become the most significant alternative form of renewable energy for producing clean energy and to protect the environment. In Algeria, some problems arise due to the high energy consumption levels of building sector. Large amounts of this energy are lost through the external envelope façade, because of poor window design. Therefore, this research aimed to investigate the optimum BIPV windows performance for overall energy consumption (OEC) in typical office buildings in the semi-arid climate. Field measurements on a tested office building were carried out during the spring and summer seasons for the calibration and validation of Energy-plus and Integrated Environment Solution Virtual Environment (IES-VE) software. The data was analysed and used to develop a model for (OEC) simulation. The results of the investigation from the site measurements show that the BIPV window application provides a sufficient quantity of uniform daylight with only 20% Visible Light Transmittance (VLT), plus a comfortable indoor temperature and a considerable amount of clean energy production. The base-model and nine commercially-available BIPV modules, with different Window Wall Ratio (WWR), cardinal orientation and tilt angles were applied in an extensive simulation exercise. The simulation was carried out using Energy-plus to evaluate the energy generated through simple and equivalent one-diode models. The thermal performance used the Ideal load Air System (ILAS) model. In addition to IES-VE for the assessment of visual comfort and daylighting performance, through a combination of daylight control method, Useful Daylight Illuminance (UDI) and CEI glare index (CGI) were done. The results from this study revealed that the optimum BIPV window design differentiates in each orientation; which is the double glazing PV modules (A) with medium WWR and 20% VLT in the Southern facade, 30% VLT toward the East-West axis. Meanwhile, the North orientation is not suitable the application of BIPV window. The Maximum energy saving can be obtained with a 60% toward the South orientation by double glazing PV module (D). On the other hand, the PV modules minimize significantly the glare index comparing the base-model. The result established that the energy output percentages in a 3D model can be used by architects and designers in the early stages of design. Thus, the adoption of optimum BIPV window shows a significant improvement of the overall energy saving and visual comfort to deem them as an essential application in the semi-arid climate.

ABSTRAK

Bangunan Fotovoltaik bersepadu (BIPV) telah menjadi alternatif yang paling penting untuk tenaga boleh diperbaharui bagi menghasilkan tenaga bersih dan juga untuk melindungi alam sekitar. Di Algeria, beberapa masalah timbul disebabkan tahap penggunaan tenaga tinggi sektor bangunan. Sejumlah besar tenaga ini hilang melalui permukaan luar bangunan disebabkan oleh reka bentuk tingkap yang lemah. Oleh itu, kajian ini bertujuan untuk mengkaji prestasi tingkap BIPV yang optimum untuk penggunaan tenaga keseluruhan (OEC) di bangunan pejabat biasa di bawah iklim separa gersang. Ukuran lapangan bagi pejabat yang diuji telah dilakukan pada musim bunga dan musim panas untuk tujuan kalibrasi dan validasi perisian *Energy-plus* dan *Integrated Environment Solution Virtual Environment (IES-VE)*. Data telah dianalisis dan digunakan untuk membangunkan model untuk simulasi (OEC). Keputusan kajian dari pengukuran di tapak menunjukkan bahawa aplikasi tetingkap BIPV menyediakan kuantiti yang mencukupi dan pencahayaan siang seragam, dengan hanya 20%, Transmisi Cahaya Boleh Dilihat (VLT) ditambah dengan suhu dalaman yang selesa dan pengeluaran tenaga bersih yang banyak. Model asas dan sembilan modul BIPV yang tersedia secara komersial, dengan Nisbah Dinding Tingkap (WWR) yang berbeza, orientasi kardinal dan sudut condong digunakan untuk latihan simulasi yang menyeluruh. Simulasi dijalankan menggunakan *Energy-plus* untuk menilai tenaga melalui model satu-diod yang sederhana, bersamaan dengan prestasi terma menggunakan model Sistem Udara Beban Ideal (ILAS). Sebagai tambahan kepada Persekitaran Maya Penyelesaian Alam Sekitar Bersepadu (IES-VE) untuk penilaian keselesaan visual dan pencahayaan siang hari, melalui gabungan kaedah kawalan siang hari, pencahayaan siang hari yang berguna (UDI) dan CEI indeks silau (CGI), dilaksanakan daripada kajian ini mendedahkan bahawa Reka bentuk tetingkap BIPV optimum dibezakan mengikut, setiap orientasi; yang merupakan modul PV kaca berganda (A) dengan WWR sederhana dan 20% di permukaan Selatan, 30% VLT ke arah paksi Timur-Barat. Sementara itu, orientasi Utara tidak sesuai untuk penggunaan tetingkap BIPV. Penjimatan tenaga maksimum sehingga 60% bagi orientasi Selatan menggunakan PV kaca berganda (D). Modul PV meminimumkan secara ketara indeks silau berbanding dengan model asas. Hasil kajian telah menetapkan bahawa peratusan penghasilan tenaga dalam model 3D boleh digunakan oleh arkitek dan pereka pada peringkat awal rekabentuk. Justeru, penggunaan tetingkap BIPV yang optimum menunjukkan penambahbaikan yang ketara terhadap penjimatan tenaga dan keselesaan visual secara keseluruhan dan ia boleh dianggap sebagai aplikasi penting di kawasan iklim separa gersang.

