

Enhancing Bifaciality Factor for Building Integrated Bifacial PV in a Double Skin Façade System

تعزيز معامل الإزدواجية للألواح
ثنائية الطور المدمجة في واجهات المباني المزدوجة الطبقات

by

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of the requirements for the degree of
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ABSTRACT

On a global scale the move towards renewable energy is at its highest rates, new technological developments aiming to increase efficiency of energy production and reducing overall cost, making renewables viable on all scales. United Arab Emirates is one of the countries that are pioneering in the area of renewable green energy, with the goal is to increase the contribution of green energy up to 50% by the year 2050 and reduce the carbon footprint by 70 % by increasing consumption efficiency and introducing versatile energy sources that are more sustainable. Considering that the region solar energy provides prospects in terms of energy yields and project scalability. Specially within the building sector, which is an energy demanding sector, lies the opportunity to cover the energy requirements through implementation of localized solar energy generating schemes in the form of standalone PV panels and building integrated photovoltaics. Moreover, applying novel innovations in solar power to maximize energy yields. One of these technologies is bifacial photovoltaic panels, which is a type of PV panels that produce electricity from both sides compared to regular Monofacial PV that utilize the front surface only. Studies shows that bifacial panels produce 25-40% more electricity than Monofacial panels in all installation schemes.

This research examines the application of bifacial PV integrated within building elements, specifically double skin façade, where the Bifacial PV presents the second outer façade in a double skin façade configuration. The study objective is to analyze the bifaciality factor under different façade material and façade gap distances using ray tracing computer simulation software (TracePro). Bifaciality factor is the ratio of irradiance hitting the rear of solar panel to the total irradiance, which is a parameter to evaluate the performance of bifacial PV panels. The optical performance of the façade envelope directly affects the value of bifaciality factor (bifacial back side irradiance to bifacial front side irradiance). Bifaciality factor significantly impacts electrical energy production of bifacial PV cells, and it is the main factor when comparing different bifacial PV technologies.

To answer the question of which façade material provides the highest bifaciality factor, therefore, the highest electrical yields of bifacial BIPV as part of a double skin system, computer simulations for optical performance were analyzed. The simulation matrix applied in this study consists of four façade materials: clear glass, reflective glass, white paint cladding and diffused white paint cladding. Each façade material was simulated for four different gap distance (0.5, 1, 2 and 3 m). The ray tracing simulation applied a solar emulator specifically for Dubai UAE solar profile. Simulation results were provided as Irradiance maps with data like façade incident irradiance, bifacial back surface incident irradiance, bifacial front surface incident irradiance and number of rays exiting each surface. Bifaciality factor was calculated using Excel for all simulation scenarios. The simulation with the highest bifaciality factor is

Scenario No.13, which is the scenario of diffused white paint cladding for a façade gap distance equal to 0.5m. With bifaciality factor of 14.32%, followed by S5, Bifaciality factor of 13.74%, presenting reflective glass façade with 0.5m gap distance. It was noticed that across the same façade material increasing the gap distance reduced the Bifaciality factor, that reduction was the highest between gap distance of 1m and 2m, almost half for all façade materials.

الملخص

التسارع العالمي نحو الطاقة المستدامة من أعلى ما يكون حالياً، التطورات التقنية الحديثة تهدف لزيادة كفاءة إنتاج الطاقة و تخفيض الكلفة الكلية في ان واحد لجعل الطاقة المتجددة الخيار على جميع المقاييس. دولة الامارات العربية المتحدة من أحد الدول الرائدة في مجال الطاقة المستدامة. حيث قامت الدولة بوضع أهداف و مخططات لزيادة إنتاج الطاقة من مصادر مستدامة بنسبة 50% في عام 2050, و العمل على تخفيض أثار الطبعة الكربونية بنسبة 70% من خلال زيادة كفاءة استهلاك الطاقة و اعتماد مصادر متنوعة و نظيفة لإنتاج هذه الطاقة. نظراً لأن المنطقة تمتلك المقومات المناسبة لإنتاج الطاقة الشمسية بكميات عالية و على مختلف أحجام التوسع. خصوصاً في قطاع الأبنية, وهو من أكثر القطاعات استهلاكاً للطاقة الكهربائية. في هذا القطاع فرص لتغطية احتياجات الطاقة من خلال تطبيقات لأنظمة محلية على صعيد المبنى نفسه لإنتاج الطاقة الكهربائية على هيئة ألواح كهروضوئية مستقلة على الأسطح أو ألواح كهروضوئية مدمجة بمكونات المبنى. استخدام الحلول المبتكرة في مجال الألواح الكهروضوئية لزيادة الانتاجية. إحدى الحلول المبتكرة هي الألواح الكهروضوئية ثنائية الطور , تمتلك هذه الألواح المقدرة على إنتاج الكهرباء من الجهة الخلفية و الأمامية في ان واحد, مقارنة بالألواح التقليدية (وحيدة الطور) التي تنتج كهرباء من الوجه الأمامي فقط. تثبت الدراسات بأن الألواح ثنائية الطور تنتج طاقة كهربائية بنسبة 25-40% أكثر من الألواح الكهروضوئية وحيدة الطور تحت ظروف التركيب ذاتها.

يهدف هذا البحث بدراسة الألواح الكهروضوئية ثنائية الطور المدمجة في المبنى كجزء من الواجهات مزدوجة الطبقات, حيث تشكل الألواح الواجهة الخارجية للمبنى. تم تحليل قيم معامل الازدواجية لمختلف المواد التي تشكل الواجهة الداخلية للمبنى, و لمختلف مسافات التجويف بين الواجهتين للمبنى. معامل الازدواجية هو تقييم مباشر لكفاءة هذا النوع من الألواح , هي قيمة تمثل النسبة بين الطاقة الاشعاعية على الجهة الخلفية من الألواح و الطاقة الاشعاعية على الجهة الأمامية من الألواح. تم تطبيق برنامج (تريس برو) في الدراسة وهو برنامج محاكاة تحليل ضوئي لتتبع الأشعة من مصدرها (الشمس) و تحديد الأداء الضوئي على الواجهات و الألواح.

تم تطبيق مصفوفة المحاكاة المؤلفة من أربعة مواد مقترحة للواجهات الداخلية للمبنى (الزجاج الشفاف, الزجاج العاكس, الدهان الأبيض, الدهان الأبيض العاكس). كل واحدة من مواد الواجهات تم تطبيقها مع أربعة مسافات مختلفة للتجويف بين الواجهتين هذه المسافات هي 0.5, 1, 2 و 3 م. تتكون المصفوفة من 16 محاكاة. تم تطبيق محاكاة تتبّع الأشعة بتفعيل المحاكى الشمسي ضمن البرنامج تحديداً لمنطقة دبي – الامارات العربية المتحدة. نتائج المحاكاة من البرنامج على هيئة خرائط اشعاعية تحتوي على معلومات مختلفة مثل قوة الاشعة الواقعة على الواجهة الداخلية , قوة الاشعة على الجهة الأمامية من الألواح الكهروضوئية, قوة الاشعة على الجهة الخلفية من الألواح الكهروضوئية و عدد الاشعة الواقعة و المغادرة من مختلف الأسطح في المحاكاة. تم حساب قيم معامل الازدواجية باستخدام برنامج أكسل لجميع سيناريوهات المحاكاة ثم المقارنة بينهم. بعد المقارنة تبين ان محاكاة رقم 13 انتجت أعلى قيمة لمعامل الازدواجية , هذه المحاكاة مثلت الدهان الأبيض العاكس للواجهة الداخلية على مسافة تجويف 0.5 م. بقيمة معامل الازدواجية 14.32% , تبعثها محاكاة رقم 5 بقيمة 13.74% لمعامل الازدواجية. هذه المحاكاة مثلت واجهة الزجاج العاكس على مسافة تجويف 0.5م. أقل القيم كانت لمحاكاة الزجاج اشفاف للواجهات الداخلية. اضافة الى ذلك, تم ملاحظة ان لجميع المواد المقترحة للواجهات الداخلية, زيادة مسافة التجويف أدت لتقليل قيم معامل الازدواجية, خصوصاً من مسافة تجويف 1م الى مسافة 2م حيث كان الانخفاض بمعدل الازدواجية الأكثر تأثيراً لجميع مواد الواجهات في المحاكاة.

DEDICATION

To the people who supported me through tough times and motivated me to keep going and push through hardships, to my precious family. My husband who is happier than I am with my work, and to the pride I see in his eyes and my daughters' eyes, this is all for you. To my parents, my mother, who is constantly positive and supportive. Her unconditional love kept me going through hard times. My father who always believed in me. A special dedication to my friend and brother Edris, you are my rock. To my special friends, a group of empowered inspiring women that never failed to encourage and motivate me.

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I would like to acknowledge the massive help received from the TracePro technical support engineers, who were patient with me while I learn an entirely new software as complex as TracePro and going out and beyond their scope to assure I reach my objectives.

I thank the British University in Dubai for being my home and a supportive family during my master's studies, I hope this journey will extend and keep going for the PhD with many projects and major milestones on the way.

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CHAPTER 1

INTRODUCTION

1.1 Global Shift to Solar Energy

Humanity's sprint towards energy sufficiency goes back in history to the Stone Age when humans first discovered fire then the use of coal igniting the industrial revolution. However, oil and natural gas fossil fuels were the game changer, igniting the rapid global industrialization and development, as the demand for energy increased so did the population, which meant accelerating energy needs. Current global requirement for electric power reached to 15 thousand terawatts with a forecast of reaching 100 thousand terawatts by the year 2050 that is equivalent to 1000 billion 100W light bulbs. Assuming that all humanity worldwide adopted a sustainable lifestyle and reduced its energy requirements there will still be a need for 30 to 40 terawatts of electric power by year 2050 (IEA 2020). Furthermore, increase in electricity demand is higher for the building sector and expected to spike up further until year 2050 to meet up with industrial consumptions (figure 1.1). Due to population increase and urban migration, global residential electric power demand will double by the year 2050.

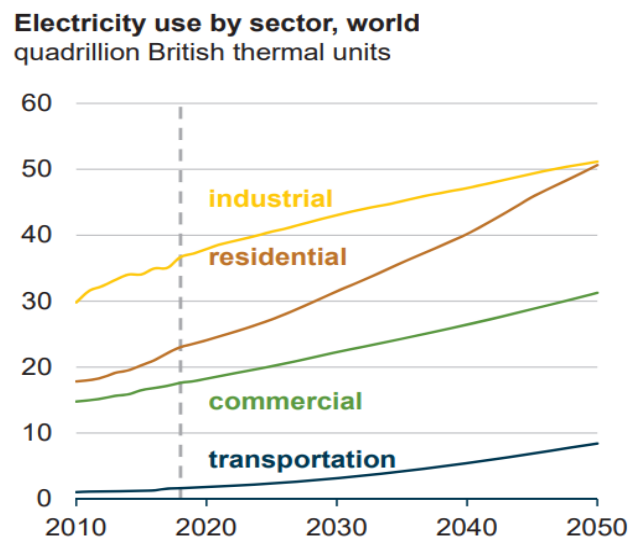


Figure 1.1: Electricity use by sector year 2010-2050 (US.EIA 2019)

Energy requirements need to be covered from sustainable sources for several reasons; firstly, if we maintain current consumption patterns, we will deplete all oil resources within 30 years and natural gas within 40 years and coal in 70 years it will take nature millions of years to regenerate these fossil fuels (Gioietta 2019). Secondly, past energy use practices have led to an environmental crisis, which is global warming. Therefore, the world is demanding change in all human practices towards Earth. Leading with the source of our energy, and drastically

decreasing all greenhouse gases emission before global warming reach to the non-turning point where it will be impossible for Earth to recover. Thus, the search for a clean renewable source of energy picked up the speed, and governments are offering incentives for using renewable energy sources like solar, wind and hydro.

Moreover, investing in renewable energy allows individuals and countries to become energy self-sufficient and enhances energy security. Renewable energy sources are free from political monopolies as they can be produced almost everywhere with no price manipulation, like in the case of fossil fuel. Lastly, investing in renewable energy opens up a whole new market, stimulate the economy and provide job opportunities that otherwise would not exist. Figure 1.2 is a chart of net electricity generation sources for current patterns and future forecast.

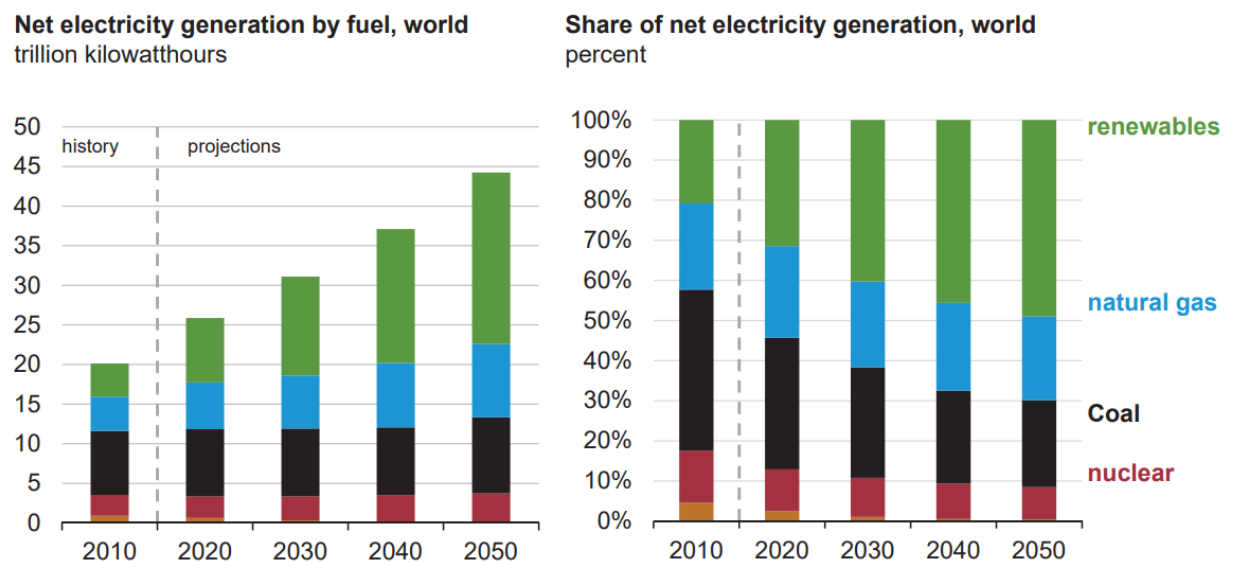


Figure 1.2: World net electricity generation by fuel type (US.EIA 2019)

There is one renewable energy that is available everywhere on Earth, which is solar energy. With 6 kilowatts per meter square electrical capacity, 50 m² of solar panels are enough to cover daily energy needs of 10 typical household (EIA 2019). Solar energy can be scaled up to power plant production capacity and down to domestic demand generation using almost same core technology. Most importantly is that solar energy can provide equality where populations living in far locations with no access to electrical grids enabling them to be self-sufficient and meet their demands with dignity and reasonable costs. All these reasons made solar energy the leading renewable source in terms of technological advancement and price fall rates. Figure 1.3 shows that solar electricity generation will make up third net electricity generation from renewable resources by the year 2050. Ultimately, the reduction in solar power production cost will produce grid parity and even compete grid electricity rates. This is encouraging power

plants to consider solar energy as a source of grid electricity and paving the way for mega solar power plant projects all around the world.

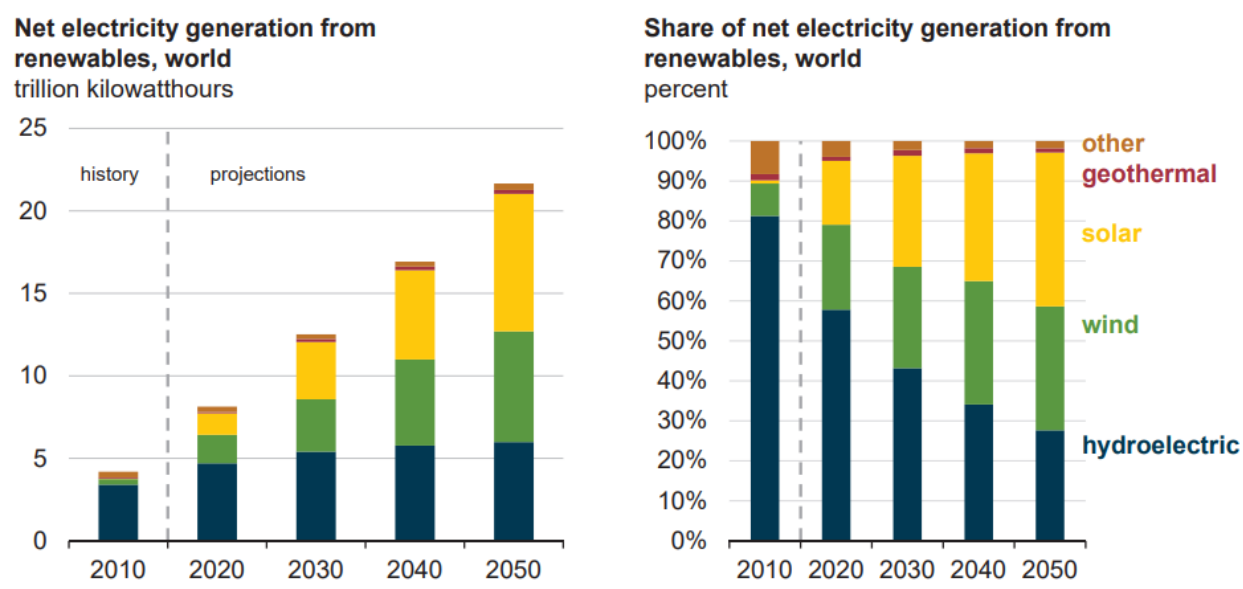


Figure 1.3: World electricity generation shares from renewable resources (US.EIA 2019)

1.2 UAE Solar Agenda

During early 1970s the UAE (United Arab Emirates) upon discovery of oil in the region, the country witnessed a vast and rapid economic growth. It became a hub of commerce, attracted several investors, and opened the market for various industries. This elevated the living standards in the country and led to an energy demanding society. In recent years, the UAE realized that conventional energy resources would not provide a sustainable future and decided to invest in renewable energy resources to reach energy security and diversity. As a country with 350 days of sunlight, over 10 hours per day with direct radiation of 4 to 6 KWh/m²/day (Al-Naser & Al-Naser 2011), solar energy holds dependable opportunities. In 2016, upon signing the Paris Agreement, the UAE vouchsafed a diversification plan and to rise green renewable energy share up to 24% by 2021 and 44% by 2050.

With development focus set on solar energy, large-scale solar power plants lead the UAE solar vision 2020 and 2030. Table 1.1 from the 2019 GCC renewable energy market analysis report by IRENA lists major solar energy projects in UAE. In 2013 Abu Dhabi commissioned 100

MW Shams 1 solar plant, the biggest renewable energy project in the Middle East. Dubai Supreme Council of Energy announcing Mohammad Bin Rashid Al Maktoum solar park with an initial 13MW PV yields capacity planned to reach 1000MW production by year 2030. Masdar City project is another one in a kind project in the region with its own self-sufficient solar powered residents, total of 30 thousand units. Masdar has also signed on a solar desalination plant project to produce 1500 m³/day implementing different technologies like reverse osmosis, membrane based and thermal desalination (Masdar 2013). Furthermore, BIPV around the UAE have reached approximately 10 MW, and is increasing substantially due to facilitating grid connection and metering updated regulations. Shams Dubai achieved a 125 MW of installed capacity in 2019 (MESIA 2020).

Table 1.1: Large-scale solar energy projects in UAE (IRENA 2019)

Country	Project/site	Technology	Size (MW)	Price (US cents/kWh)
 United Arab Emirates (Dubai)	Mohammed bin Rashid Al Maktoum Solar Park, Phase IV	CSP	700	7.3
		Solar PV	250	2.4
	Mohammed bin Rashid Al Maktoum Solar Park, Phase III	Solar PV	600 (of 800)	2.99
			200 (of 800)	
	Mohammed bin Rashid Al Maktoum Solar Park, Phase II	Solar PV	200	5.85
 United Arab Emirates (Abu Dhabi)	Mohammed bin Rashid Al Maktoum Solar Park, Phase I	Solar PV	13	
	Noor Abu Dhabi, Sweihan	Solar PV	1 177	2.42 (non-weighted price of 2.94)
	Shams 1	CSP	100	

1.3 Building Integrated Bifacial Photovoltaics

Bifacial Photovoltaics are able to generate electricity from both sides, unlike Monofacial PV that produce electricity from front side only. This means higher electricity yields for the same area of PV panels. In a recent study by Kopeck & Liable (2021), new bifacial modules produce 30% more than equivalent Monofacial peers. Integrating PV in building elements have many benefits additional to producing electricity, they add to building air-water tightness and structural integrity. functions as traditional finishing materials. Furthermore, employing

vertically mounted solar systems avoids production losses due to dust and debris accumulation consequently increasing energy yields (Jouttijarvi et.al 2022).