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LIST OF ABBREVIATIONS

BIPV	-	Building Integrated Photovoltaic
BAPV	-	Building Added Photovoltaic
IEA	-	International Energy Agency
APRUE	-	Agency for the Promotion and Rational Use of Energy
CREDEG	-	Electricity & Gas R&D Center
UDTS	-	Unit for the development of silicium technology
CDER	-	Centre for Renewable Energy Development
UDES	-	Unit for Developing Solar Equipment
NEAL	-	New Energy Algeria Company Specialized in Development of Renewable Energy
OEC	-	Overall Energy Consumption
STC	-	Standard Test Condition
UDI	-	Useful Daylight Illuminance
DA	-	Daylight Autonomy
Lux	-	Unit of illuminance
CEI	-	Commission International d'eclairage
W	-	Watt
kWh	-	Kilo-watt Hour
IES-VE	-	Integrated Environment Solution Virtual Environment
FC	-	Foot-Candle
Ei	-	Exterior illuminance
ii	-	interior illuminance
m	-	meter
ɳ	-	Efficiency of Module
Pmax	-	Max power
Vpm	-	Max power Voltage
Ipm	-	Max power Current
WWR	-	Windows Wall Ratio
WPI	-	Work Plane Illuminance
DF	-	Daylight Factor
VLT	-	Visible Light Transmittance
SHGC	-	Solar Heat Gain Coefficient
N	-	North
S	-	South
E	-	East
W	-	West
S-E	-	South-east
S-W	-	South-west
N-E	-	North-east
N-W	-	North-west
MBE	-	Mean Bias Error
CVRMSE	-	Coefficient Variation of Root Means Square Error
GHI	-	Global Horizontal Irradiance

DHI	-	Direct Horizontal Irradiance
CGI	-	CEI Glare Index
GVCP	-	Guth Visual comfort possibility
DGI	-	Daylight Glare Index
URG	-	Unified Glare index
DGP	-	Daylight Glare Index
CdTe	-	Cadmium Telluride
Mu-Si	-	Micro-morph Silicon
a-Si	-	Amorphous silicon
CIGS	-	Copper Indium gallium diselendide
OPV	-	Organic Photovoltaic
DSSCs	-	Dye sensitised solar cells
m-Si	-	Mono-crystalline
STPV	-	Semi-transparent Photovoltaic
PV-IGU	-	Photovoltaic insulated glass unit
PV-DFS	-	Photovoltaic Double skin facade
NEB	-	Net Electricity Benefit
ZEB	-	Zero Energy Building

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CHAPTER 1

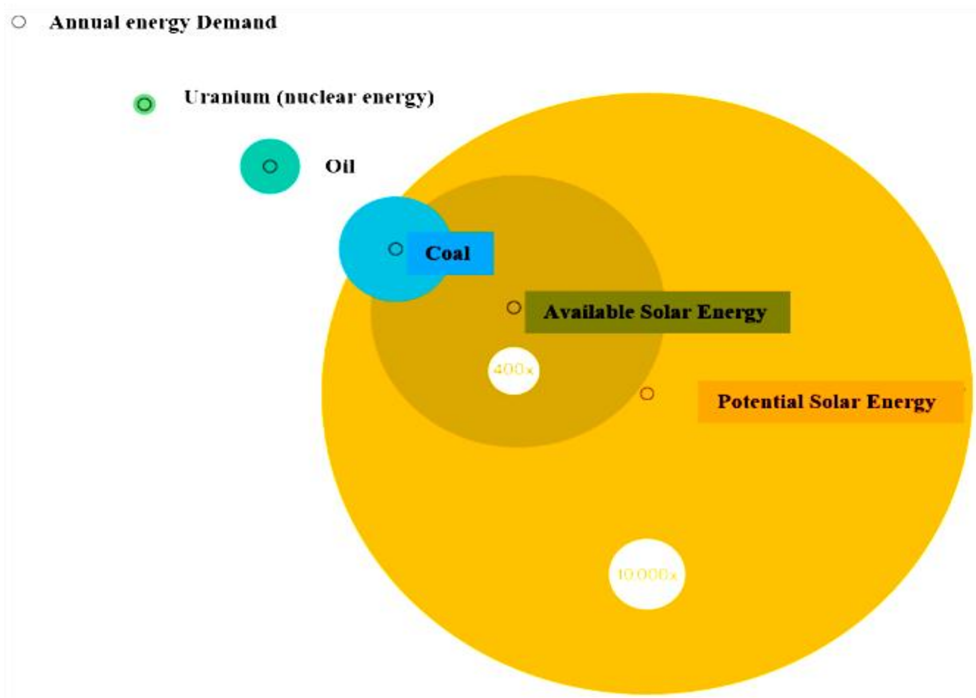
INTRODUCTION

1.1 Background

Sustainable developments in the field of architecture are turning out to be increasingly vital which requires the utilization of renewable energy and the reduction of energy consumption. The effect of global warming is the result of pollutant emissions from both traditional and conventional energy resources which takes account of the reduction of fossil fuel, intensification of oil consumption and the increment in the energy demand (Stoppato, 2008). These concerns have led to the emergence of significant development of renewable energy industries. Several studies show that this new sector played a vital role and many countries such as Algeria have taken measures to ensure sustainability of the utilization of global alternative energy resources (Hui, 1997; A Boudghene Stambouli, Khiat, Flazi, & Kitamura, 2012).

According to International Energy Agency (IEA) world council, solar energy is natural and a clean energy source as the current availability of the energy surpasses the annual energy demand by 400 times, whereas its potential surpasses the demand by 10,000 times. The sun will provide roughly limitless energy for the next 4-5 billion years (IEA, 2013) as shown in the Figure1.1. Hepbasli (2008) stated that solar energy resource such as photovoltaic is commonly used along with the leading technologies such as geothermal, biomass and hydroelectric energy. According to the Renewable Energy Policy Network for the 21st Century (REN21), there has been a noticeable growth by 55% in the utilization of photovoltaic (PV) as it is considered to be the most substantial energy resources available. In addition, study by Zahedi (2006) found that it is expected that solar PV electric's capacity worldwide shown to incline tremendously by 2030 from 1,000 MW in 2000 to 140,000 MW. By 2040, the renewable electric energy may possibly become adequate to support the base load and half of the global electricity energy demand claimed by the European Renewable Energy Council (Teske, Zervos, & Schäfer, 2007). Further, studies shows that the amount of solar electricity produced surpasses the global need as projected by the solar pyramid in the case of the Algerian Sahara with 50% of the space, 10% of the system energy efficiency and 14% PV module coverage (A Boudghene Stambouli et al., 2012).

Figure 1.1: : The amount of solar energy could be exploited, source: (IEA, 2013)



In this decade, the ability to fully utilize renewable energy innovation in building as well as environmental sustainability is the main topic for human societies around the planet. Many researchers such as (Huijts, Molin, & Steg, 2012; Rogers, Simmons, Convery, & Weatherall, 2008; Vlek & Steg, 2007; Wüstenhagen, Wolsink, & Bürer, 2007) stated that quality is taken into account of all countries in short and long term of natural resources, sustainable development and in addition to the technology used to designate economic, social, and environmental dimensions of our upcoming survival. According to Intissar Fakir (2016), low oil prices affects immensely on Algeria's finances and energy use leaving the economy at struggle in 2016. Alternatively, Algeria is interested to supplant fossil fuels and natural Gas with renewable energy resources. However, , it is a challenge for the government to promote renewable energy to minimize the utilization of energy in buildings as it is a new sector in the country (Himri, Malik, Stambouli, Himri, & Draoui, 2009; A Boudghene Stambouli et al., 2012).