Utilizing innovative technologies such as bifacial cells add to the benefits of building integrated PV by increasing the energy production. Bifacial PV can be implemented as many different structural configuration, Figure 1.4 illustrates the applications of regular and semi-transparent bifacial panels in different inclinations including vertical applications. In this study configuration (f) double skin façade is the examined scheme for bifacial PV building integrated system.

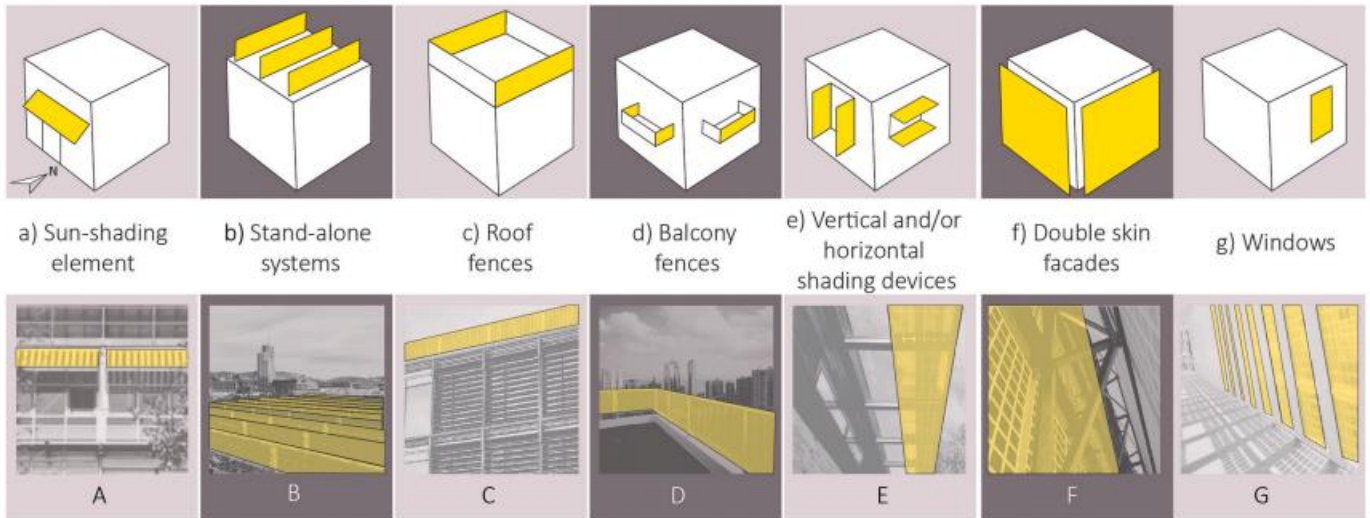


Figure 1.4: Several building integration schemes of bifacial PV (Jouttijarvi et.al 2022)

Building integrated PV double skin facade is comparable to a typical double skin facade, be defined by an outer façade, an inner façade with an air cavity between the two facades with ventilation openings. The semi-transparent PV panel acts as the external window glazing on the outer facade, while the inner façade is composed of different envelope layers. The outer part of the BIPV double skin facade acts like a barrier against outdoor environments, while the gap between aids ventilation in the air cavity due to the stack effect (Yang et.al 2021). Moreover, the energy production generated by PV panel promotes energy sufficient buildings.

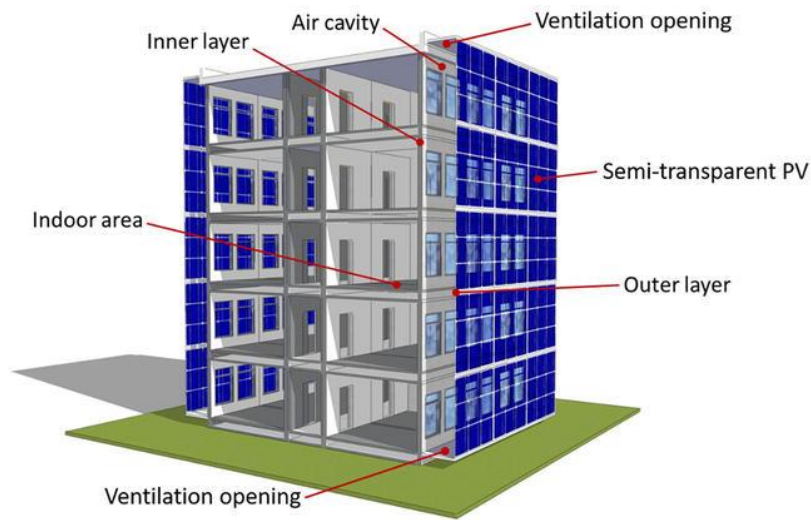


Figure 1.5: Schematics of a BIPV Double Skin façade (Yang et.al 2021)

1.4 Research Rationale

Bifacial photovoltaic cell converts direct light radiance falling directly and indirectly on the front side. Simultaneously, the rear surface will capture reflected light from ambient surfaces to produce electricity. For crystalline silicon cells, the bifacial type produces additional 5 to 20 % electricity compared to Monofacial cells depending on structural details and ambient optical environment (Lim Cha et.al 2018). Increasing yields with the same area makes bifacial panels a logical choice for building integrated PV (BIPV). The vertical installation of BIPV have benefits in reducing problems of dust, snow, and other debris, however, creates a less optimal inclination (Soria et.al 2016).

BIPV can be designed in many configuration such as shading elements, curtain walls or double facades. Figure 1.6 display different applications of building integrated bifacial PV panels.

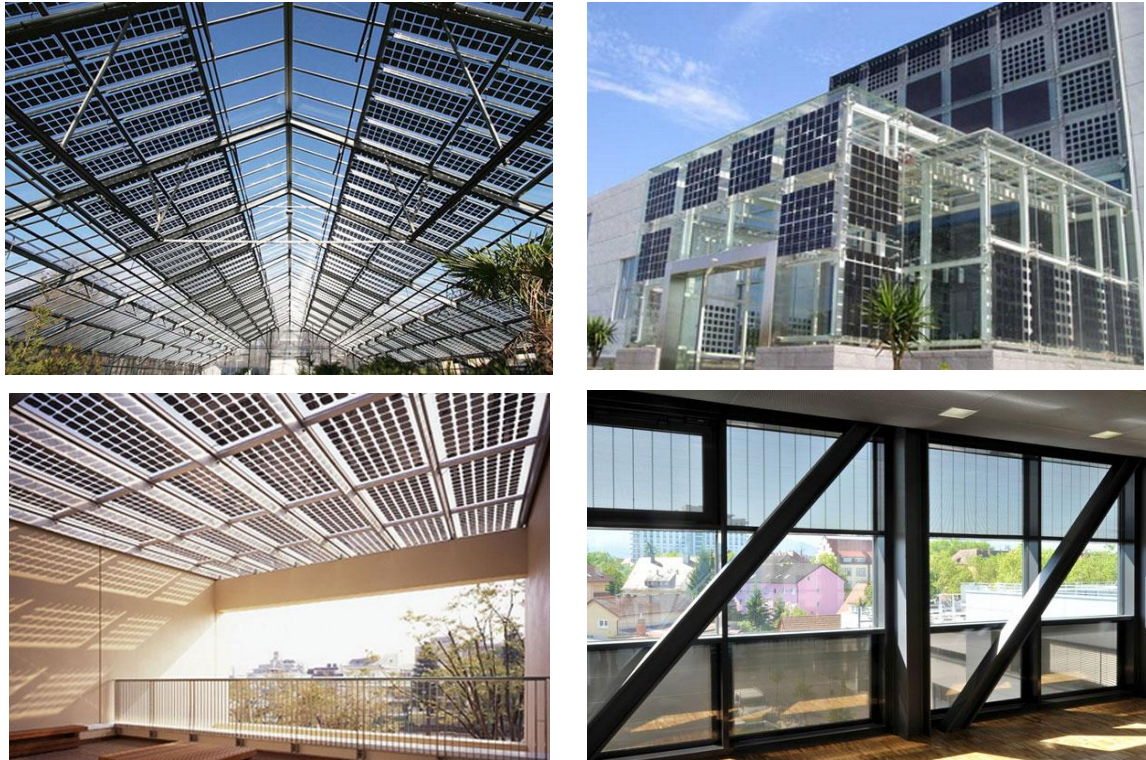


Figure 1.6: Different building integrated schemes for Bifacial PV panels (Kopeck & Libal 2021)

As solar energy is becoming more popular and feasible, all research work is heading for optimizing electrical production and utilizing different technologies of Photovoltaics. One of the technologies that are showing great promise is Bifacial PV panels with expectation to make 40% of the solar market by year 2028 (ITRPV 2018). The literature related to this topic is picking up momentum to cover all aspects of optimization and modularization for all applications of bifacial Photovoltaics technology. The key element in bifacial PV is that the rear side efficiency depends on reflectivity of material facing the rear side, ground, or walls behind the bifacial panel. Objective of this dissertation is to analyse the effect of different material for the façade standing on the rear side of bifacial panels that are acting as the skin of the building. The study simulates the optical performance of light hitting these surfaces and its effect on the bifaciality factor for the BIPV.

Integrating bifacial PV within building façade increase number of variables and raise many questions about effect of mounting configurations and background material on the rear side of the Bifacial PV panels. This study focuses on possible configurations in buildings facades (detailed in chapter three) and provide an analytical comparison between these configurations optical performance based on computer simulation. Consequently, calculating bifaciality factor which is the ratio of back side irradiance to front side irradiance to calculate electricity yields and assessing which is the optimal façade configuration for bifacial BIPV in Dubai UAE.

1.5 Dissertation outline

The dissertation consists of the following eight chapters:

Chapter 1; Introduction

This chapter provides an insight on the reason behind the world's shift towards solar energy and UAE as a country located in the Sunbelt region adopted solar energy as the major renewable source of energy with mega projects and its 2030 and 2050 plan to be the region leading country in solar energy production. In this chapter, a general review into building integrated photovoltaics and its significant role in reducing electrical power consumption by the building sector.

Chapter 2; Literature Review

A detailed review on the technology of photovoltaics in general and bifacial photovoltaics in specific as examined in available published literature. The history of the technology up to current date and the science basis with an explanatory comparison between Monofacial and bifacial photovoltaic cells anatomy, design and encapsulation. This chapter details the mathematical analysis of bifacial PV cells efficiencies and limitations calculations. Moreover, the optical and electrical mathematical modeling of bifacial modules as explained in the literature, which will form the stepping-stone and reference for chapter five.

Chapter 3; Research Methodology

An elaboration of research methodology and study criteria further to a comparative analysis of various research methodology applicable to dissertation research topic with reference to published literature, consequently choosing preferred research methodology that will be applied for this study given available resources and method effectiveness in achieving study aims and objectives. Additionally, in this chapter, simulation matrix is detailed for façade bifacial BIPV modules general configurations and study parameters are specified.

Chapter 4; Computer Simulation

Details of simulation setups, parameter setting and justification of dependent and independent variables of the study. Moreover, an explanation of software raytracing methodology.

Chapter 5; Results and Discussion

Presentation of simulation results with a comparative analysis to highlight differences and similarities. Discussion of effects of each façade material and gap spacing on the incident irradiance on back surface of bifacial panel. Calculating bifaciality factor for each scenario and determines the scenario with the highest energy yield.

Chapter 6; Conclusion

A holistic overview of the study objective and results, to summarize as a conclusion the façade scheme in terms of material and gap distance that produced the highest bifaciality factor and to be considered the optimal scenario. Research limitations are addressed in this chapter.

Chapter 7; Further Work

In this chapter future work in the subject of building integrated bifacial PV is identified.

CHAPTER 2

LITERATURE REVIEW

Most people take electricity for granted not aware of the massive carbon footprint associated with producing those kilo watts that run each part of our lives, or aware of the scarcity for some countries where consumption per capita is measured in hundreds rather than thousands of kilo watts hour like developed countries. Solar energy holds the potential for equitable source of energy available for everyone on earth without the heavy price the environment has to pay.

Cost of PV panels in 2005 reached tenth of its KWh price in 2000 under standard condition production, in the year 2009 the cost of panel installation was 8.5 \$ per watt dropping to less than half in 2017 and rapidly going down to 2.77\$ per watt in 2020 (Figure 2.1). Worldwide PV generated power reached 386 GWp in 2018. By the year 2022 the world will significantly rely on PV power as a source of electricity. Decreasing the cost of Photovoltaic technology is significantly correlated with increasing system efficiency, energy yields and panels lifetime. Literature argues that bifacial PV cells have the potential of achieving that objective. Collecting photons from both sides of solar cells will increase energy yields with minimum additional costs (Kopecek & Libal, 2018).

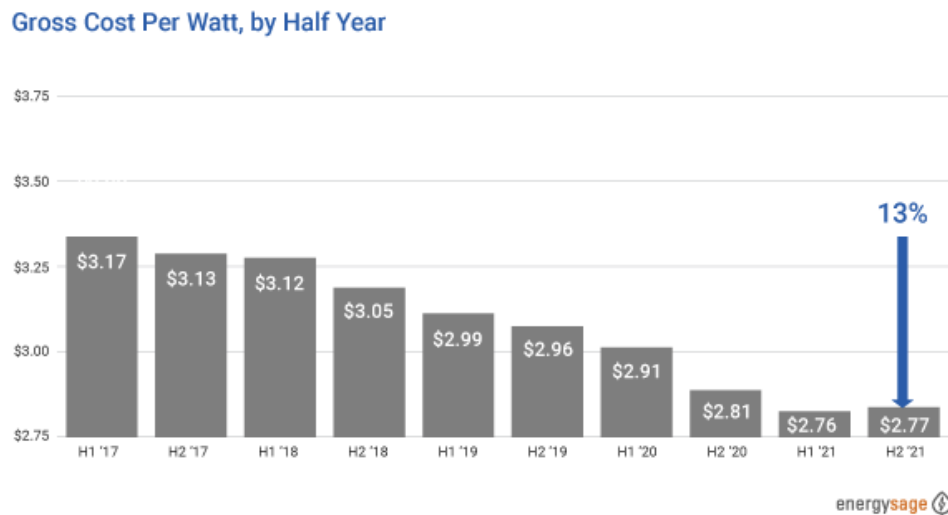


Figure 2.1: Solar panel cost drop over time (Energysage.com 2022)

Moreover, the market for building integrated PV (BIFACIAL PV) increased substantially with the legislation of building energy production and green building codes. worldwide BIFACIAL

PV market size valued at USD 16.62 billion in 2021 and is estimated to increase at a rate 20.5% from 2022 to 2030 (GVR 2022). The rapid expansion of the solar photovoltaic (PV) installation capacities of different countries, coupled with increasing demand for renewable energy sources, is expected to drive the growth of the market across the world. BIFACIAL PV as semitransparent façade and curtain walls serve a double benefit by producing electricity and decreasing solar heat gains simultaneously, this led to the increasing popularity of BIFACIAL PV in the solar industry (Baenas & Machado, 2017). Bifacial solar cells represent a unique option for building integrated systems, since it is not bound with direction of light as Monofacial solar cells are.

2.1 History of Photovoltaics and Bifacial Cells

Since the beginning of time, humans realized the significance of the sun energy, at some point worshipping the sun as the source of life, now after thousands of years, humankind are producing electricity directly from solar energy through Photovoltaics technology. The phrase Photovoltaic is the combination of two parts “photo” the Greek word for light “phós, ph tós“, joined with the name of the physicist who discovered the unit of electricity and the electro-chemical battery “Alessandro Volta” (Martens 2014).

To look into the history of photovoltaics we must go back in time, specifically to 1839 when Alexandre Edmond Becquerel a physicist from France discovered the Photovoltaic effect. Covering two electrodes with material sensitive to light AgBr and AgCl in an acidic solution within a black box, exposing the electrodes to different types of light, the electrical current increased with the increase of light intensity (Ramrakhiani 2017). Afterwards in 1877, Willoughby Smith was an English engineer searching a high electrical resistance material for testing underwater cabling, choosing selenium as a famously resistant material. With no uniform readings, failing to achieve expected results, but Smith noticed the relation of light to the selenium electrical resistance. He tested his theory by placing the selenium in a closed box and measured electrical resistance, readings were high as long as the box lid is closed, but once the box is open and light flood onto the selenium, resistance readings dropped proportionally to the intensity of light (Komp 2001). Interested in Smith’s findings on photoconductivity of selenium another two English researchers, W. G. Adams and R. E. Day. They performed further experiments on selenium photoconductivity. In one of their experiments they did not connect the selenium to an electrical current, rather they exposed it only to light from different sources and used galvanometer to measure the electrical current, and when the needle moved the discovery was made, a material that produce and maintain electrical power by light alone “photoelectric “ (Komp 2001). Later in 1880, an American inventor Charles Fritts constructed the first selenium based solar battery, producing a continuous strong electrical power with no material loss or heat waste. As the scientific theory was still not explained, the invention was dismissed and accused with fraud, since scientist were not convinced that energy can be generated without consuming material (Solar Energy International 2007). The scientific

community remained skeptical, until quantum physics came with the simple yet brilliant explanation for the photoelectric phenomenon. When Albert Einstein published his paper in 1905 about the photoelectric effect with a contemporary theory describing light dual behavior as waves and as quanta, small energy bundles called photons, these photons with enough energy to knock electrons out of its orbit in metals and semiconductors creating an electrical current (Gevorkian 2010). At that point, electrical efficiency was still too low to utilize and manufacture PV cells was extremely expensive, therefore, had no promises of an energy source. Meanwhile, Silicon had become the backbone of transistor technology and the perfect semiconductor for the electrical transmission industry.

In the Year 1954 at Bell labs in the United States, Calvin Fuller and Gerald Pearson were working on silicon rectifiers, a device that converts electrical current from alternating to direct current. They discovered that the converter generated sufficient power and what started as a rectifier testing experiment became a solar project. Joining them Darryl Chapion working together on a silicon solar battery increasing the efficiency to 6% and introducing the first Photovoltaic cell to the world at the National Academy of Science in Washington D.C (Komp, 2001). Silicon solar cells first used to power a telephone relay system in distant locations of Georgia that required a battery for nighttime. Operating for a year the cost analysis showed that solar power was not economically feasible, slowing down the photovoltaic development. Just as everyone gave up on solar cells technology the race to space began, and with a need for consistent source of energy, conventional fuel and batteries could not provide enough energy, the solution was Photovoltaics. The sun shines 24/7 in space the energy was abundant, continuous, consistent lightweight and safe to use in outer space. By 1960, all American satellites were powered by silicon solar starting with 108 cells on Vanguard 1 (Solar Energy International 2007). The cells manufactured by Bell laboratories had an efficiency of 4% increasing to 11% with a high cost of 1000 \$ per watt, research focused on increasing electrical efficiency of photovoltaic cells, reaching 14% in 1960 by Hoffman Electronics (NREL 2018). Five years later in 1965 a prototype of solar vehicle (Sunmobile) revealed in Chicago (Ramrakhiani 2017).

In 1966, a Japanese scientist named Hiroshi Mori suggested a cell with bifacial properties as a solution to increase the conversion efficiency, by enhancing collection efficiency of photons with long wavelength. Creating a cell with pn junctions on both sides of the silicon wafer, Figure 2.2 is an illustration from Mori's original patent report for "Radiation energy Transducing Device". The result is a $p^+ n p^+$ structure capable of double illumination while using vertical and horizontal reflectors (Cuevas 2005).