Across all nations, the sector of energy consumption in buildings alone consumes around 20% to 60% of the overall account that is used by all sectors, and an average of about 31% worldwide. Algeria, a standout amongst the most nations on the planet's energy utilization assessed 42% more than the average by more than 10% as shown in the figure 1.2. However, according to latest statistic of the Algerian agency for the promotion and rational use of energy (APRUE) in 2015, this percentage varies from zone to others, the Zone 2 and 7 represent the context of this study (Semi-arid climate) include Tebessa city. Subsequently, Figure 1.3 shows the final energy consumption by 35% in transport sector, 16% industrial sector, 6% agricultural sector and 45% residential & office building sector as shown in Figure.1.3. The utilization creates 25% of the national CO_2 outflow as these measurements are liable to ascend over the later because of the developing interest for convenience in building sector (Sotehi, Chaker, Benamra, & Ramoul, 2015b). This major consumption level warrants a point by point comprehension of the building sector's consumption elements to formulate and guide the sector's energy consumption in the attainment to stimulate efficiency, conservation, technology implementation and energy source substituting such as to on-site renewable energy.

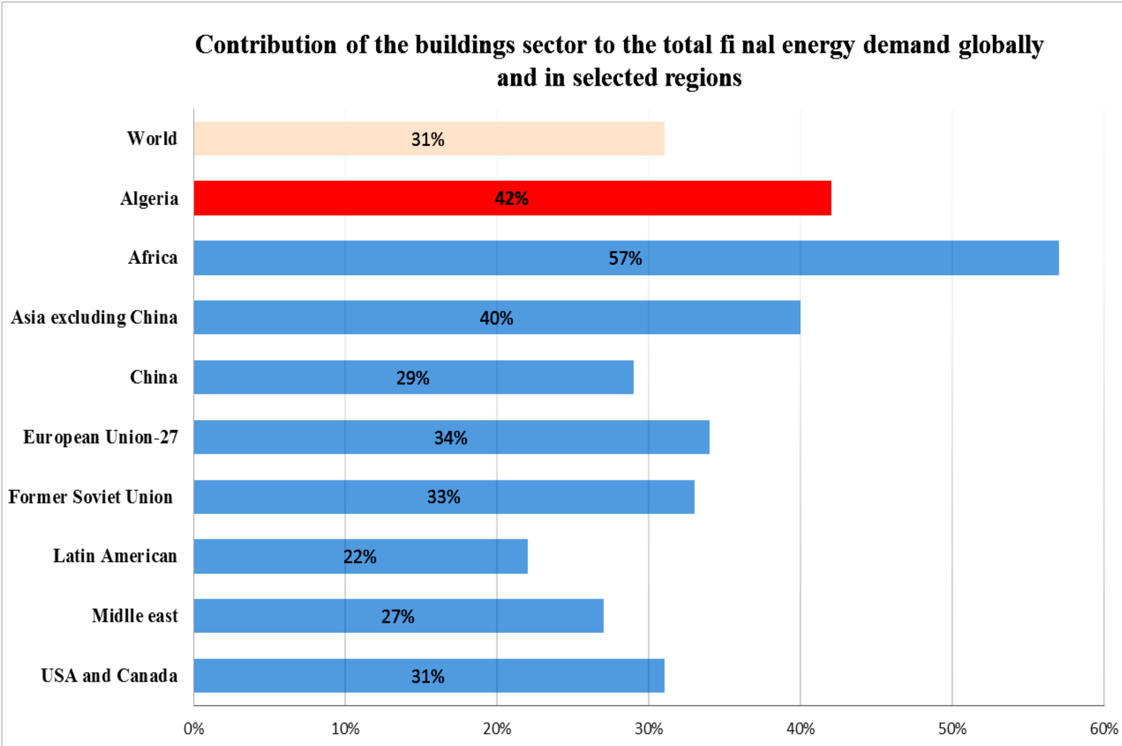


Figure 1.2: The average of building's energy consumption shown as a percentage of national energy consumption and in relative international form, Source: (IEA online

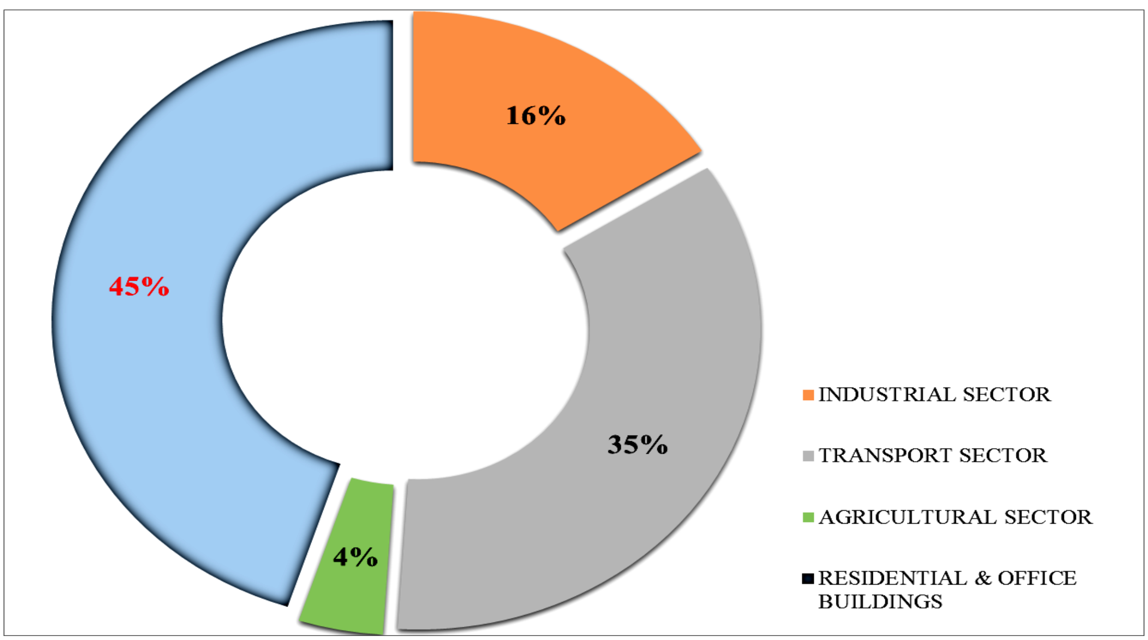


Figure 1.3: Final energy consumption by sector in Algeria -Zone 2. under semi-arid climate, Source: (APRUE, 2015).

The building sector is the largest consumer of energy, with a share of almost 50% of the entire energy consumption for all types of buildings, according to experts at Bayer, the German company that facilitated a meeting on the topic of energy efficiency on 29 May 2012 (the German-Algerian Chamber of Commerce). Approximately, 60% to 80% of this energy is lost. Up to 60% of the energy loss is attributed to air-conditioning and heating acquired through external envelopes (openings, roofs, walls and grounds). This percentage is in line with a recent study carried out by Missoum and Draoui in (2016). According to an APRUE report in 2013, the demand for electricity in Algeria has been increasing at a normal rate of 9.5% over the past five years, with 42% of the energy consumption being accounted for by residential and offices buildings, where 58% of the energy is from gas and 61% from electricity. According to studies by Bélaïd and Abderrahmani in (2013), electricity production is estimated to double in the next decade in order to maintain the economic growth and demographic expansion. On the other hand, a vital portion of the energy consumption in the building sector is marked by a solid annual growth rate of 6.28%, thereby making it necessary to consider energy saving measures (Ferhat & Boutrahi, 2014).

From another perspective, a study showed that there are no building regulations or any recommendations for daylighting and window-to-wall ratios (WWR) for public buildings. Thus, poor window designs and the absence of regulations in Algeria will lead to higher energy consumption (A. Belakehal, 2014). However, electric lighting now makes up 25% of the total energy consumption, making it one of the main consumers of electricity in buildings (Amirat & El Hassar, 2005).