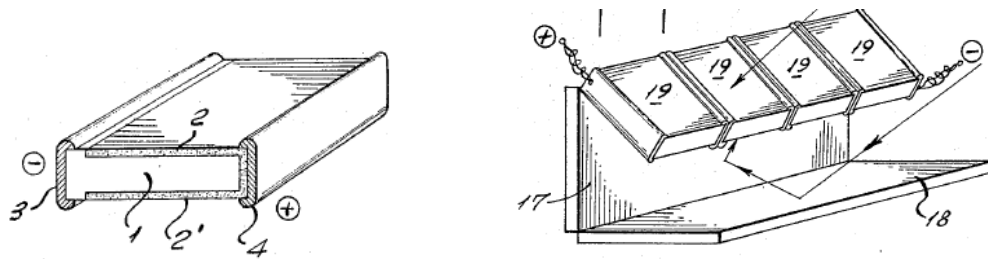


Figure 2.2: Mori's n-type double junction bifacial cell, numbers indicate 1: n-type silicon, 2 & 2': P-type silicon, 3 & 4: metal contacts, 17: vertical mirror, 18: horizontal mirror and 19: front side of bifacial solar cells (Mori 1966).

The first back surface field solar cell (BSF) in Russia 1970 was a bifacial cell, BSF cells have higher doped regions at the back to reduce rear recombination and improves V_{oc} , the Russian researchers presented homo-polar nn^+ back junction opposite to the hetero-polar pn junction using an arrangement of Boron and Phosphorus diffusion (Bordina et.al 1970). Afterwards, in the Year 1977, the concept of dielectric passivation made bifacial cells possible, replacing the rear metal with a grid and the inter-metallic gap with dielectric layer. Producing higher efficiencies for bifacial cells up to 15.7% under front and 13.5% for rear illuminations; numbers were considerably high at that time, which was the type industrially produced by the company Isofoton (Duran 2012).

Later, different technologies emerged from the same concept of passivated rear for instance; p-type passivated emitter and rear cell (p-PERC), interdigitated back contact cells (IBC) and n-type passivated emitter rear totally diffused cells (n-PERT), technologies suitable for mass production for both mono-facial and bifacial PV cells with efficiencies reaching 20% (Libal & Kopecek 2019). Moreover, the optical advantage of bifacial cells made it a more suitable choice for outer space applications, in a research by Letin et.al states that replacing regular mono-facial PV cells with bifacial cells in Russian space stations "Zarya" and "Zvezda" increased energy production 10% to 20% (2000). First terrestrial implementation of bifacial modules by TNC as railway noise barriers in Switzerland (TNC n.p). The Year 2003 was when bifacial were integrated in buildings as window shades in a study by the Institute for Solar Energy Research Hamelin (Hezel 2003).

Japanese company Sanyo first to commercially produce amorphous silicon solar cells, researching on (a-Si:H) by incorporating it in contact layers in n-type crystalline silicon cells. The key step forward was developing the heterojunction intrinsic Thin-layer (HIT®) technology, the technology concept is inserting an interstice thin layer of (a-Si:H) between the doped (a-Si:H) and the silicon wafer. Commercial production of HIT® technology began in 1997 as mono-facial panels although the technology is bifacial by nature. In 2006 HIT bifacial and HIT glass on glass introduced to the market by Sanyo. In 2011 PVGS marketed the n-PERT

bifacial panels, their significantly higher energy yields caught the attention of the PV industry (Burgers et.al 2011).

Modern Photovoltaic technologies are already ready to be bifacial modules, currently companies like LG and Neo Solar Power manufactures n-PERT cells for both mono-facial and bifacial modules. Panasonic/Sanyo supplies n-type heterojunction cells and modules as well as new companies rising to mass production such as Sunpreme. Alternatively, other technologies are not inherently bifacial, like Al-BSF p-type cells (PERC) due to the full contact of Aluminum sheet to the rear surface. Conversely, by screen printing aluminum with H-pattern finger grid on a laser contact openings at the rear passivating coat instead of a full aluminum layer the PERC type can become bifacial PERC⁺ (Dullweber et.al 2016). The process of converting production from PERC to bifacial PERC⁺ does not call for supplementary tools, but merely change the Aluminum screen print layout, therefore, with the PERC technology presenting 20% of global Si PV manufacturing capacity, it is highly feasible to switch cell production to bifacial technology. Most solar manufacturers such as Trina Solar, Neo Solar Power, LONGi Solar and SolarWorld are heading towards bifacial production (Libal et.al 2019).

2.2 General Science of Bifacial Cells

2.2.1 Solar Radiation

This section dedicated to the understanding of solar irradiance: factors affecting solar energy, sun location calculations and spectral characteristics. Solar power hitting PV modules depends on a number of factors such as precise position of sun in the sky, cloud coverage and panel inclination. Irradiance intensity change with the change of distance between earth and sun, nevertheless, a universal average value established for direct extraterrestrial irradiance of 1.353 kW/m² used in climate modeling programs. Sun path is elliptical this causes a variation by 3% plus or minus in sun irradiance received by earth (Coddington et al. 2016).

The distribution of the light spectrum referred to as Air mass zero radiation (AM0) which reflects how much of the spectrum intensity affected by the atmosphere absorption of the energy, air mass calculated as per Eq. (2.1) (Labouret et.al 2010):

$$\text{Air mass} = 1 / \cos \theta \quad (2.1)$$

θ : the angle of sun rays with reference to earth axis.

Air mass is always equal or greater than 1 at the surface of Earth. This means that Air mass equals 1 when the sun is over head ($\theta = 0$). AM1.5 ($\theta = 48.2^\circ$) is what generally used when comparing solar cells standardizing the solar intensity to 1 kW/m². Figure 2.3 compare the incident power and spectrum wavelengths for AM0 and AM1.5g (adjusted to scattered and

reflected sunlight) compared to a black body, which is an ideal body that absorbs all thermal energy, black body has temperature of 6000 °C, approximately the temperature of the emitting layer where more than 99% of the solar irradiance arises.

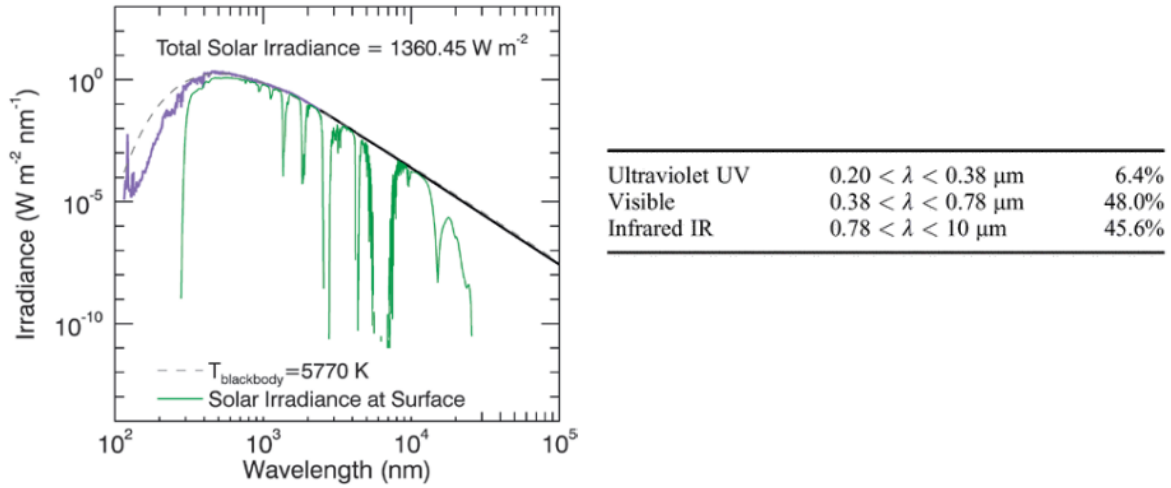


Figure 2.3: Solar radiation spectrum energy (Coddington et al. 2016. P. 1265)

The value of extraterrestrial solar energy is a known depending on Sun's position in the globe, but that does not mean we know how much exact solar energy received by the ground due to the effect of earth atmosphere absorbing and scattering some of this energy. Almost half is lost in diffusion, lux values received by planer ground surfaces depends on uncertain factors; atmosphere gas combination, cloud coverage, relative humidity, wind speed and ground reflectivity (Albedo) (Labouret et.al 2010).

The light that does not get scattered and end up reaching surfaces referred to as direct normal incident (DNI), calculating this value using NREL's View Factor method:

$$I_{Beam} = I_{DNI} + I_{Circumsolar} \quad (2.2)$$

I_{Beam}: light from the sun.

I_{Circumsolar}: Light scattered by particles in the atmosphere

After calculating the value of diffused light measured assuming an isotropic radiation from the Global Horizon Irradiance (GHI) equation (Pelaez 2019)

$$I_{Global} = I_{Beam} \cos\theta_z + I_{Diff} \quad (2.3)$$

2.2.2 The Photoelectric Effect

Process of solar incident photons holding a certain amount of energy cause the release of an electron free within the matter called the photoelectric effect. The photon's energy must exceed the energy needed for an electron to leave its valance band (last orbit around nucleus) where the electron can move freely towards the conduction band. The minimum energy required to release an electron is the work function of the material, any energy beyond work function transfer to the electron as kinetic energy. Whereas the distance between the valance band and the conduction band determines the material electro-conductivity, in metals, these two bands overlap causing a free movement of electricity, as for insulators the gap between both bands is larger restricting the electrons movement. The third material that is specifically interesting in solar photovoltaics are Semiconductors, with narrow bandgaps, this material behavior shifts between metals and insulators depending on the amount of energy received. Silicon is the most famous material for solar photovoltaic cells, with a bandgap E_g responsive to the majority of sunlight spectrum (Van Zeghbroeck 2011). For the photoelectrical effect to happen photon absorption energy must exceed E_g giving enough energy to excite the electrons in the valance band to move towards the conduction band leaving behind positive holes. Figure 2.4 is a simplified illustration of the Energy band for direct bandgap semiconductor.

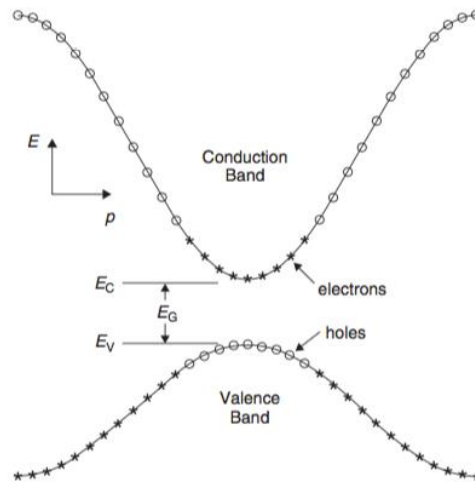


Figure 2.4: Semiconductor bandgap (Labouret et al 2010, P.86).

Single bandgap cell efficiency is limited by the Shockley-Queisser limit, approximately 30% at 1000 W/m^2 (one-sun illumination). When bandgaps are relatively low (1-1.4 eV) the losses are mainly heat dissipated during the electro chemical process, most silicon-based cells have a bandgap of 1.1 eV. One of the methods to overcome this efficiency barrier is multi-junction cells. Typical commercial mono-crystalline cells have a Shockley- Queisser limited efficiency of 24% assuming common sunlight environment (Manor et.al 2016).

When the electron is free from the valance band and move to the conduction band, it leaves behind a positively charged valance band, referred to as holes. Silicon in its pure state has four electrons in its valance band, once they cross over to the conductive band, the silicon atoms will seek equilibrium with the number of holes equal to number of free electrons this will be achieved the moment it receives photons energy, this type of semiconductors are called “intrinsic”. In manufacturing solar cells, pure silicon does not serve the purpose because of this instantaneous equilibrium and limited number of carriers. Therefore, silicon is doped with other elements. Boron doping produce a positively charged semiconductor “P-type”, hence Boron (atomic number =5) has three electrons in it valance band that will bond with three silicon atoms leaving the crystal positively charged (Figure 2.5). A negatively charged crystal achieved by Phosphorous doping, Phosphorous (atomic number = 15) with five electrons in its valance band will leave the crystal negatively charged producing an n-type semiconductor (Komp 2001).

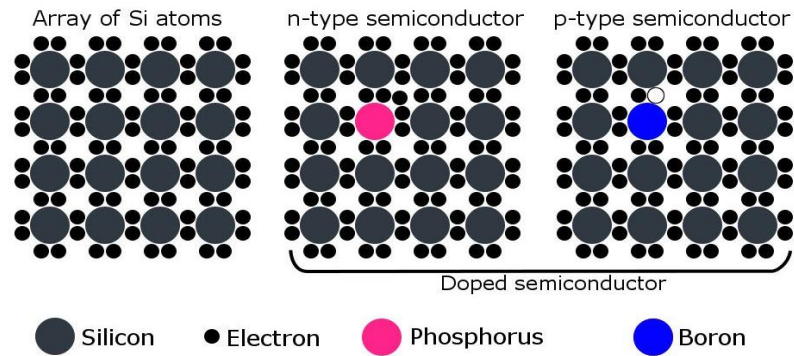


Figure 2.5: Silicon crystal semiconductor types (Peshin 2015).

In semiconductors, the Fermi level is within the bandgap, Fermi level is a hypothetical level that represent the thermodynamic energy required to move electrons to conductive band, in the state of equilibrium the probability of this level being occupied is 50%, moreover, the position of the fermi level to other band is the key determinant of electrical property of materials. Doping silicon crystal shifts the fermi level according to the dopant type. In an intrinsic silicon crystal, the fermi level is halfway between valance band and conductive band, as illustrated in Figu

2.6, whereas in n-type it is closer to the conductive band. In p-type crystal, the fermi level fall near valance band level (Melicov 2016).

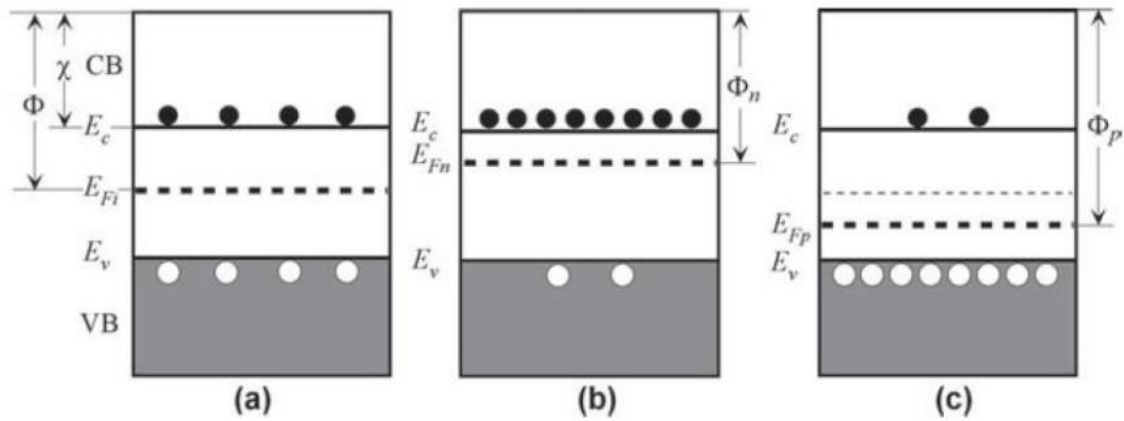


Figure 2.6: Fermi level in different silicon crystal types a) Intrinsic Si crystal. b) n-type. c) p-type (Melicov 2016).

Doping process also used to maximize the photo-thermal conversion efficiency and expand the optical absorption range. Additionally, doping can improve the probability of non-radiative recombination creating more free carriers and consequently increase photo-thermal conversions even further. The process will prompt changes to the structure of semiconductor's band, such as energy intraband state, bandgap narrowing, and absorption range broadening caused by impurity formation. Figure 2.7-b the doping cause optical excitation and extending the absorption curve to longer wavelengths due to local states acting as the dominant centers. In the second case (Figure 2.7-c) doping is narrowing the bandgap by shifting the conduction or valence band, which will shift at the absorption spectrum edge. Lastly, higher doping concentration can increase the intensity and blue-shift the LSPR band (Gao et.al 2018).

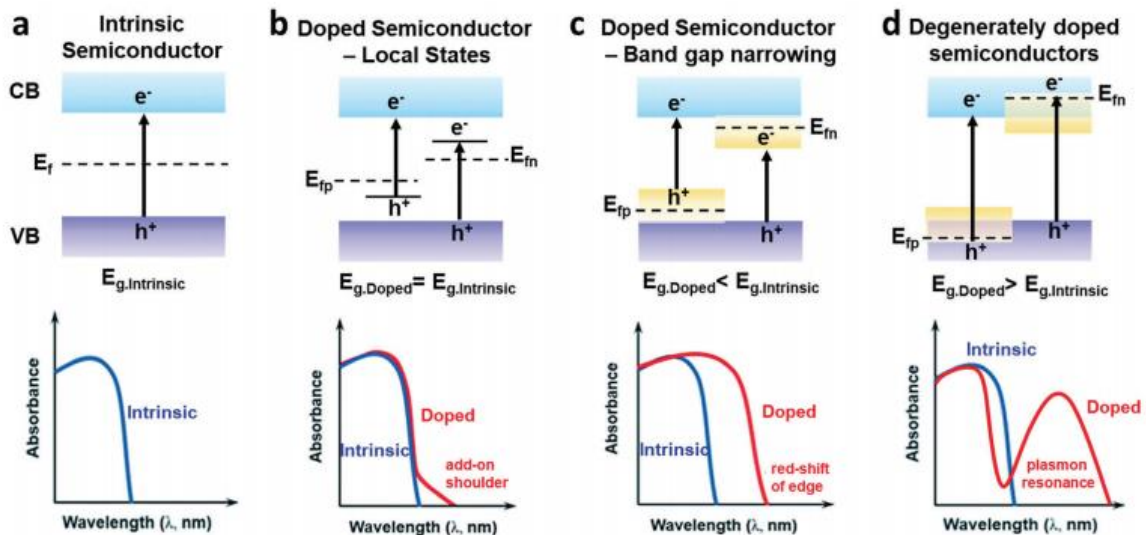


Figure 2.7: Semiconductor band structure and optical absorption curves (Gao et.al 2018, P.10).

2.3 Photovoltaic Cells: Mono-facial and Bifacial

Typically, the solar cell consists of a p-n junction, two layers of doped semiconductor such as silicon stacked creating a junction. The n-type is thinner allowing light through and into depletion layer. The positively charged p-layer have the necessary holes that will induce electrons in the negative n-layer to move with the purpose of filling those holes and reaching equilibrium, thus, creating an electrical current. Eventually once equilibrium is reached within junction the voltage will be zero and the layers will reach depletion state, therefore the cell is connected to an external circuit to drain the electrons out of the cell and overcome depletion, a wire is connected from cathode to anode will carry electrons maintaining flow of current. Holes created by the dislodged electron migrates to the back electrical surface. Thin layer of dielectric

material or an antireflection coat (ARC) covers solar cell to minimize reflection from the top layer, Titanium dioxide usually used as an ARC. A standard assembly of a PV solar cell shown in Figure 2.8.

Different new techniques of cell assembly implemented with the goal to improve the cell efficiency such as layering different junctions and integrated back contact where there is no shadowing effect and many other enhancements to the standardized cell.

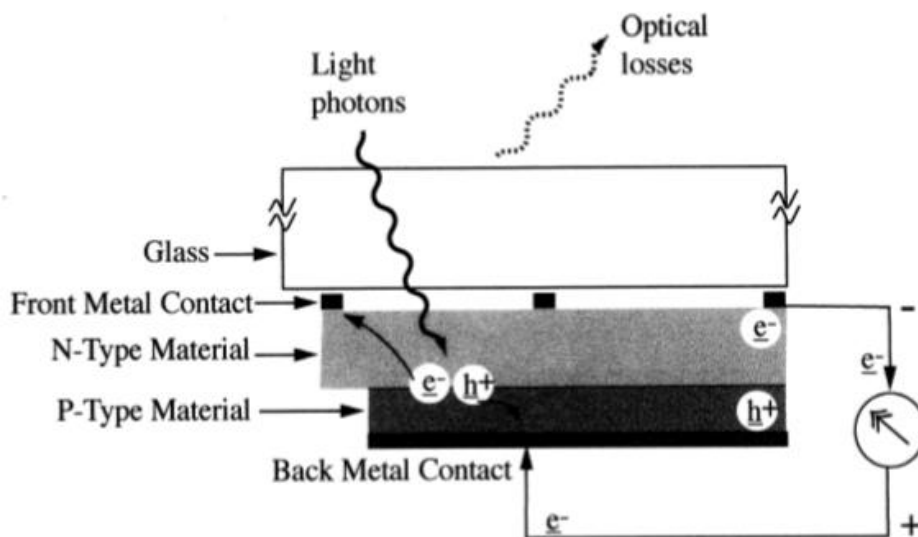


Figure 2.8: Typical p-n junction (Smestad 2002, P. 37).