There are concerns about the incorporation of PV on buildings, as the experience of various disadvantages has prevented the building sector from understanding the capability of this advancement in Algeria’s building envelope. The main problems blocking improvements in solar technology have been identified as being in relation to financial issues, the extremely high cost of equipment and the time taken for returns on the capital invested for such innovations. In addition, householders are not interested in enhancing their energy efficiency by installing building-integrated photovoltaics (BIPV) in their homes to keep energy costs low. According to (Maafi, 2000; Semache, Hamidat, & Benchatti), and the APRUE report (2010), PV power is used for rural electrification, pumping, telecommunication repeaters, refrigeration and ventilation. The report published in APRUE (2010) by the European Commission on the 6th framework program on research uncovered the deficiency of the policy regarding building-integrated PVs, while construction grants for both public and private buildings do not include any regulations with regard to the utilization of energy by buildings in this country. The awareness and doubts of households with regard to the installation of photovoltaics in residential buildings also need to be considered. In addition, studies by (Chaurey & Kandpal, 2010; Haw, Sopian, & Sulaiman, 2009) have stated that these are some of the fundamental limitations that need more attention in most countries as with other concerns arising from limitations in the system design (Heinstein, Ballif, & Perret-Aebi, 2013). In particular, these new technologies, such as BIPV systems (Goh, Goh, Yap, Masrom, & Mohamed, 2017; R. J. Yang & Zou, 2016), which can substitute historical building elements and can achieve additional purposes needed for the building's envelope (Maturi, 2013). Lately, it has been popular to produce electrical energy from windows and glass (Li, Lam, Chan, & Mak, 2009). This has been made possible by employing photovoltaic (PV) panels combined within windows. Such technology is created to aid several functions. In addition to the basic task of generating electricity, the multiple-use of BIPV window indicates that it is able to give glare protection and reduce heat gain and loss to save energy (Attoye, Tabet Aoul, & Hassan, 2017). However, there are insufficient researches and analyses in this domain, thereby making the development of this technology an urgent task in Algeria.

1.2 Problem Statement

In Algeria, the energy consumption levels for buildings are very high. A large amount of this energy is lost through the external envelope façade of buildings (claddings, openings), while energy demands for both heating and cooling are high in summer and winter respectively due to the nature of the Algerian climate. Since mid-rise buildings (4-11story) are the dominant typology in Algeria (Senouci et al., 2012), it has been suggested that window glazing should play a significant role as a building material, for which BIPV windows can be an alternative.

It has been noticed that literature exhibited a significant lack of BIPV windows energy support and performance in Algerian building sector (Maafi, 2000; A Boudghene Stambouli et al., 2012). Besides, the integration of BIPV windows into the façade of mid-rise buildings instead of conventional windows is almost non-existent as shown in figure 1.4, even though Algeria has an enormous potential in solar energy in addition to an obvious drop in PV prices in the market over the last few years.

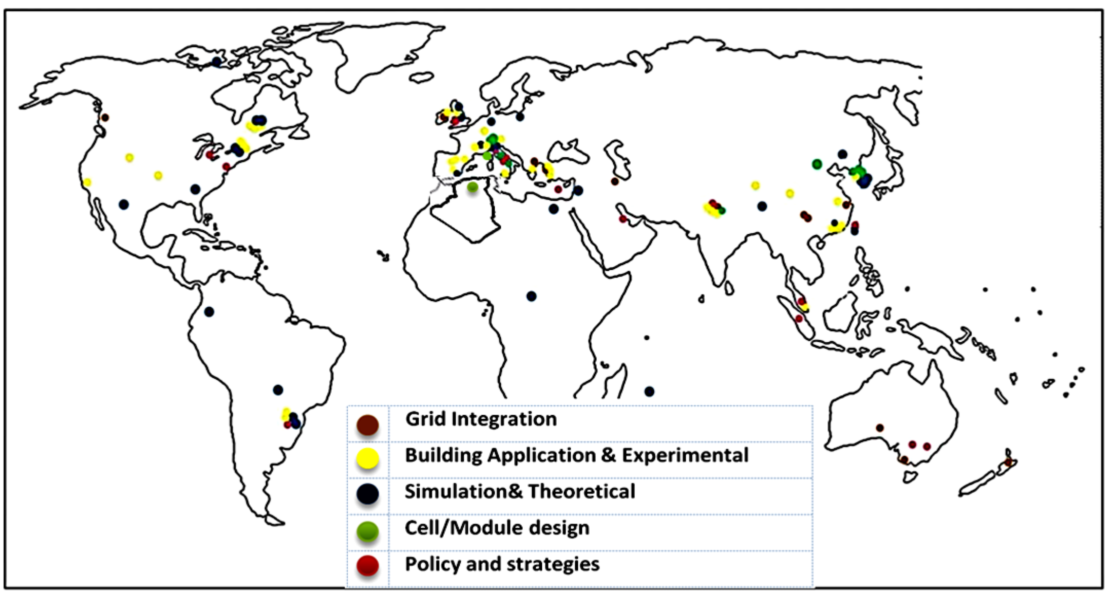


Figure 1.4: The Application of BIPV window technology in the world, Source: (Biyik et al., 2017)

The on-going research into energy consumption in the building sector in Algeria is mainly concentrated on several areas including the output efficiency of PV plants that are connected to an installed grid. This application was implemented on the site of the Centre for Development of Renewable Energy in Bouzaréah (Algiers) (Cherfaa et al.). This technology is considered to be the first of its kind in Algeria. In addition, the research has also been focused on minimising energy consumption by utilizing thermal insulation technology. The most common application is the usage of adobe (mud bricks) building material. Other techniques that have been given extensive importance in researches and practical applications in Algeria are the application of BIPVT systems (Sotehi, Chaker, Benamra, & Ramoul, 2015a) and the manipulation of the orientation of the building or natural ventilation in summer to obtain optimum performance (Hacene & Sari, 2013; Zemmouri & Schiler, 2005).

For all the reasons mentioned above, this research attempted to make use of the enormous solar energy potential of Algeria by utilizing the BIPV windows technology. This aim was accomplished by investigating the optimum performance of BIPV windows as an alternative solution for minimizing energy consumption in the building sector. The outcome of this research, if implemented, will positively impact energy savings for the occupants and beneficiaries of office buildings, as they comprise the most common category of energy consumers.

1.3 Research Gap

Architectural practices in Algeria generally do not keep pace with the use of the aspects of sustainability and technology to reduce energy in the building sector. Based on the literature and the observations of this researcher as an architect, the use of renewable solar energy panels in buildings is limited, except for those installed on the roofs of a few houses. The installation of BIPV windows in the vertical façade of mid-rise buildings is completely scarce even though the use of BIPV windows is linked with the huge vertical façade areas compared to roof areas. The solar radiation supplied by the vertical installations might not be at a maximum, but the energy savings could be compensated by the use of a huge façade such as in mid-rise and high-rise buildings. The majority of the studies that focused on the overall energy performance of BIPV windows targeted the climate of Asian countries, while no study has been performed in countries with a similar climate to Algeria. Consequently, in order to fill the gap, this research targeted the overall energy performance of BIPV windows in relation to the WWR, and the orientation and tilt angles in terms of four factors: visual comfort with energy output, utilization of day lighting, and heat gain and loss to achieve the optimum performance of a BIPV window façade in a semi-arid climate.

1.4 Research Aims

This research was aimed in determining the optimum performance of BIPV windows in a typical office building while maximizing daylighting and minimizing the heat gain/ heat loss into the interior in order to obtain a visually comfortable internal micro climate and energy savings in a semi-arid climate.

1.5 Research Objective

1. To investigate a level of the overall energy (Energy output, Heat gain/loss and Daylighting) of BIPV windows performance of a typical office building under Semi-arid climate in Algeria.
2. To evaluate the performance of different BIPV windows types based on (conversion Efficiency, visible Transparency, Solar Heat gain Coefficient

SHGC and U-value) orientations, Window to Wall Ratio (WWR) for assessment of overall energy use.

   a. To determine the optimum tilt angle design of BIPV window in term of energy output.
   b. To compare the overall energy performance of base-model with different BIPV window modules

3. To recommend an optimum design model of BIPV windows in cardinal orientations to improve energy saving and visual comfort in Algeria.