Layer combination of doped silicon determines if the solar cell is an n-type cell or a p-type cell, although the first solar cell was an n-type, p-type solar cells became more popular after utilizing them for space applications. P-type solar cells proved to be more resisting to space radiations and presented less degradation. Nevertheless, recently more manufacturers are considering n-type cells because boron doped silicon (P-type) is prone to boron oxygen degradation; whereas Phosphorous doped silicon is not therefor, n-type solar cells have longer lifetime (Agrawal & Tiwari 2011).

Bifacial cells are designed to capture the light from both surfaces (front and back), in concept same technologies of mono-facial cells being used in bifacial cells, Figure 2.9 presents the difference between basic P-type mono-facial solar cell and P-type bifacial cell. Both include a semiconductor wafer, front contacts, anti-reflective coating, emitter, back surface field. Bifacial cells have an additional anti-reflective coat at back surface and rear contacts. Although p-type technologies with Passivated Emitter and Rear cell (PERC) make up 65% of bifacial cells market (Fakhfour 2015). N-type solar cell technologies adopted in bifacial manufacturing are passivated emitter and rear totally diffused (PERT) and locally diffused (PERC) (Figure 2.9-c). Moreover, applying integrated back contacts, which is a technology, developed to enhance the performance of mono-facial cells in bifacial manufacturing where metal contacts are on the rear side only (Figure 2.9-d) this configuration recorded the highest efficiency ever with 26.7 % for silicon-based cells (Pelaez 2019).

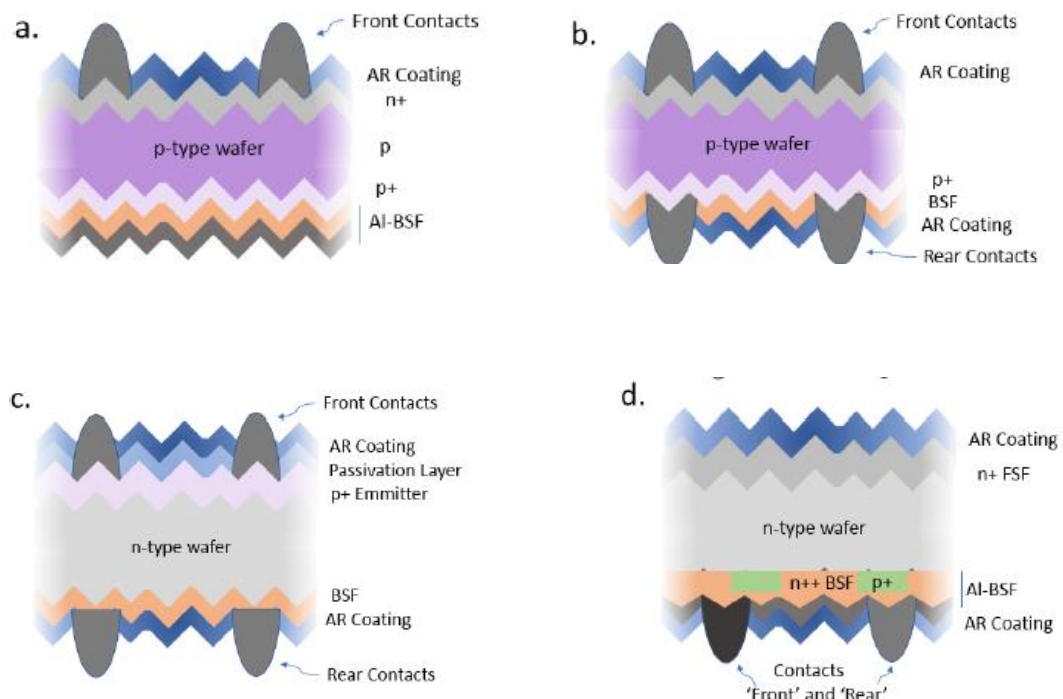


Figure 2.9: Four Solar Cell technologies: a) Standard P-type mono-facial. b) P-type bifacial PERC.

c) n-type bifacial PERT. d) IBC n-type bifacial. (Pelaez 2019, P. 56).

Experimental testing and modeling simulation results of previous research and literature, show that thickness of silicon substrata of n-type and p-type bifacial solar cells performance enhance when reducing thickness from 240 μm to 140 μm , due to reduction of rear and bulk recombination. Meanwhile small efficiency decrease occurred when silicon thickness reduced to 58 μm but achieving significant manufacturing cost reductions (Guerrero-Lemus 2016). Increasing light trapping in bifacial cells is achieved by texturing the surface to boost light absorption, this can be for front surface or both front and rear. The choice depends on existence of reflective devices and albedo of adjacent surfaces, as it was observed that scattering effect is higher by reflection than direct transmission, therefore, in case of no reflectors at the back, the rear surface must be textured. In case of no reflectors, bifacial cells with texturing for front surface only performed better in light trapping than front-rear textured cells (Simashkevich et.al 2011).

Monofacial cells undergo doping process once to create the n-p junction while bifacial cells require two doping processes, therefore, decreasing thermal processes is crucial for manufacturing feasibility and efficiency. One of the researched methods is co-diffusion, which is simultaneous doping of Boron and Phosphorous on both sides of material via a spin on method, consequently reducing the high temperature processes from three to two, concern is potential cross doping (Rothhardt et.al 2013). In a study by Kania et.al (2013) combination of Boron diffusion and Phosphorous ion-implantation in a single high temperature process. Studies showed that P activation of ion- implant at lower temperature than Boron diffusion results in slight improvement of conversion efficiency causing a lower ion-implantation cost as a replacement of standard diffusion for mass production. Doping by laser for Silicon based bifacial cells of precise emitter on both sides in one-step process causing a local melt of silicon to prompt diffusion with dopant in liquid form will result in reduction of thermal processes for bifacial solar cells production (Lanterne et.al 2014).

Both Monofacial and bifacial research all possible methods to reduce Silver (Ag) screen-printed front contacts, studies included replacement of Ag with Cu, Al, and the use of transparent conductive oxides (TCO), another method is trying to reduce amount of silver used as contacts. Copper (Cu) holds many advantages as a replacement of Ag; firstly, by having a significant lower cost and having a lower lamination temperature, consequently reducing manufacturing cost. Moreover, it is better than Al, since it does not have a high recombination rate like Al that cause reduction in conversion efficiency, Al was found to reduce short circuit voltage because of the depassivation during screen-printing. In fact, Copper plated solar cells scored an efficiency of 23.1% (Heng et.al 2015). The downside for using copper is the high possibility of contaminating Silicon based wafers and shifting junctions. Untila et.al (2014) tested a bifacial cell configuration of indium tin oxide/(p⁺nn⁺) Cz-Si/ indium fluorine with copper wire contacts attached to TOCs on both front and rear sides. TOCs usually used in Ag screen-printed solar cells to prevent the heavy Ag metal from penetrating the Si wafer, in the study by Untila et.al the front-rear efficiency was not high as expected with 17.6%/16.7%. Cost reduction can be achieved by decreasing quantity of Ag screen printing to 40 mg per wafer and using thin wire

contacts for front surface (32 μm thin) boosting conversion efficiency above 23%. Metal wrap through Structures reduces shading losses from front surface (Strahm et.al 2014).

Bifacial solar cells are subject to added resistance losses due to multi-dimensional current crowding caused by restricting rear side metal contact grid or dots, therefore, silicon surface passivation is applied at both front and rear surface; by adding a thin layer of silicon nitride (SiN_x) through a plasma- enriched vapor chemical deposition. This layer acts as an anti-reflective material and surface passivation especially for low optical bandgap, improving optical absorption for wavelengths less than 600 nm (Janben et.al 2007). Spin coating front and rear surface with Aluminum rich Zinc oxide (AZO) is an alternative more economic process. Galvanization in atmospheric pressure followed by Hydrogen surrounding, results are reducing reflectance and substantially increasing open circuit voltage because of the back surface passivation (Khan et.al 2013).

2.4 Bifacial PV Modules Design and Encapsulation

Solar cells are electrically connected together to form a PV module, the way these cells are connected play a major role in efficiency and lifetime of the module. Encapsulation function is to protect the solar cells and the electrical wires from surrounding environment, prevent mechanical damages to the cells and protect the wires from water or/and water vapor that can cause corrosion (King et.al, 2000). Encapsulation material is usually EVA (ethyl vinyl acetate), EVA sheets sandwiched with solar cells and polymerized under 150 $^{\circ}\text{C}$ temperature bonding all module elements. Front side of the encapsulation must have a high transmissivity, wavelengths from 350 nm to 1200 nm, and low reflectivity to allow all sunlight into the solar cell layers. Other important characteristics of front encapsulation is waterproof material, impact resistance, sustainable under UV exposure and thermally conductive. Glass with low iron content presents a good option and been used by the industry for years given its low cost and all previously mentioned required features (Honsberg & Bodwen 2019).

A bifacial cell can be utilized in both bifacial and Monofacial module design configuration. Monofacial back side foil reduces optical losses, losses are higher for black foil sheets 6.5% compared to white sheets 4.8%, whereas for bifacial configuration with transparent back foil sheet losses are 5.3%, which doesn't matter because bifacial cells can still harvest the light from the rear side (Halam et.al 2014). Bifacial cells have the advantage of being encapsulated in many different front-back structures; Glass-Glass, Glass-transparent and glass-backsheet. Glass-glass and glass-transparent bifacial module performs better since it has better light absorption. Unfortunately, encapsulating solar cells change the thermal flow in and out of the cells, this of course increase the operating temperature and cause further efficiency reductions and speed up degradation. Theoretically the Current-Voltage profile of module must match

individual cells profile with scale change only, since the characteristics of all cells connected together are identical, if not the cell with the lowest efficiency will lower the actual module output. Figure 2.10 show two modules one as a Monofacial configuration with a white color backsheet and a bifacial module with glass-glass structure.

Solar module packing density is a term that represents the number of cells in an area unit of the cell, higher number of cells in the module is a module with high packing density, consequently, a higher power yield module. Factors controlling packing density are shape of solar cell, cutting solar ingots into circular or square wafers decides the gaps between the cells, hence the circular once have more gaps when connected together, and they are being cut into semi square cells to reduce gaps in module. On the other hand, the space between the cells can increase the yields by the effect of the zero-depth concentration, when light in bifacial cells or cells with reflective rear surface is reflected within the module and reach active zones in the module.

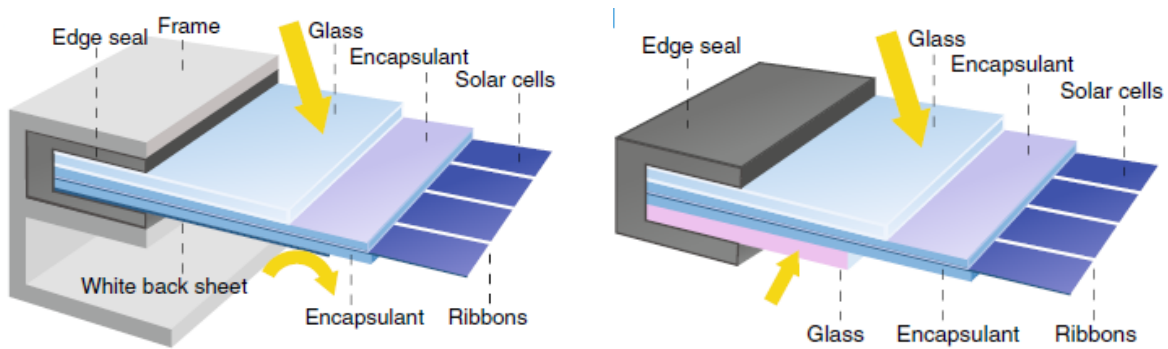


Figure 2.10: Solar module encapsulation designs, left; Monofacial configuration with white back sheet. Right, Bifacial glass-glass solar module. (Kopecek & Libal 2018, P. 443).

2.5 Light Converters

Typically, single junction solar cells undergo inherent efficiency losses due to its inability to absorb photons that have energy lower than semiconductor's material band gap "transmission losses". As well as losses from photons with energy higher than band gap energy "thermalization losses". The polychromatic nature of the sun light will always cause a exchange between these losses, therefore, the conversion efficiency will always be limited by these losses; this limit is known in the industry as the Shockley–Queisser limit (Wild et.al 2011). Stacking solar P-n junctions with different band gaps is the common way of overcoming the Shockley-Queisser (SQ) limit. Each junction will respond to a part of spectrum photons, however, the fact that

these junctions are connected in series, makes the solar cells sensitive to spectral changes due to climatic changes because the junction with is the lowest current will limit the efficiency. Spectral conversion to optimize the solar cell band gap with corresponding wavelengths by the use of converters (Trupke et.al 2006).

Converters are designed to capture photons that falls below of band gap energy and re-emit photons with energy higher than band gap into active zones within the solar cell. In bifacial cells up-converters utilize the radiation that otherwise would be transmitted by the solar cell and utilize it in electrical conversion, hence, the up-converter is applied on the rear side of bifacial cells to avoid deficiency of incident radiation (Pan et.al 2010). Up-converters increase efficiency of bifacial cells depending on design schematics of geometry of BSF, anti-reflective coating and light concentrators. Additional efficiency enhancement is achieved by adjusting material emissivity, controlling spectral range irradiance through adding a material that has a wider spectral range or co-doping with a dye sensitizer, but this could cause temperature sensitivity (Goldschmidt et.al 2014). Another approach suggested in the literature is coupling the up-converter with an array of parabolic concentrators with dielectric on the rear surface, resulting a 35% increase in up-converter efficiency at 1523 nm compared to cells with no concentrators (Arnaoutakis et.al 2015). Furthermore, deposition process of the up-converters affects its efficiency, for example, silicone gel deposition, spin on oxides or powder-form quantum dots up-converters which reduce reflection losses from back surface of solar cells (Pan et.al 2014).

2.6 Solar Cell Characterization

To identify solar cells characteristics the comparison criteria have to be specified and determined under standardized conditions, these conditions are referred to by the literature and the solar industry as standard testing conditions (STC) which are:

- Irradiance intensity: One sun illumination; 1 Kw/m².
- Air mass: 1.5 spectrum (AM1.5). This is equivalent to solar irradiance on a clear sky day at a surface tilt of 37° and the sun above horizon at 41.8° angle.
- For space use, it is AM0.
- Cell temperature: 25 ° C.

The percentage of light energy that is converted to electrical energy is represented by the conversion efficiency (η). Efficiency is the ratio of power out, that is the power from the PV panel to power in which is the sun illuminance.

$$\eta = \frac{\text{Power out}}{\text{Power In}} = \frac{P_{max}}{E.A_{cell}} \quad (2.4)$$

When examining the power out from a PV module, the I-V curve (Current-Voltage curve) provide a mathematical presentation of the PV module as it represents all possible operating points that a PV device could be at for a given set of testing conditions (irradiance, temperature, and spectrum). The IV curve of the PV module is similar to a Diode IV curve with a key difference that the Y-axis is super positioned by the value of incident radiation (Figure 2.11). The curve has few important parameters, first one is the short circuit current I_{SC} , and that is the highest current value with zero voltage, the PV will operate at I_{SC} when it is at a zero or near zero resistance load. Short circuit current varies linearly with light intensity. The second parameters on IV curve is the open circuit Voltage V_{OC} , that is the point where the PV cell will operate if attached to a load with extremely high resistance, so it's the point with highest voltage at zero current. Open circuit voltage varies logarithmically with irradiance; therefore, it is not as sensitive as current to light intensity. However, V_{OC} is more sensitive to temperature than I_{SC} , in a typical silicon solar cell V_{OC} decrease by 0.3% for each 1° C increase (Maammour et.al 2013).

$$I = I_L - I_0 \left[\exp \left(\frac{qV}{nKT} \right) \right] \quad (2.5)$$

I : Current

I_L : Light generated current

I_0 : Dark saturation current

n : Ideality factor

T : Temperature in Kelvin

K : Boltzmann constant 1.38×10^{-23}

q : Electron charge 1.602×10^{-19}

V : Voltage

Electrical power is the product of current by voltage, therefore, the maximum power point at the IV curve is when the product of both axis (X,Y) is at its maximum point, That is located at the knee of the curve. This maximum power point P_{max} represents the value of the maximum real power that could be extracted from the PV device under a given set of conditions. This value is the common comparison value within the solar industry.

$$P_{max} = I_{mpp} \cdot V_{mpp} \quad (2.6)$$

The general performance of a solar cell is observed through a parameter that can also be extracted from IV curve, it represents the ratio between the rectangular area under the curve ($I_{mpp} \times V_{mpp}$) and the maximum theoretical power rectangular area ($I_{SC} \times V_{OC}$). This ratio is the fill factor (FF). In other words, it is the maximum power possible for that solar device P_{max} over the short circuit current and open circuit voltage. The higher the FF value the more efficient is the solar module; hence, a higher FF means the actual solar cell is closer to theoretical maximum power.

$$FF = \frac{P_{max}}{I_{SC} \cdot V_{OC}} = \frac{\eta \cdot A_c \cdot E}{I_{SC} \cdot V_{OC}} \quad (2.7)$$

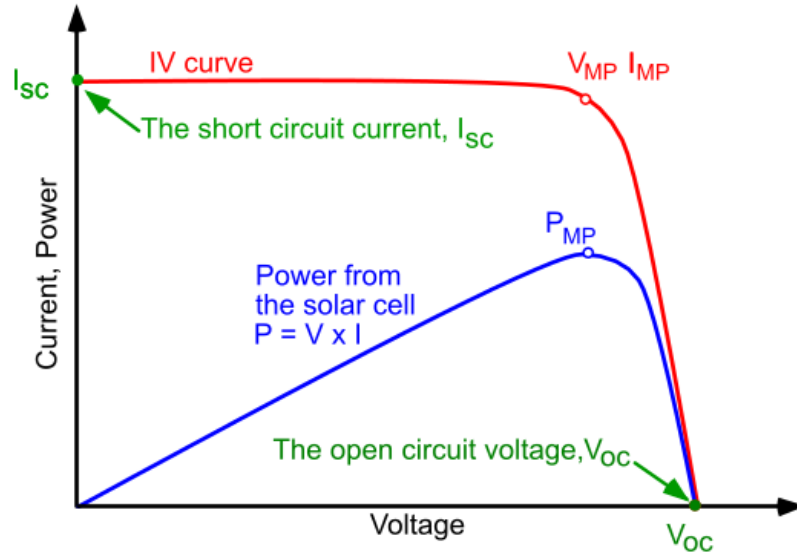


Figure 2.11: Current Voltage curve for a PV solar cell (Honsberg & Bodwen 2019. P)

The performance of PV cells is typically modeled with equivalent circuits such as the one diode model (Figure 2.12), the one diode model contains four components; the ideal current source driven by light intensity, a diode, Parallel Shunt resistance (R_{sh}) and Series resistance (R_s). An ideal solar cell should have a high R_{sh} value and a low R_s value. Both values can be extracted from the IV curve; the series resistance value is the slope of the IV curve near V_{OC} , whereas the shunt resistance is the slope of IV curve near I_{SC} .

The R_s is an indication of overall series resistance of bus bars, metal contacts, adhesion of contacts to the cell, etc. R_{sh} designates cell's whole health; a low R_{sh} could be a sign of localized short circuits due to manufacturing errors, micro cracks causing these shunts, mechanical vibrations, or induced degradations, which decrease the power outputs of solar cell; a lower FF value (Figure 1.6.3).

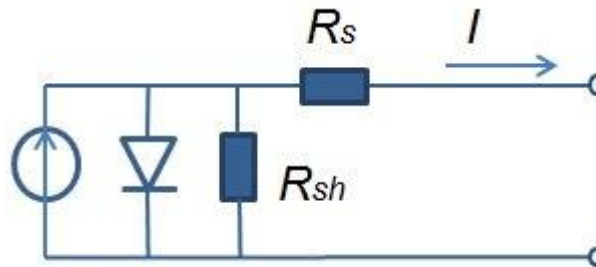


Figure 2.12: One diode equivalent model (Guo et.al 2012. P.113)

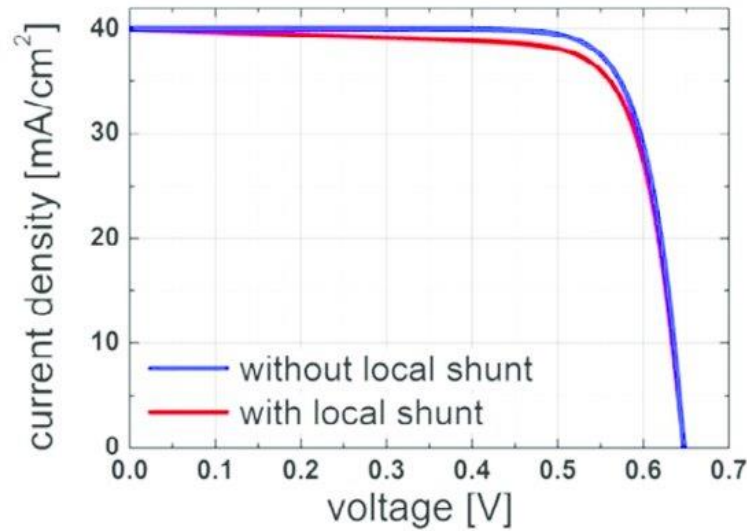


Figure 2.13: FF reduction due to solar cell shunts (Guo et.al 2012. P.114)

Maximum power conversion of light to electricity is governed by the Carnot's thermodynamic limit (93%) that is based on the Second law of thermodynamics of thermal energy exchange (Green et.al 2017). Specifying the characteristics of a bifacial solar cell can be done through different electrical and optical parameters, current-voltage readings, spectral quantification efficiency (QE), electroluminescence, dark measurements and series resistance are the major methodologies carried out by the solar power industry. First two methods are the most applied. The bilateral nature of bifacial solar cells readings and the influence of measuring equipment present difficulties to the measurement process. Therefore, the measurements are done in a special setting with no reflective surfaces to the rear side of the solar module (Rauer et.al 2019). One method to overcome the impact of sample holder is the Flash measurement; instantaneous illuminance on both front and rear side of module to present actual working conditions of a bifacial module. This method provides fast characterization on bifacial module performance.

2.7 Bifacial Solar Cell Conversion Efficiencies

Efficiency of bifacial cells could be measured under independent irradiation one sun simulation with two readings for front and rear side or only measuring front side efficiency; the later method is equivalent efficiency, based on comparison with a Monofacial solar cell performance under same circumstances with same parameters. Equivalent efficiency is considered the summation of front and rear yields under test conditions (Janseen et.al 2017). For independent irradiation the ratio of rear efficiency to front efficiency is referred to as "Bifaciality Factor",

hence the bifacial solar cell is not symmetrical the factor is less than one. The goal is always to obtain a high Bifaciality factor to optimize the use of this technology. Typically, Bifaciality factor (BF) is determined under one sun standard testing conditions, but recent studies show that BF must be determined under different optical and thermal scenarios for accurate estimations; this can be achieved with the use of simulations (Singh et.al 2014).

$$\text{Bifaciality factor (\%)} = \left[\frac{\eta_{\text{rear}}}{\eta_{\text{front}}} \right] \times 100 \quad (2.8)$$

Separation rate % is another way of measuring bifacial efficiency where the short circuit currents are the definitive values, so the resistance losses are eliminated.

$$\text{Separation rate (\%)} = \left[\frac{I_{\text{sc rear+front}}}{I_{\text{sc front}} + I_{\text{sc rear}}} - 1 \right] \times 100 \quad (2.9)$$

Absolute bifacial effect on any parameter can be used to measure bifacial efficiency, parameters (X) can be short circuit current (I_{sc}), maximum power of independent (P_{max}) or efficiency (η).

$$\Delta = X_{\text{rear+front}} - \{X_{\text{rear}} + X_{\text{front}}\} \quad (2.10)$$

All methods of assessment bifacial efficiency available in literature separates front and rear performance and calculate for a linear mixture of both, no method available that provide simultaneous efficiency for the solar cell a whole. In a study by Edler et.al (2012) a simultaneous front-rear measurement method was introduced by adding mirrors and filtering radiation under standard testing conditions, Edler et.al presented two parameters, which are 1.x efficiency and gain efficiency product. Irradiant gain is calculated as following; G_f is the irradiance on the front side, G_r irradiance on the rear side. Bifacial gain is the additional power produced due to the solar cell Bifaciality. For simplification efficiency losses due to the non-uniform irradiance on the rear surface are neglected and shading losses factor is zero.

$$g = \frac{G_f + G_r}{G_f} \quad (2.11)$$

$$x = g - 1 \quad ; x \text{ is the irradiation facto} \quad (2.12)$$

When simultaneous irradiance on the front and 1.x on the back of a solar cell the bifacial 1.x efficiency achieved. When the irradiance gain decreases the 1.x efficiency increase, Figure 2.14 is a chart showing the relation of computer-generated bifacial $\eta_{1.x}$ efficiency and gain-efficiency product as a function of the radiance gain for two different simulated bifacial solar cells. A higher 1.x efficiency is achievable by maximizing the rear-front I_{sc} ratio and fill factor; fill factor (FF) is “the ratio of the maximum power to the product of V_{OC} and I_{sc} ”. To calculate

the factor at which current of the bifacial cell increase for bifacial illumination compared to Monofacial (R_{ISC}) they used equation [6] below, the factor is always less than (g) given that rear side current is less than front side current.

$$R_{ISC} = 1 + x \frac{I_{SCR}}{I_{SCF}} \quad (2.13)$$

Finally, the 1.x bifacial efficiency equation is simplified to:

$$\eta_{1.x} = \eta_f \left(\frac{R_{ISC}}{g} \right) \left(\frac{V_{OC-bi}}{V_{OC-f}} \right) \left(\frac{FF_{bi}}{FF_f} \right) \quad (2.14)$$

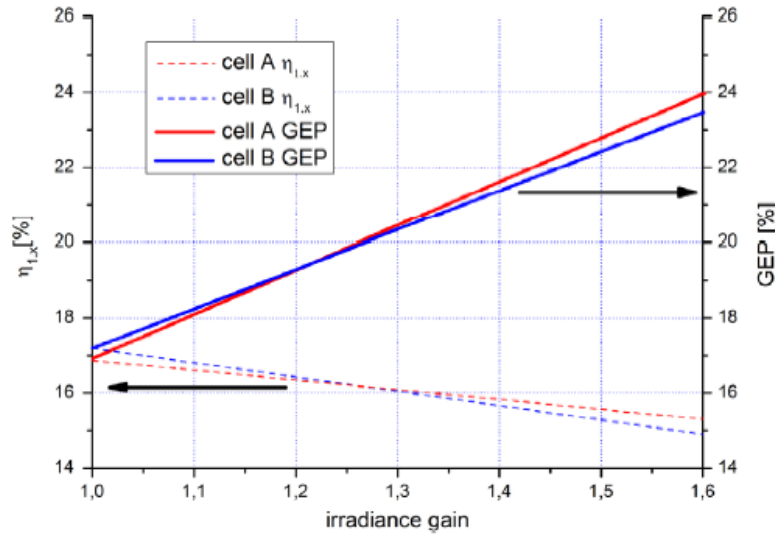


Figure 2.14: Simulated bifacial solar cell efficiency 1.x and gain efficiency product as a function of irradiance gain (Singh et.al 2014. P 906)

Because the irradiant on the rear side of the cell is not the same of the front side where most of the incident light fall, there will always be a mismatch in power production. To evaluate the non-uniformity of irradiance, multiple sensors are placed on both front and rear side, by having a number of irradiance readings, the maximum and minimum values will be determined for rear side then applied in equation [8], nevertheless, non-uniformity of rear side irradiance has minimal impact on overall efficiency (Bailey & Jaubert 2018).

$$\text{Non-uniformity} = \frac{\max G_{rear} - \min G_{rear}}{0.5 (\max G_{rear} + \min G_{rear})} \quad (2.15)$$

2.8 Solar Cell Losses

Fundamental losses within a solar cell are observed as low energy photons, hyper energy photons, voltage losses and FF losses. Other losses are categorized as technical losses generated from optical and electrical nature (Figure 2.15). Optical losses are caused by shading, reflection and non-absorption and they typically affect the short circuit current, as it is the most sensitive parameter to solar irradiance. Ideally, the full visible spectrum is absorbable and capable of inducing the photoelectric effect. Optical losses are photons with lost potential to create an electron-hole pair due to several optical deficiencies. Firstly, the light being reflected from the surface of the cell; moreover, the photons being absorbed into an inactive zones; parasitic absorption losses occur when the light enters the solar cell but get absorbed or reflected by other elements within the solar cell. Additionally shading losses, the metal contacts are oblique and cast a shade on the PV surface consequently reducing short circuit current. Hence reducing the gross area of the contact grid will increase the resistance, researchers try to balance the tradeoff between active area coverage factor C_f and R .

$$C_f = \frac{A_f}{A_{total}} \quad (2.16)$$

$$R = \frac{\rho L}{WH} \quad (2.17)$$

C_f : Active area coverage factor.

A_f : Solar cell area not covered by metal contacts.

A_{total} : Solar cell total area.

R : Resistance.

ρ : Resistivity of metal.

W : Width

H : Height.

Recombination is an electrical loss that affect the open circuit voltage and fill factor of the cell. Recombination is the process of electron annihilation from the conductive band back to the valence band, this process resembles a backward photoelectric sequence, and therefore, the recombination will generate a photon. This process is reduced by surface passivation using silicon oxides or silicon oxide Nitride at the emitter side. As for recombination happening at the back surface field using back surface field methods which is mainly adding a heavily doped P+ layer at the back surface to repel the negatively charged electrons away from the back surface and into the emitter contacts. Lastly Ohmic losses due to resistance of solar cell components. (Martens 2014). Figure 2.15 a summary of solar cell losses.

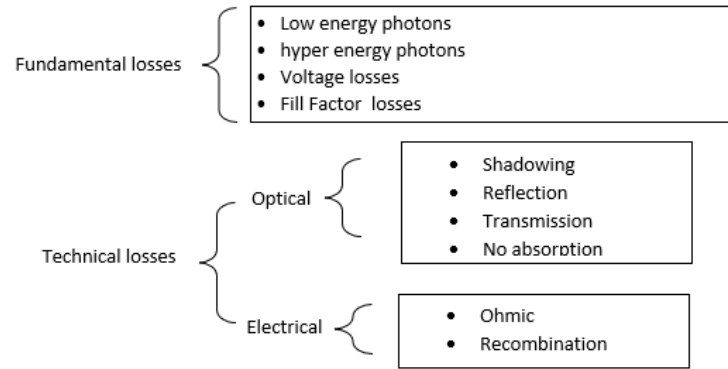


Figure 2.15: Summary of energy losses within a solar cell

2.9 Mathematical Optical and Electrical Modeling of Bifacial Modules

For calculating the irradiance of a solar panel two values obtainable from location weather profile are needed, the global horizontal irradiance (GHI) with the diffused horizontal irradiance (DHI), afterwards by applying following mathematical calculations the front and rear side irradiance can be determined. The total power of the bifacial module is a relation of front and rear irradiance summation with the effect of cell Bifaciality ϕ_{Bifi} (Figure 2.16)

$$G_{\text{total}} = G_{\text{front}} + [G_{\text{rear}} \times \phi_{\text{bifi}} \times (1 - \eta_{\text{loss}})] \quad (2.18)$$

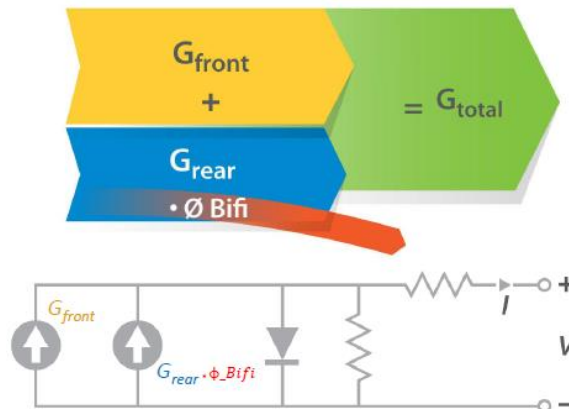


Figure 2.16: Components of irradiance on a bifacial cell (Deline & Sekulic 2019, P 8)

- Front side global irradiance

$$G_F = G_b^F + G_d^F + G_r^F = (GHI - DHI) \cdot R_b^F + DHI \cdot X_{F,sky} + GHI \cdot P_p \cdot X_{F,grd} \quad (2.19)$$

G_b : Beam irradiance

G_d : Diffused irradiance

G_r : Reflection irradiance

$X_{F,sky}$: View factor of front panel to sky

$X_{F,grd}$: View factor of front panel to ground

P_p : Ground albedo

R_b^F : front irradiance to horizontal irradiance ratio

$$R_b^F = \begin{cases} \frac{\cos \theta^F}{\cos \theta_Z^F} & \gamma_p - \frac{\pi}{2} \leq \omega \leq \gamma_p + \frac{\pi}{2} \\ 0 & \omega < \gamma_p - \frac{\pi}{2} \text{ or } \omega > \gamma_p + \frac{\pi}{2} \end{cases} \quad (2.20)$$

γ_p : Azimuth

θ : incident angle

θ_Z : Zenith angle

ω : Hour angle ; Angular distance from a point at a specific hour on the celestial path from the meridian in the west direction.

- Rear side global irradiance

$$G_R = G_b^R + G_d^R + G_r^R = (GHI - DHI) \cdot R_b^R + DHI \cdot X_{R,sky} + GHI \cdot P_p \cdot X_{R,usgrd} + DHI \cdot P_p \cdot X_{R,sgrd} \quad (2.21)$$

For the rear side the albedo of the ground is considered with ground view factor on rear panel for shaded ($X_{R,usgrd}$) and unshaded ground ($X_{R,sgrd}$). Rear irradiance to horizontal irradiance ratio can be determined by making tilt angles in minus sign as following

$$R_b^R = \begin{cases} 0 & \gamma_p - \frac{\pi}{2} \leq \omega \leq \gamma_p + \frac{\pi}{2} \\ \frac{\cos \theta^R}{\cos \theta_Z^R} & \omega < \gamma_p - \frac{\pi}{2} \text{ or } \omega > \gamma_p + \frac{\pi}{2} \end{cases} \quad (2.22)$$

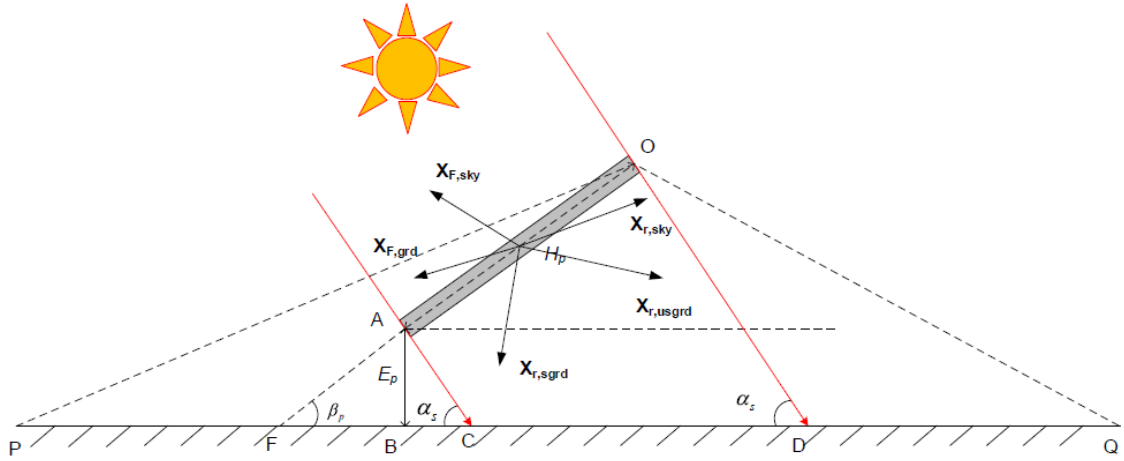


Figure 2.17: View factor points schematic (Gu et.al 2020. P 5)

View factor highly influence the front and rear irradiance values, therefore, to analyse the view factor values a bifacial panel schematic (Figure 2.17) used as a reference of the analysis. The panel height is H_p and tilt angle β_p and an elevation from ground E_p . For the front surface, there is two viewpoints, from the sky and from ground. As for the rear-side, there is three viewpoints, sky, shaded ground and unshaded ground.

- Front side view to the sky

$$X_{F.Sky} = \frac{X_{OF.Sky} \cdot \overline{OF} - X_{AF.Sky} \cdot \overline{AF}}{\overline{OA}} \quad (2.23)$$

$$X_{OF.Sky}^F = X_{AF.Sky}^F = \frac{1 + \cos \beta_p}{2} \quad (2.24)$$

Substituting equation (24) in (23) ;

$$X_{F.Sky} = \frac{1 + \cos \beta_p}{2} \quad (2.25)$$

- Front side view to ground

$$X_{F.grd} = \frac{X_{OF.grd} \cdot \overline{OF} - X_{AF.grd} \cdot \overline{AF}}{\overline{OA}} \quad (2.26)$$

$$X_{OF.grd}^F = X_{AF.grd}^F = \frac{1 - \cos \beta_p}{2} \quad (2.27)$$

Substitution of equation (27) in (26);

$$X_{F.grd} = \frac{1 - \cos \beta_p}{2} \quad (2.28)$$

- Rear side view to sky

$$X_{R.Sky} = \frac{X_{OF.Sky}^R \cdot \overline{OF} - X_{AF.Sky}^R \cdot \overline{AF}}{\overline{OA}} \quad (2.29)$$

$$X_{OF.Sky}^R = X_{AF.Sky}^R = \frac{1 + \cos \beta_p}{2} \quad (2.30)$$

$$X_{R.Sky} = \frac{1 - \cos \beta_p}{2} \quad (2.31)$$

- Rear side view to unshaded ground

$$X_{R-usgrd} = X_{R-DQ} + X_{R-CF} \quad (2.32)$$

$$X_{R-DQ} = \frac{X_{OF-DQ}^R \cdot \overline{OF} - X_{AF-DQ}^R \cdot \overline{AF}}{\overline{OA}} \quad (2.33)$$

$$X_{R-CF} = \frac{X_{OF-CF}^R \cdot \overline{OF} - X_{AF-CF}^R \cdot \overline{AF}}{\overline{OA}} \quad (2.34)$$

$$X_{OF-DQ}^R = X_{OF-FQ}^R - X_{OF-FD}^R = \frac{1 + \cos \beta_p}{2} - \frac{\overline{OF} + \overline{FD} - \overline{OD}}{2 \overline{OF}} \quad (2.35)$$

$$X_{AF-DQ}^R = X_{AF-FQ}^R - X_{AF-FD}^R = \frac{1 + \cos \beta_p}{2} - \frac{\overline{AF} + \overline{FD} - \overline{AD}}{2 \overline{AF}} \quad (2.36)$$

$$X_{OF-CF}^R = \frac{\overline{OF} + \overline{CF} - \overline{OC}}{2 \overline{OF}} \quad (2.37)$$

$$X_{AF-CF}^R = \frac{\overline{AF} + \overline{CF} - \overline{AC}}{2 \overline{AF}} \quad (2.38)$$

- Rear side view to shaded ground

$$X_{R-sgrd} = \frac{\overline{OC} + \overline{AD} - (\overline{AC} + \overline{OD})}{2 \overline{OA}} \quad (2.39)$$

Where the vectors equations are;

$$\overline{OA} = H_p \quad (2.40)$$

$$\overline{OF} = \sqrt{\left(H_p \cos \beta_p + \frac{E_p}{\tan \beta_p}\right)^2 + (E_p + H_p \sin \beta_p)^2} \quad (2.41)$$

$$\overline{OD} = \sqrt{\left(H_p \cos \beta_p - \frac{E_p \cos \alpha_s + H_p \sin(\alpha_s + \beta_p)}{\sin \alpha_s}\right)^2 + (E_p + H_p \sin \beta_p)^2} \quad (2.42)$$

$$\overline{OC} = \sqrt{\left(H_p \cos \beta_p - \frac{E_p}{\tan \alpha_s}\right)^2 + (E_p + H_p \sin \beta_p)^2} \quad (2.43)$$

$$\overline{AF} = \frac{E_p}{\sin \beta_p} \quad (2.44)$$

$$\overline{AC} = \frac{E_p}{\sin \alpha_s} \quad (2.45)$$

$$\overline{CF} = E_p \left(\frac{1}{\tan \alpha_s} + \frac{1}{\tan \beta_p} \right) \quad (2.46)$$

$$\overline{FD} = \frac{H_p}{\sin \alpha_s} \sin(\alpha_s + \beta_p) + \frac{H_p}{\tan \beta_p} + \frac{H_p}{\tan \alpha_s} \quad (2.47)$$

$$\overline{AD} = \sqrt{\left(\frac{E_p \cos \alpha_s + H_p \sin(\alpha_s + \beta_p)}{\sin \alpha_s}\right)^2 + E_p^2} \quad (2.48)$$

To calculate the electrical power output of the PV module the Shockley diode equation (49) of an equivalent circuit, parameters that are related to manufacturing process are extracted under STC, afterwards, the non-fixed parameters can be determined under actual conditions in relation with irradiance and cell temperature in equation (51) with reference values from STC I-V curve (Gu et.al 2020).

$$I = I_{ph} - I_d - I_p = I_{ph} - I_0 \left[\exp\left(\frac{V + I.R_s}{V_t}\right) - 1 \right] - \frac{V + R_s.I}{R_p} \quad (2.49)$$

For a number of solar cells N_s connected in series the equation becomes;

$$I = I_{ph} - I_0 \left[\exp\left(\frac{1}{V_t} \left(\frac{V}{N_s} + I.R_s\right)\right) - 1 \right] - \frac{1}{R_p} \left[\frac{V}{N_s} + I.R_s \right] \quad (2.50)$$

I_{ph} : Photo current

I_d : Diode current

I_p : Current through parallel resistance

I_0 : Diode reverse saturation current

R_s : Series resistance

R_p : Parallel resistance

V_t : Diode thermal voltage

$$V_t = \frac{n.k.T}{q}$$

n : Ideality factor, k : Boltzmann constant (1.381E), T : Cell temperature , q : electronic charge (1.602E)

$$I_{ph} = \frac{G_E}{G_{ref}} (I_{ph,ref} + \alpha(T - T_{ref})) \quad (2.51)$$

$$G_E = G_F + G_R \cdot \phi \quad (2.52)$$

G_F calculated from equation (19) and G_R from equation (21).

$$\phi = \begin{cases} \min\left(\frac{I_{sc,ref,R}}{I_{sc,ref,F}}, \frac{P_{max,ref,R}}{P_{max,ref,F}}\right) & , Bifacial \\ 0 & , Monofacial \end{cases}$$

2.10 Building Integrated Bifacial Photovoltaics

Building integrated solar system is defined as photovoltaic modules that replace building material partially or fully in many different architectural components of the house like Roofs, shading devices, envelope façade, glazed elements, curtain walls, etc. Figure 2.18 illustrates some possible integration methods of PV panels within a building.