1.6 Research Questions

After reviewing the past literature, and in line with the above-mentioned objectives, this study will seek answers to the following research questions:

1. What are the influences of applying BIPV windows technology on overall energy performance under a Semi-arid climate of Algeria?
2. Does modifying the configuration of BIPV windows design (Orientations, types of PV, WWR) affect reducing the quantity of energy output?
3. What is the optimum tilt angle to maximise the energy output?
4. What is the optimum WWR and orientation of BIPV windows modules according to Algeria climate in the office buildings in view to optimise day lighting and maximise energy output?
5. Is it possible that the use of BIPV window as an alternative to conventional window could lead to zero energy saving?

1.7 Scope of the Study

The scope of this study covered the following points:

i. Building sector, including residential and public buildings, which is comprised of different activities such as for tourism (hotels, restaurants), education, health, administration, offices (financial institutions and other private services). However, this study focused on office buildings.

ii. Office building structures contain many spaces such as individual or open offices, laboratories, meeting rooms, and conference rooms. An individual office was chosen for this study because it is considered to be the most important element in an office building; however, a computer used as (electrical equipment) always has constant energy consumption for all scenarios.

iii. This study focused on second-generation PV modules (thin film technology) that are available in the market rather than on first-generation modules (silicon wafer-based technology).

iv. Algeria is a large country with four different climatic zones. The overall energy performance analysis of this study was limited to the Haut-plateau region of Algeria, where the majority of the offices are concentrated (the region is located between latitudes 34°-36° and is within a semi-arid climate zone).

v. This study focused on the effect on the overall energy performance of a BIPV window installed on the vertical façade rather than on the roof area of a building mainly because the roof area is relatively small compared to the external façade of a high-rise and mid-rise building. Furthermore, a large portion of the roof area is usually occupied by various building service installations such as water tanks, chillers, cooling towers, a lift machine room, etc.

vi. The EnergyPlus and IES-VE (Integration Environment Solution Virtual Environment) simulation software were chosen from several simulation software, including Design-builder, Ecotec, Velux, and Revit. Energy-Plus was chosen for its ability to simulate the BIPV window application accurately and to provide all the necessary details. At the same time, IES-VE was selected for its many properties and its accurate annual calculation of daylight through the WPI data, useful daylight illuminates and glare index metrics, and diminished light control (IES, 1993; IES-VE. 2006;(CF Reinhart & Breton, 2009).

1.8 Significance of the Research

There is no specific design of BIPV window in Algerian office buildings in relation to its orientation, sunlight permissible in office, and visual comfort of occupant through regulations to achieve the maximum energy saving and environmental needs. The Authorities of Algeria has not put in place a proper design procedure for office building energy consumption and visual comfort for users. Therefore, this research aims to generate significant information to serve as a platform for overall energy performance requirements for office building design. Subsequently, the requirements would form a basis for future overall energy and visual comfort recommendations for Algerian office building design.

1.9 Organisation of Thesis

Chapter Two reviews the state-of-the-art BIPV technology in the world and, particularly, in Algeria. This is followed by an explanation on the concept of the BIPV window and its classification and design. Furthermore, this chapter presents the electrical, climatic and architectural factors that influence the performance of the BIPV window technology. In addition, it reviews the experimental applications and heat transfer model of the BIPV window. It also provides an explanation of the visual comfort in offices and the metrics used to evaluate the quantity and quality of day lighting using the BIPV window. Furthermore, this chapter presents the performance of the BIPV window within an office building. It concludes with an examination of the relevant researches on this topic.

Chapter Three explains the research methodology, which is a combination of two methods. The first consists of a site visitation and experimental measurements in a selected Algerian office building, followed by computer simulations using EnergyPlus and IES-VE Integrated Environment Solution Virtual Environment.

Chapter Four presents the results of the field measurements in a tested office in Tebessa during critical time periods, and compares these results with the international standard. This chapter also presents the results from a simulated overall energy model of a base model and different BIPV window modules in the office in order to determine the maximum energy saved and to meet the criteria of visual comfort.

Chapter Five reviews the research objectives highlighted in Chapter one and examines the impact of the findings revealed through the outlined objectives. The practical implications and recommendations are highlighted, and the limitations of the study are discussed, with suggestions offered for further research.

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