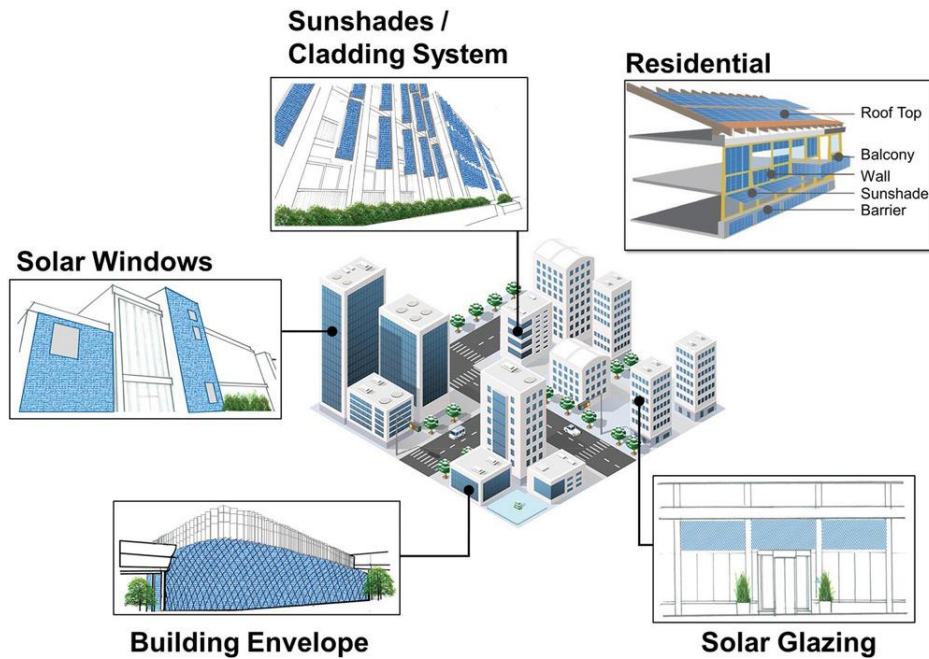


Figure 2.18: Different PV integration methods within buildings (Ming Koh et.al 2021)

Building integrated photovoltaics Bifacial PV is rapidly increasing due to several factors, like further enhancement in electrical and optical performance of Bifacial PV as well as its aesthetic developments (Chatzipanagi et.al 2016). Furthermore, according to new building codes, buildings are required to produce a minimum amount of electricity from renewable resources such as solar, and in most cases roof spaces are not sufficient to produce required loads, especially in high-rise buildings. Taking advantage of other components like the façade is a multi-beneficial application of photovoltaics, a higher square meter coverage of solar cells, building material savings and replacing normal glazing with low heat gain material, that end up reducing conductive heat gain (Cronemberget et.al 2014). Figure 2.19 shows different applications of Bifacial PV and its market status, where 80% of installed PV worldwide is roof application and 20% are different façade applications (Shukla et.al 2017). A market analysis report for BIPV application trends in 2021 revealed that façade application increased globally to 39% (Figure 2.20). This is due to increase of building material prices making BIPV facades more viable.

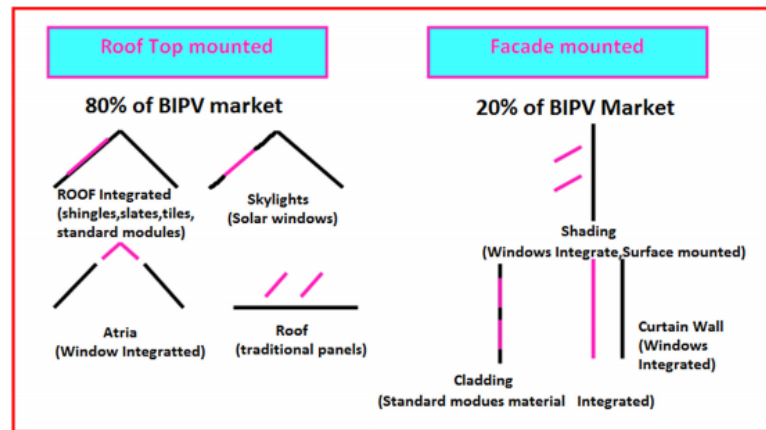


Figure 2.19: Bifacial PV applications in Market (Shukla et.al 2017. P 189)

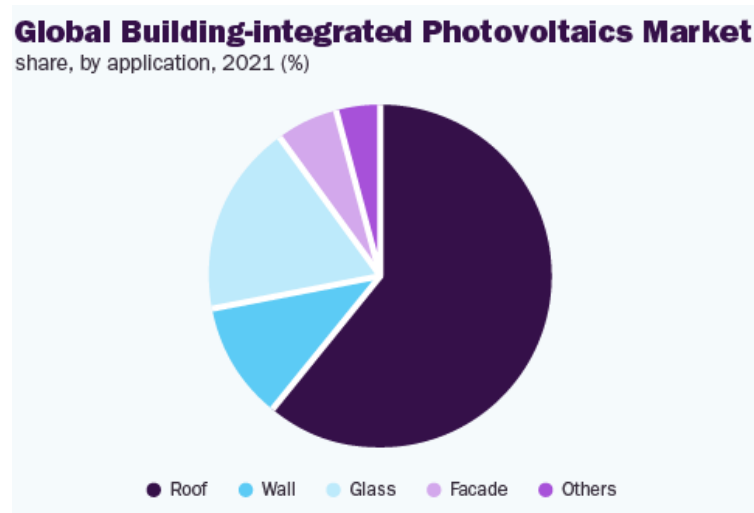


Figure 2.20: BIPV global market application distribution (GVR 2022)

Monofacial silicon based solar cells are commonly used for building integrated photovoltaics, however, several studies proved the additional efficiency in electrical yields when using bifacial solar cells. Reininghaus et.al (2017) studied n-type single junction amorphous silicon cells as vertical elements in Germany, documenting cells received 13% additional irradiance compared to traditional tilted south orientation, I_{SC} Bifaciality 98% and 99% for V_{OC} Bifaciality with a 0.4% efficiency increase from its Monofacial reference cell. A field experiment study in UAE examined energy yields of six different types of PV modules as BIPV, one of which is Bifacial Si based PV, with three different tilting angels 5°, 25° and 90°. Results shown in Figure 2.21 (Elnosh et.al 2018). Looking at Bifacial PV we observe that 90° tilt will produce lower energy yields than other two tilts, nevertheless, still higher than Monofacial PV modules. Moreover, 90° tilt lowest soiling loss (Figure 2.22).

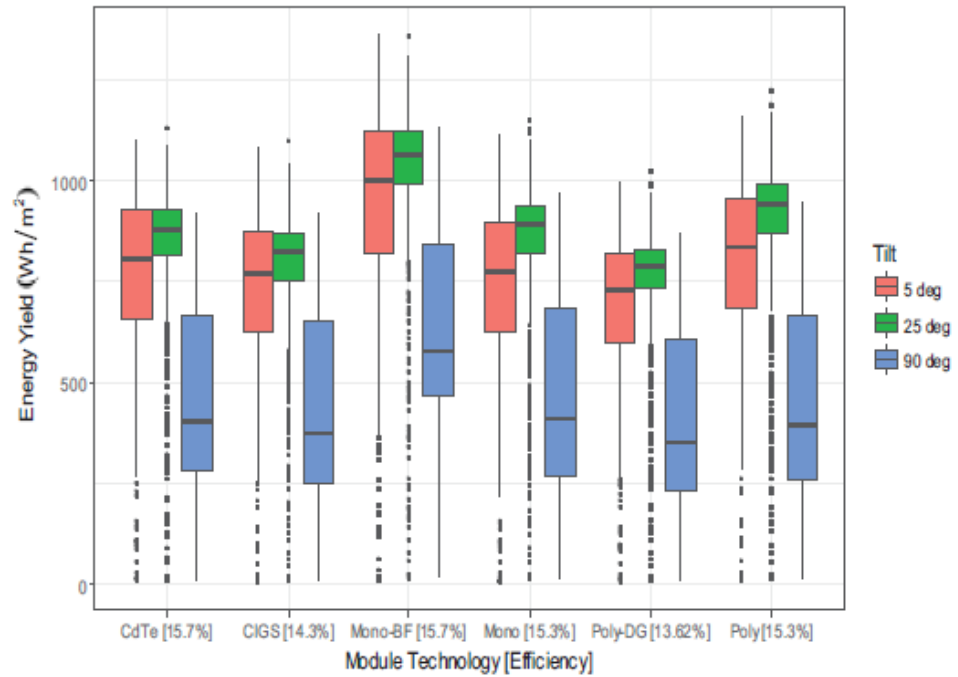


Figure 2.21: Different types of BIPV modules daily energy yields in UAE (Elnosh et.al 2018. P 566)

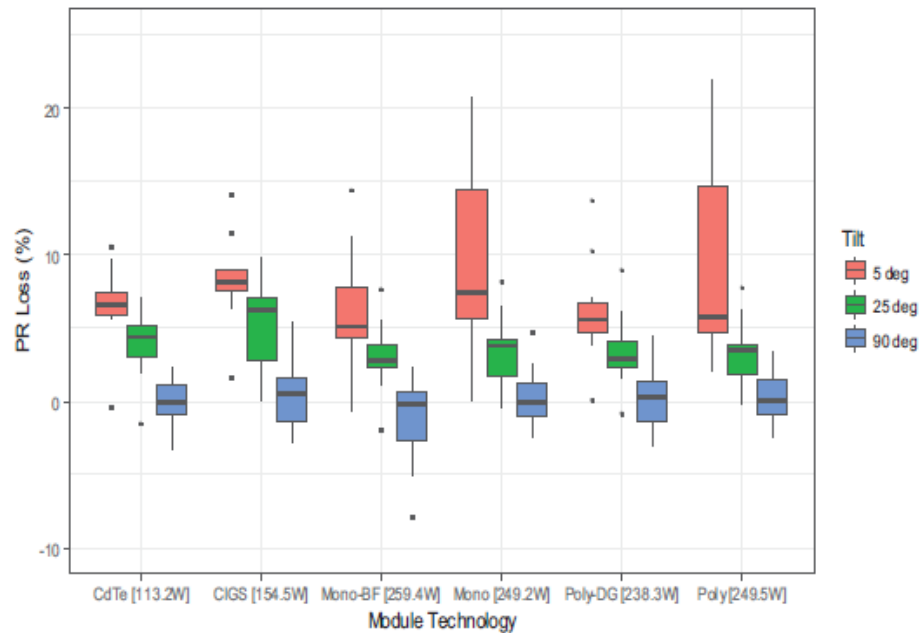


Figure 2.22: Soiling loss in different BIPV modules for three tilt angles (Elnosh et.al 2018. P 567)

A study by Assoa et.al (2021) applied field testing for a mockup building to compare the energy yields of bifacial PV panels as a vertical building integrated element with a Monofacial PV in

the exact same configuration. The study was carried out for a full year with readings for electrical outputs and panels thermal performance. The findings clearly highlighted that bifacial PV outperformed Monofacial panels with an annual bifacial gain of 22.48% varying from summer and winter, the results showed that bifacial gain is maximized during cooler months.

Utilizing bifacial modules as BIPV call for a defined distance between the panels and background surface to ensure sufficient radiation on rear surface of module. In a study by Moehlecke et.al (2013) of bifacial modules as part of building envelope-using panels integrated with reflectors, the study established a 35% boost in generating electricity reference to Monofacial modules of exact surface area. Another examined architectural configuration of BIPV, is bifacial solar module as a shading structure on the building with a 45° from windows with semitransparent reflector, light would pass within transparent gaps to be reflected by reflector material at the back surface, the gaps ratio within the bifacial module is 50%. This configuration achieved 37% performance improvement from a regular Monofacial module (Hazel 2003).

Performance of bifacial modules integrated as building elements is a function of multiple factors related to installation details, Figure 2.23 shows factors researched by Kang et.al (2016) for bifacial BIPV as part of building envelope, Kang investigated the module cell gaps ratio; space between solar cells within the module. His research established that 30% transparency within the panel provided higher electrical out puts when wall was painted light colors and 40% transparency with darker walls.

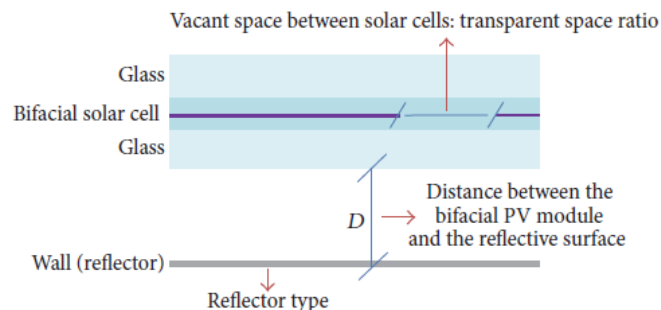


Figure 2.23: Factors affecting bifacial BIPV performance (Kang et.al 2016. P 3)

double skin façade setup, the objective is to study the effect of façade envelope material and the distance between BIPV and building envelope (gap distance). Façade material chosen for the study are commonly used façade material (glassing and cladding). Moreover, the study will be conducted for the specific solar profile of Dubai -UAE. After examining available research literature, such study specifically for bifacial BIPV facades performance under different façade material and gap distance is missing. This research seeks to answer this question and provide analytical analysis of different configurations that affects Bifacial BIPV performance.

CHAPTER 3

RESEARCH METHODOLOGY

In this chapter, research methodologies previously utilized to study the topic of optical performance for building integrated bifacial photovoltaics systems. Following the objective from this study for examining the effect of different façade material on the bifaciality factor of bifacial BIPV panels as part of a double skin façade system. The analysis of these methodologies will provide a solid reference to establish the optimal research approach for this study based on effectiveness and available resources. Investigating previous studies will establish the research boundaries, limitations, and restrictions as well as present necessary validation of approach and proof of concept to facilitate further enhancement to the nominated study approach. The literature review will be explored based on common denominators with the ongoing study given its multivariate, therefore, research reviewed are related to Photovoltaic technology, bifacial PV cells, building integrated solar modules, building solar facade and the combination of all. The subject of bifacial building integrated façade is relatively recent; thus, there are few studies of exact topic. However, studying vertical bifacial modules provided significant knowledge about the optical behavior useful for this study. For this research the parameter in concern is the optical behavior of rear ambient of bifacial modules to all solar irradiance types, specifically the inner façade material of the double skin façade system, requiring a ray tracing analytical foundation. Electrical yield change is due to variant optical changes for different architectural configuration of the double skin façade. Specifically, reflectivity and emissivity of the back surface material behind the BIPV, therefore, optimizing optical performance will produce higher electrical outputs. Four solar façade designs selected for this research based on available literature review is detailed in this chapter.

Structural details are the same across all scenarios, the variations between the study scenarios are the material of the façade and the gap distance between the façade and bifacial PV panel. First configuration is when the façade is clear glass, and the second skin is the bifacial PV panels as seen in figure 3.1. The gap between the two components is the other parameter analyzed, where four gap distances will be examined to highlight the effect on performance. Other façade material examined are reflective glass, white paint cladding and diffused white cladding. Various research approaches were utilized to study and analyze the performance of bifacial photovoltaic cells, different methodologies rise from different research objectives as well as availability of resources to conduct a comprehensive investigation. In this section, an identification and comparison of some research methodologies previously applied for similar subject is carried out with an objective of identifying the most suitable approach for the ongoing study. Three methods are examined: experimental testing, mathematical analysis, and computer simulation.

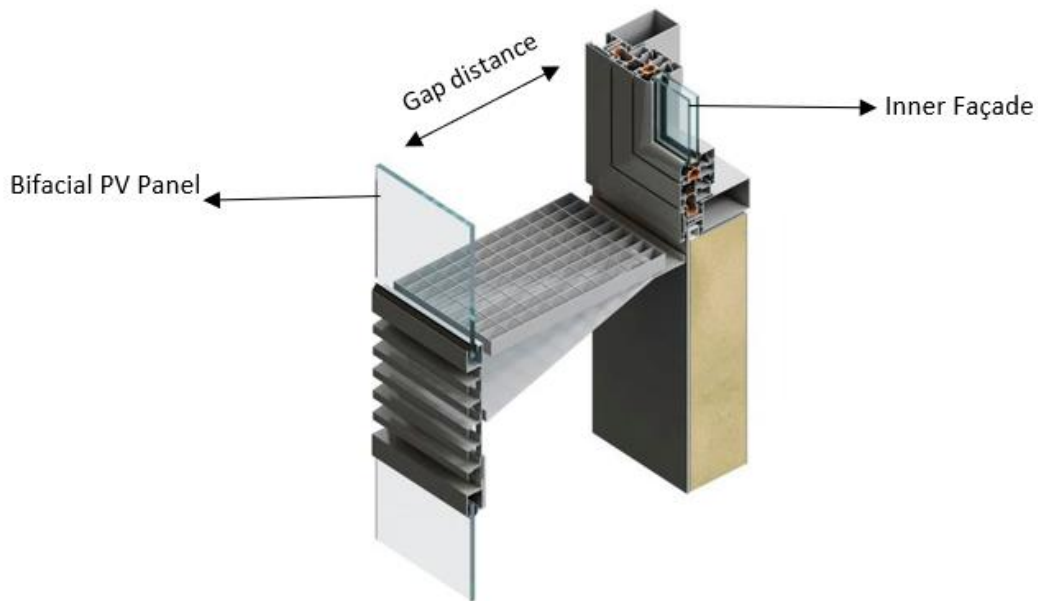


Figure 3.1: Double skin façade glass with aluminum structure (Archiexpo 2020)

3.1 Experimental testing

Experimental testing includes field and laboratory testing each with different set of variables. As the factors affecting the power output of back side of a bifacial panel are related to the type of bifacial cells, the environment surrounding the panels, reflectivity of surfaces behind the bifacial panel and the mounting details such as angle and elevation from ground. When evaluating one variable, all others are to be unified to neutralize their effect on the performance and isolate the results.

Malik et.al (2016) carried out a field experimental on silicon based bifacial modules in vertical configuration, both as standalone open field panels and building integrated, with comparison to Monofacial silicon panels in exact configurations. Main objective of the study was to investigate field behavior of rear side bifacial modules under various incident angles, research details setup, testing, and measurement sequence. with an individual-driven two-axis tracking system, the panels were tested for 90°, 180° and 270° tracker azimuth once with standard two axial sun tracking. Another with focus on back side and third being completely vertical. The results showed an incident irradiance(I_{sc}) gain of around 4-5% for the bifacial modules under clear conditions from its similar Monofacial module

Application of bifacial panels as building integrated elements the angle of inclination is also a concern. Frontini et.al (2016) analyzed five different integration scenarios of bifacial modules. Fully integrated as double glazed, ventilated units and different inclination angles 0°, 30° and 90° against different types of PV cells.

The effect of rear side characteristics has a major impact on bifacial module performance from an optical as well as thermal perspective. Experimental testing research addressed reflectivity and the heat up effect on bifacial module electrical production. Irradiance was examined in experimental research by Garcia et.al (2019) to determine the optimal distance between the solar panel and non-reflective back surface and its effect on rear irradiance and energy yields under solar irradiance (Figure 3.2). Ground or backside reflectivity is widely examined by many scientists and developers to optimize the installation conditions that will produce higher electrical power. Latest study by Zhang et.al (2020) tested three different ground configuration and effect of surface reflectivity on the thermal state of bifacial solar cells. Zhang et.al tested models on cement background, water, and grassland. Water surface background resembled the least heating effect followed by grassland then finally cement which had a significant impact on cell temperature which consequently affect cell current and degradation rates.

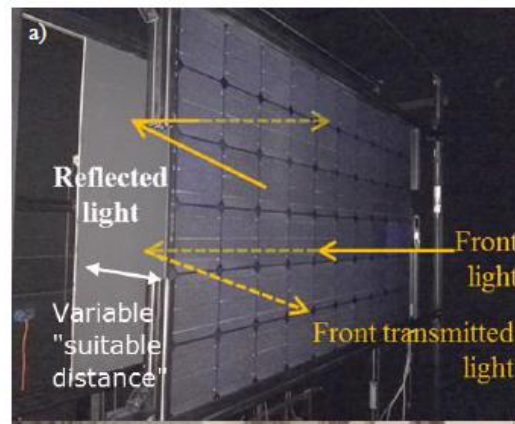


Figure 3.2: Garcia experiment setup of an open rack BIPV configuration (P 906, 2019)

Type of bifacial cell is the basic factor to address in experimental research. Muller (2018) compared different types of silicon based bifacial solar modules, in both laboratory and field conditions. Field experiment setting of a 75-80% albedo background and a 35% average irradiation gain. Muller examined the performance of two bifacial structures for a full year; n-PERT and P-PERC with a Monofacial n-PERT as a reference sample, the experiment showed that Bifaciality is not a constant value in field conditions, additionally n-PERT module has higher Bifaciality.

Moreover, the mounting scheme is one of the significant aspects investigated with accordance to its effect on bifacial solar module energy yields. A study by Dittmann (2018) investigated different mounting scenarios for open rack and façades, following the IEC61853 standards for measuring rear side yields. Deviation between mono and bifacial I-V curve is higher in open rack configurations than in façade mounting scenarios due to the cooling effect and enhanced optical performance. A field test research by Chatzipanagi et.al (2016) implemented bifacial panels in different configurations and inclination angles on the same structure as illustrated in

figure 3.3, the findings were that vertical panels showed higher overall front and rear energy yields than 30° and horizontal panels 0°.

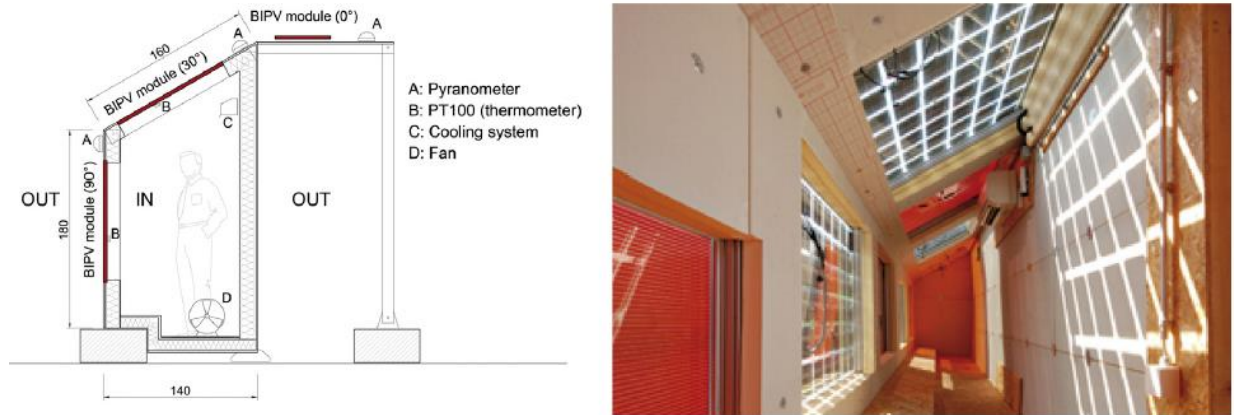


Figure 3.3: Different inclination installation of BIPV (P.4, Chatzipanagi et.al 2016)

Pros and Cons of Experimental Testing Method

Experimental testing whether it is a field test, or a laboratory test is the most direct approach to proof a hypothesis or a theory about a certain technology. Experimental validation is an inevitable step in any research process. This methodology has many pros starting with providing actual data of system performance under a set of conditioned designed by the researcher, experimental data has high reliability and can reveal new results that were not considered before by researchers. Following the scientific steps of testing the researcher will have control over test factors this is particularly for laboratory testing where there is complete control over environment and variables. Moreover, in experimental testing there is always room for improvement and advancement, the nature of trial in testing aids in defining cause and effect factors clarifying dependent and independent variables. When highlighting the advantages of experimental testing the most significant one is applicability to any industry or scientific field.

All mentioned advantages are encountered with disadvantages, firstly, human bias can affect in several forms as variable control selection, human error, and result interpretation. Secondly, selected sample may not be completely representative therefore produce artificial results. Furthermore, selected variable matrix might be tailored to a specific sample and cannot be grouped or duplicated for others. The integrity of the test highly reliant upon tools and equipment quality and capability, hence, the test is subject to available technologies to construct the experiment and conduct accurate measurements. In terms of resources, experimental testing is costly and time consuming.

3.2 Mathematical Modeling

The process of describing a system variables and performance in mathematics language is mathematical modeling; such models applied in natural science, engineering, economics and social science fields. In the field of bifacial photovoltaics, many researchers presented several mathematical modeling to different aspects of this technology; optical, electrical, thermal and combined models. Essentially these equations are the mathematical representation of the physics behind the phenomena related to that specific technology. Moreover, it is the bases of the logarithms for computer simulations.

In a paper by Tina et.al (2020) a mono dimensional multilayer model that calculates the cell temperature for both Monofacial and bifacial cells taking in account solar irradiance on the rear side of modules. The novel mathematical model is based on energy equilibrium equations for front and rear side. The model is for three layers of the panel, the output is cell temperature at each layer, which is typically difficult to measure, and the inputs are weather data with electrical yields, the model was validated against field measurements. The proposed model made of a serial compiling of layers. The energy balance equations are defined in the middle of each layer and three independent equations are derived calculating the three temperatures, T_{fg} = center of front glass, T_{pv} =PV layer and T_{bg} = back glass (Monofacial/bifacial module).

Front layer energy balance equation:

$$C_{fg} \frac{dT_{fg}}{dt} = (q_{r,fg-sky} + q_{r,fg-gr} + q_{conv,fg} + q_{cd,fg-pv} + q_{cd,fg-bg} + \Phi_1) \quad (3.1)$$

PV layer energy balance equation:

$$C_{pv} \frac{dT_{pv}}{dt} = (q_{cd,pv-fg} + q_{cd,pv-bg} + \Phi_2 + \Phi_3 + \Phi_4) \quad (3.2)$$

Back layer energy balance equation:

$$C_{bg} \frac{dT_{bg}}{dt} = (q_{cd,bg-pv} + q_{r,bg} + q_{r,bg} + q_{conv,bg} + q_{cd,bg} + \Phi_5). \quad (3.3)$$

In research by Zahng et.al (2020), they combined mathematical modeling with experimental testing for a steady thermal state model to measure bifacial module working temperature under different back surface albedo settings. Calculating module temperature based on the effect of ground type with different reflectivity and heat capacities with reference to view factor of backside, view factor is a means to compute radiant energy reflected from a surface and received by another. A comprehensive illumination model for a large field of bifacial PV panels detailed in a paper by Jager et.al (2020) it accounted for direct and diffused light as well as differentiating ground reflected light according to source from diffused sunlight and direct sunlight. The model determines the irradiance at many points along the panel, therefore, considering minimal irradiance affecting module performance. Accurate calculation of illumination leads to accurate calculation of energy yields. Direct normal irradiance and diffused horizontal irradiance adjusted as per Perez model used as inputs. Jager et.al (2020) assumed that the field is so big that surroundings have no effect on modules; they also assumed

the panel homogeneous with no spacing between cells to analyze the model as two dimensional with intermittent limits. Irradiance I is based on radiance (L) watt per steradian per meter square. An integral equation for a range of coordinates among the panel with respect to the polar angle of azimuth and the angle between the evaluated ray and the normal to the surface, the cosine of this angle as per Lamberts law calculates the decrease of beam irradiance with the increase of the angle.

$$I(r) = \int_{\Omega} L(r, \theta, \varphi) \cos \theta \cdot d\Omega \quad (3.4)$$

where Ω is the set angles of the analyzed wedge. θ is the angle spanned between the directional unit vector the normal n . n is either the module normal n_m or the normal to the ground n_g .

$$d\Omega = \sin \theta \cdot d\theta \cdot d\varphi$$

A three-dimensional model is proposed by Galluzzo et.al (2020) where the mathematical model is a function of tilt angle, height, and albedo. Effect of adjacent area around string of 30 or 60 modules is accounted for in the model. Galluzzo et.al assumed two scenarios first with a fixed tilt according to latitude and facing south and a second with a uniaxial solar tracking system and calculated for different geographical locations, the model was validated with field testing data. This research proofed the significant effect of surrounding area size on the energy yields of bifacial modules using differential equation of global irradiance with reference to ground area (dA) then carrying the integral for full surface to calculate the short circuit current once for front side and another for rear side. A more direct approach previously suggested by Singh et.al in 2014 based on an assumption of linear current- irradiance response. The PV module treated as a Monofacial panel when front side yield calculated with rear side covered in matt concealment, similarly for rear side, covering front side and illuminating the back to calculate short circuit current and open circuit voltage, moreover, calculating fill factor, Bifaciality and efficiency.

Pros and Cons of Mathematical Modeling Method

Mathematics is the language of science, when making any hypothesis it must be presented with mathematical equations and based on a proven scientific concept, which will be the reference for establishing a new mathematical model. Therefore, in any research methodology chosen by scientists, mathematical modeling method is integrated either directly or indirectly. This research methodology is an easy and fast approach, simplify complex schemes and provide complete control over variables by creating assumptions or deliberately neutralizing specific factors, hence, scheming dependent and independent variables to investigate the hypothesis integrity.

Moreover, mathematical analysis enables predictions based on the core scientific concept of the study and facilitate the flexibility to examine different scenarios. Mathematical modeling aids with understanding the real-world behavior while presenting a model repeatedly applicable for similar studies, additionally, offer a base to establish other mathematical models. Disadvantages of mathematical modeling is generated from the assumptions made by the researcher and the process of manipulating the variables, the more factors were neutralized the further away the model from real life behavior, therefore, the integrity of the model depends on the quantity and accuracy of data included in the study. Limited data and inputs will produce an unrealistic model, too many variables compromise reliability of dependent outputs and makes it extremely hard identify and isolate ineffective elements. Most researchers consider mathematical modeling as a part of a more holistic research process and not an autonomous methodology to verify a hypothesis. Since the mathematical model is unable to include all dependent and independent variables at once, it is merely considered as a simplified interpretation of a real-life problem.

Mathematical models with the use of computer mathematic software like Matlab and Analytica increase the application of mathematical model and facilitate integrating more variables, hence, producing faster more accurate results for larger amount of data. Furthermore, applying mathematical models with these softwares provide the base for simulation modeling and visual data presentation software.

3.3 Computer Simulation

With the advancement of simulation software, many recent studies are, partially or completely, based on a virtual simulation of system scheme and its environment. To estimate energy yields of bifacial modules it is crucial to analyze illumination models. In order to model a virtual representation of a bifacial solar system and accurately predict optical performance, irradiance must be accurately calculated for front and back sides as well as modeling system aspects that affect the panel performance for example mounting scheme, tilt, clearance, modules per row, number of rows and size. The second set of parameters are related to the surroundings such as albedo, nearby obstacles, reflections and shading around system. Furthermore, parameters for illumination accurately modeled; sun position, weather profile and radiation components direct and diffused. Most commercial software available calculate front side radiation for typical Monofacial solar panels. Whereas for a bifacial system, rear-side irradiance analysis must be included for direct, diffused and ground reflected illumination. To do so, modeling softwares are based on three main techniques; raytracing analysis which calculates all possible reflection and absorption paths of a single ray falling on to an object. Secondly, View factor technique that calculates different segments of irradiation from sky, ground and diffused. The view factor technique accepts an isotropic illumination scattering. Third technique is the empirical model, based on the combination measurements of direct and diffused irradiation; it is a simplified

approximation of rear side share of surrounding irradiation. Table 3.1 list some of widely used softwares for bifacial computer simulation and the technique it applies (Silvana 2019).

Table 3.1 Bifacial computer simulation software (Silvava 2019)

Software Name	Technique	Additional notes
Polysun model www.solarworld.de/fileadmin/calculator	Empirical	Include different installation schemes.
Prism Solar Model	Empirical	Two models available with preset parameters.
NREL view factor (VF Model) https://github.com/NREL/bifacial_radiance	View Factor	Consistent array layout assumes infinite number of rows.
PVSyst www.pvsyst.com	View Factor	Based on infinite rows. Lambertian isotropic sky.
NREL Radiance Bifacial Model https://github.com/NREL/bifacial_radiance	Raytracing	Utilize reverse raytracing and any number of rows.
FRED-Bifacial Raytrace https://github.com/shirubana/FREDGenCumSky	Raytracing	Utilize reverse raytracing and any number of rows. Complex schemes
SunSolve v5.2.9	Raytracing	Specific system parameters available. Ignores surrounding environment.
TracePro LAMBDA software	Raytracing	Various Illumination and optical scenario analysis.

Kim Lo et al. (2015) developed a simulation tool using several open-source software to estimate annual energy yields of bifacial photovoltaic panels with reflectors, the tool considers the thermal and optical changes through the day on the front and rear side of PV panels, the objective of the research was to optimize the surrounding objects reflectivity to increase electricity production. To begin with, the simulation tool inputs the climatic data of a specific geographical location to conduct required irradiance data using the open-source tool SMARTS. Utilizing the software RADIANCE for specified installation and surrounding environment is simulation using a reverse raytracing method. Solar cell design and materials are modeled using PC1D subsequently, cell properties with irradiance results the tool can simulate the I-V curve for each solar cell then calculate I-V curve of the solar panel to get maximum power point power and finally obtain time related power values.

In another study by Asgharzadeh et al. (2019) both raytracing and view factor-based simulation softwares were used to validate four commercial types of bifacial panels against field measurements, results show that softwares using straight forward view factor method did not vary in accuracy from complex ray tracing tools. Customization of existing simulation methodology to adapt for bifacial cells accounting for rear side additional conversion is a straightforward way to estimate power generation. Katsaounis et al. (2019) developed a 2D simulation tool integrated from the mathematical transport equation solution using finite element approach, inherent – plain alternative of Newton’s method to linearize the conversion where each equation is solved independently. Surrounding reflections, shading and temperature dependence parameters were considered within the tool.

In 2014 research by Yusufoglu et al. for the conference on silicon based photovoltaic cells a simulation tool based on view factor irradiance analysis and a predetermined I-V data and fitted into two diode circuit and an 80% Bifaciality. The research focused on the effect of module height, tilt, and albedo on annual energy production (Figure 3.4). Research established that a 2 meter distance between modules and ground increased energy yields by 30% than closer installations. That and a linear relationship between ground albedo and energy yields (Figure 3.5).

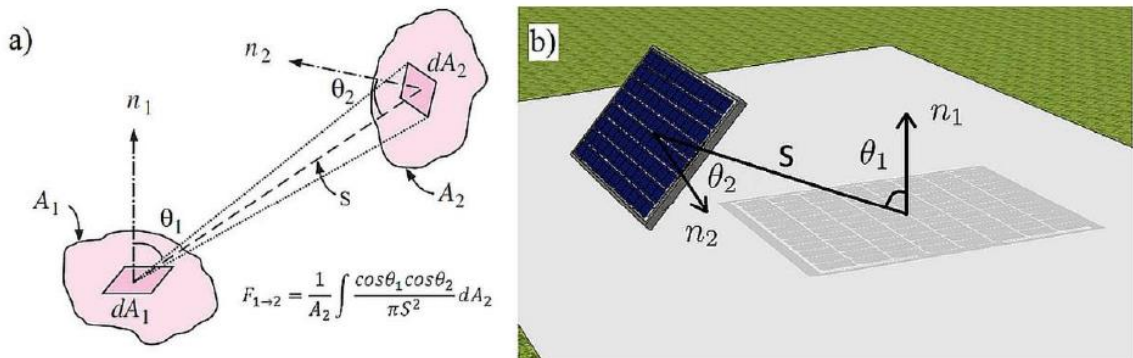


Figure 3.4: a) View factor analysis and; (b) application for the ground reflected radiation
(Yusufoglu et al. 2014)

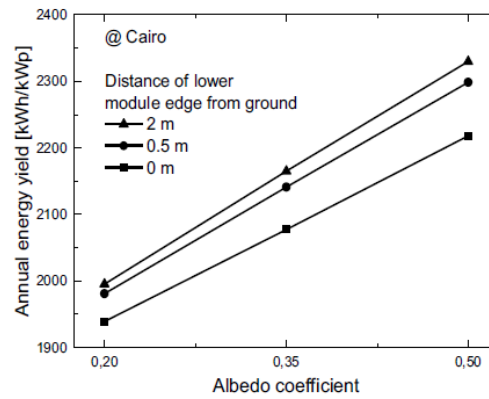


Figure 3.5: Relation between albedo coefficient and annual energy yields (Yusufoglu et.al 2014)

Third technique applied in computer simulation of optical performance is the ray tracing technique. Softwares like TracePro and SunSolve apply the methodology of tracing each ray from its source through all the different probable paths for that ray. In a study by Liang et.al (2020) TracePro tool was applied to validate the technical requirements of four commercial bifacial modules with different back-panel material against the standards published by the International Electrotechnical Commission. Modeling the illumination on the non-irradiant side of the panel for 1000 W/m² irradiance using a solar simulator within the software testing different configurations of surface characteristics, results were presented in form of irradiance maps for the different designs such as the example in figure 3.6.

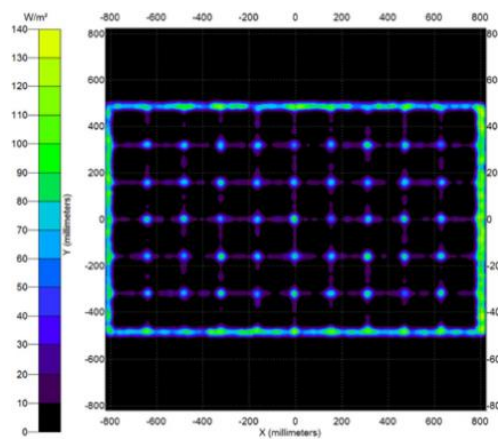


Figure 3.6: Irradiance map of configuration A1 in Liang research (P 13, Liang et.al 2020)

In a study by Soria et.al (2015) TracePro was applied to validate field testing results of vertical bifacial PV compared to mono facial PV test size panel. Field testing set up shown in figure 3.7 whereas TracePro simulation results illustrated in figure 3.8 in form of irradiance map.

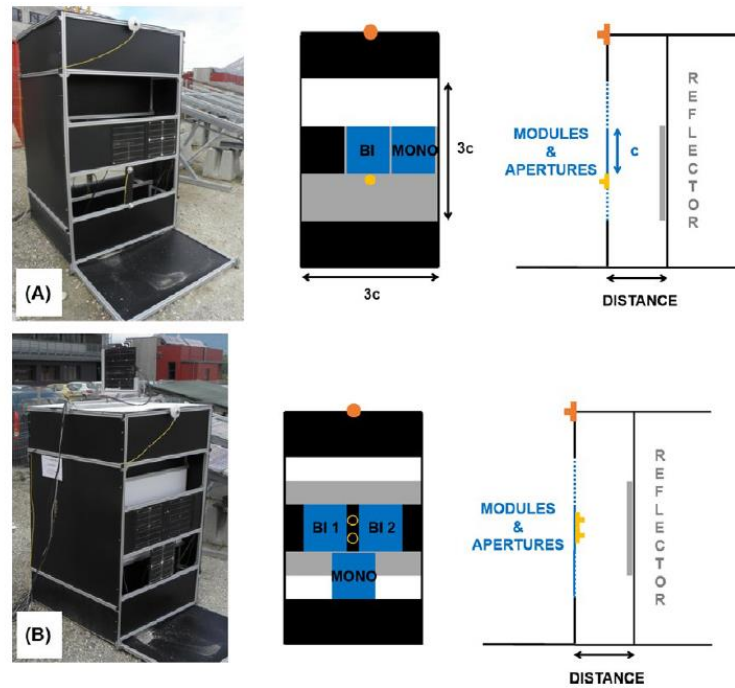


Figure 3.7: Picture and schematics the test bench for field testing (P56, Soria et.al 2015)

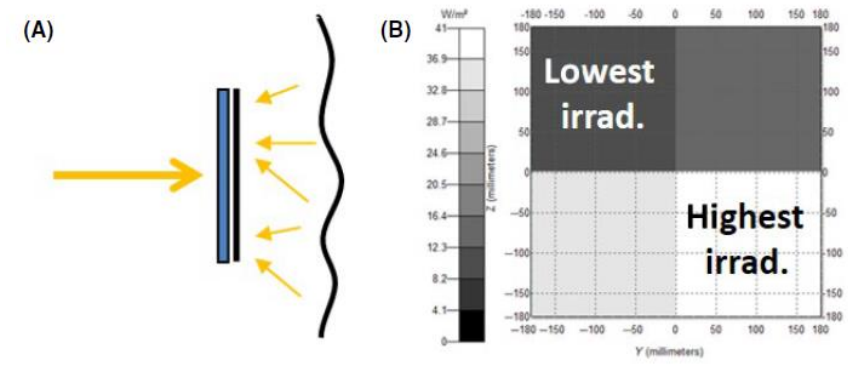


Figure 3.8: TracePro irradiance map simulating field test parameters (P57, Soria et.al 2015)

Pros and Cons of Computer Simulation Method

Simulations are an excellent tool for areas of high uncertainty where it can produce outputs with limited inputs, where the software itself is designed to fill the gaps, thus modeling the system with minimal requirements and be able to provide answers for very specific questions. Moreover, computer simulation of the system allows unlimited what- if scenarios to be applied providing researchers with the opportunity to easily test and analyze every theory the study produces as well as forecast additional new scenarios that did not occur yet. Computer simulation softwares support innovation and outside of the box type of thinking that would not be easily applicable using currently available technologies. Perhaps the most vital benefit of software modeling is its low-cost low risk characteristic compared to field-testing and other experimental approaches, and with time being the most critical resource in the rapidly accelerating fields of technological research, computer simulations can reduce significantly research time from years down to few months. Additionally, permit ultimate control of all variables as well as the flexibility to modify study environment either to analyze what already happened or to forecast what might happen.

On the other hand, confidence in a simulation tool competence to reflect actual system dynamics requires validation across authenticated data, validation process is nothing but simple and calls for various data resources where a certain percentage of discrepancies are inevitable. These discrepancies are minimized by adjusting the theoretical guidelines controlling the simulation and continuously testing until the simulation tool is calibrated and validated or else the analysis holds no credibility, those adjustments can balance the variables on one side and disrupt on another, thus, the researcher must find the optimal balance that produce the best results.

Another disadvantage of computer simulation is that like every technology it depends on the user input data, if the inputs are accurate the output will be accurate, therefore, the qualifications of the scientist in operating the simulation tool has an immense effect of the research quality. In some cases, the research is limited by the capabilities of the software itself where not all variables and tasks can be integrated. Moreover, because computer simulation is a relatively new approach some people in the research field are skeptical and conservative about this novel method. This however is decreasing with the increasing number of successful simulations-based research published in past few years.

3.4 Research Plan and Methodology of Choice

This research objective is to compare the energy yields of a silicon-based building integrated bifacial module in different architectural façade schemes in Dubai-UAE, the performance of rear side bifacial panels depends significantly on reflectivity, irradiance distribution due to surrounding environment, thus, directly affecting the optical behavior of bifacial solar cells.

The existing literature discussed the effect of reflectivity, albedo coefficient of surrounding surfaces and dimensional special parameters. This study aims to cover the effect of different façade material with four spacing between the bifacial PV panel and the building envelope. Study results is presented as a ratio between front side incident irradiance and back side incident irradiance. This ratio is used to calculate overall bifacial panel electrical energy yields.

The study objective achievable in all previously discussed research methodologies. Experimental testing by means of test size mockups for each façade configuration under real time irradiance and climatic considerations. Mathematical modeling by using existing optical and electrical models for tilted bifacial then adjusting the angles to fit vertically mounted modules. Lastly, computer simulation by modelling all façade schemes and run a simulation specifically for Dubai-UAE solar data and optical profile to analyze and compare electrical performance of bifacial modules in different façade configurations of building integrated PV façade.

For this research computer simulation is the methodology of choice using TracePro software. By crossing four sets of variables representing different façade material with four envelope gap values (distant between façade and bifacial module) based on previous research. Total of Sixteen schemes were developed as detailed in matrix below

According to the literature the main objective of the gap in a double skin façade is to achieve an effective air flow within cavity, which aids in cooling the envelope and the PV panels, consequently increasing energy outputs (Loncour et.al 2005). The gap width between 500-2000 mm considered accessible to people while serving as an air cavity within the double skin façade. For gap width above 2000mm the cavity will be regarded as an atrium that also functions as a ventilated air cavity.

In the case of bifacial PV panel integrated within the second skin of the façade, that gap have an effective role in enhancing the optical performance of the bifacial panel as analyzed in this study. The choice of the four gap distances simulated in the research is based on previous literature. In a study by Yusufoglu et.al (2014) the performance of bifacial modules was tested for different ground reflection values and distance between the PV panel and the ground surface, specifically 0.5, 1 and 2 m from lower edge of module to ground. Results showed a linear relationship between albedo coefficient and energy yields with higher yields for larger distances. In this research the modules are vertical where the distances between façade and bifacial module (gap distance) are based on previous studies. Schemes were modeled to identify irradiance on back surface of the bifacial module and its ratio to front of the bifacial PV panel, schematics of the modeled setup illustrated in figure 3.9.

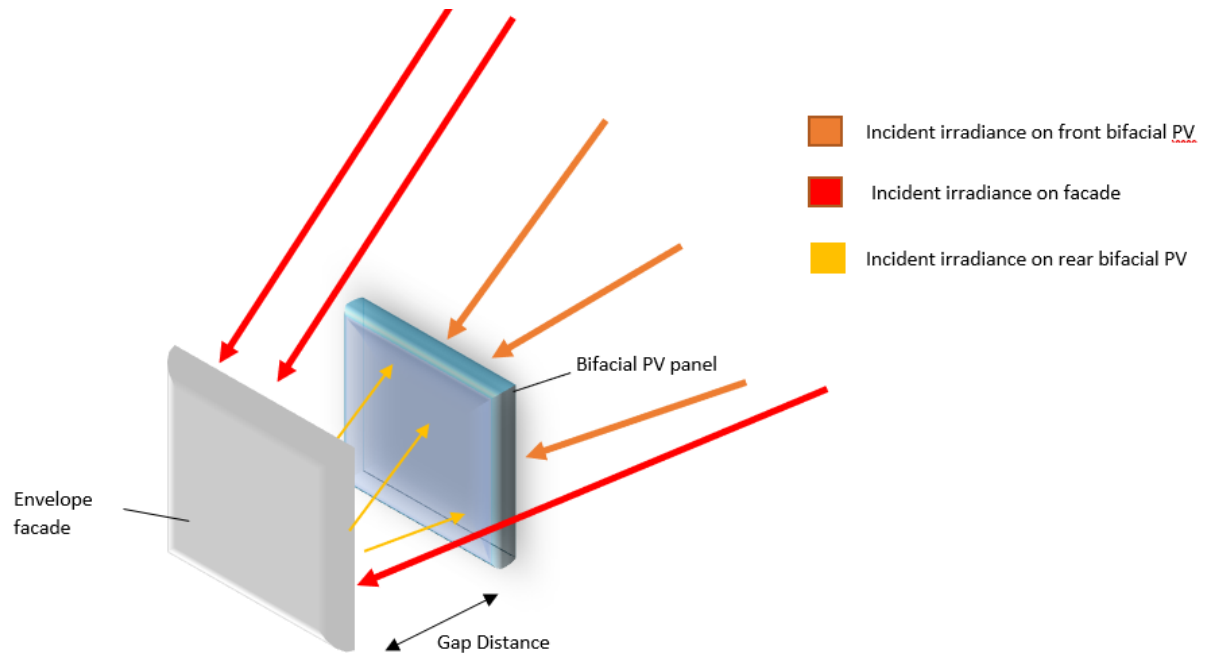


Figure 3.9: Schematics of modeled setup

Second set of variables is related to the façade material that are typically used by the industry. Brennan et.al (2014) studied the effect of spectral albedo on different solar photovoltaic types, they tested 20 different materials usually occurring in industrial, commercial, and residential settings. Material implemented in this study exhibited highest potential energy yields. First scheme is an envelope of a typical glazed façade and bifacial PV panels where the envelope is 0.5, 1, 2 and 3 meters consequently. Second scheme is with a reflective glass façade with four envelope gaps. Third façade simulated is with white paint. Last façade scheme simulated is reflective white paint façade and bifacial PV panels at same gaps used for all simulations (Figure 3.10). The effect of shading from adjacent objects is neglected and only shading from the PV module itself is analysed within the simulation.

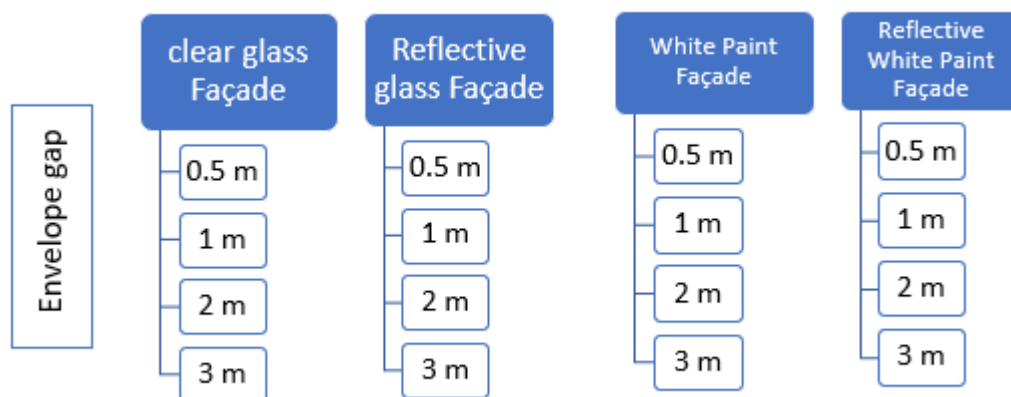


Figure 3.10: Simulation matrix of different façade schemes (Author 2021)

The choice of simulation software was based on the ability to model required settings and flexibility to choose material. Further to exploring bifacial simulation tools in the literature review and examining each software capabilities, as mentioned in previous section. It was concluded that TracePro® complies with all study requirements. With a CAD graphical interface, this allows import and export from any CAD software. TracePro®, a tool developed by Lambda laboratories for illumination and optical design and analysis with the option to both visually and numerically present simulation analysis. TracePro® includes an advance solar emulator that runs simulations for precise period of sun travel for irradiance analysis for direct and indirect solar illumination. TracePro is a professional; software that considers reflection, refraction, scattering, absorption, and aperture diffraction of light. Analysis of simulation results are displayed by candela plots, irradiance maps, tabular form, and contour maps. The software is based on the Monte Carlo ray tracing methodology, utilizing optics geometrical principles, probabilities, and statistical applications to achieve a full and comprehensive optical analysis.

Defining the ray by its original source point and the path which the ray travels through reflecting, diffracting, or scattering along the way to the end point defined by the exit surface in TracePro. A random start point is chosen within the emitting surface, taking in consideration the properties of emitter as well as the characteristics of irradiance whether it is random or directional. For instance, for a Gaussian source(diffused) the surface normal required to determine direction post contacting the model, reflected, refracted, or absorbed. Furthermore, the new direction of the ray will be estimated and so on multiple times for the same ray until the ray is out of the system (Senjyu et.al. 2021).

Irradiance source will define the method of ray launching for the model, in this case the sun, therefore the solar emulator will be activated, this enables the analysis to be for a specific geographical location. Solar source emissivity spectral type is the standard solar spectrum ASTM E-490-00 a radiometric irradiance source with emission value of 1366.1 W/m^2 , spectrum range from 0.1195 um to 1000 um (TracePro® 2020). Further to running full simulation, the irradiance quantification absorbed by both front and rear surface of bifacial PV panels through one year will produce the annual energy yields based on a specific type of bifacial modules I-V curve. Results of all proposed façade schemes as irradiance maps of incident and reflected irradiance will be analyzed and compared. highlight all differences in terms of reflectivity and rear side optimization. The ratio between bifacial PV panel front incident irradiance and back PV incident irradiance is calculated for each scenario. This ratio defines the energy yields of the overall panel. Based on this analysis the optimal façade design in terms of envelope material and gap distance is determined.

CHAPTER 4

COMPUTER SIMULATION

4.1 Simulation Setup

The study focusses on the reflectivity of light from the first façade skin to the back of the bifacial PV panel acting as the second skin within Dubai-UAE irradiance parameters for a specific date and time. Ray tracing takes in account incident, reflected, absorbed, scattered, and diffracted light rays based on object material and object surface properties. After analyzing computer software applied in available literature of bifacial PV as discussed in chapter 3, TracePro was chosen to carry out the simulations of this research. The software applies generalized ray tracing methodology and keep track of the optical flux correlated with each ray. The software operates with the Monte Carlo ray tracing methodology which is a statistical application of each light ray geometry given the initiated point of the ray and its exit surface (the surface where the light projected at). For this study the source of the light is the sun, therefore the TracePro solar emulator is launched for the coordinates of Dubai- UAE.

TracePro solar emulator setup requires that the simulation boundaries in terms of time to be determined, start and finish date and time. The day and time chosen for this study is based on when the sun is highest in the northern hemisphere. Another boundary to be fixed is the duration of the simulation. Multiple trials carried out for different duration prospects, taking in consideration simulation running time, which increase substantially with the increase of time, and the value of the added data to the study integrity. Therefore, a one-hour frame was chosen as an optimal simulation duration. Consequently, the simulation takes place for sixty minutes from 1pm to 2 pm. The date chosen for the simulation is middle of summer (15th August). Figure 4.1 is the annual solar path for Dubai location showing the solar path for the selected date of simulation. The cartesian chart (Figure 4.2) and solar elevations in table 4.1 clearly illustrate that the highest sun elevation is between 1pm to 2pm.

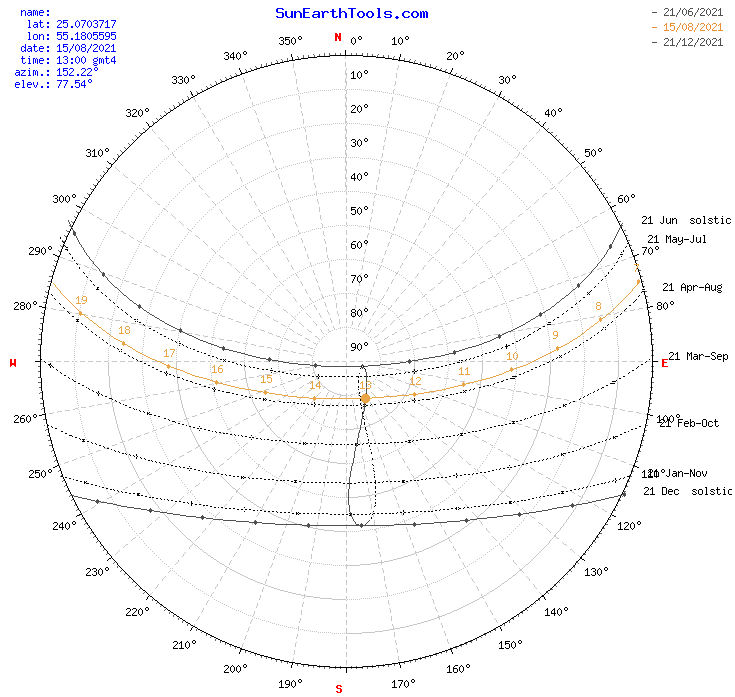


Figure 4.1: Annual Solar path for location Dubai -UAE (Sunearthtools.com)

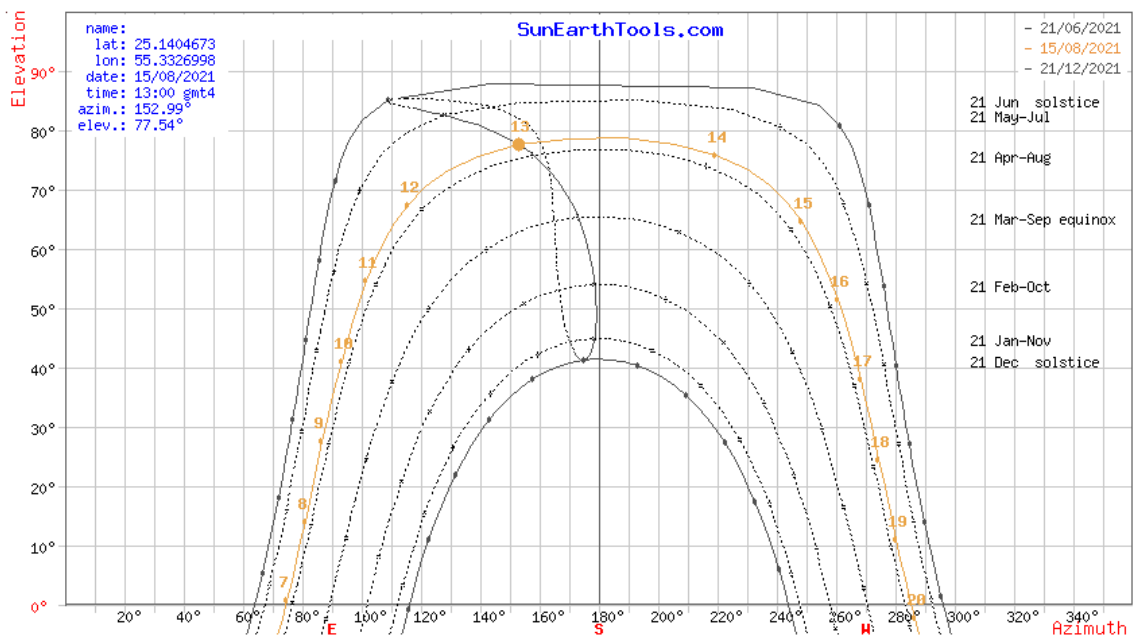


Figure 4.2: The cartesian chart for location Dubai-UAE (Sunearthtools.com)

Table 4.1: Solar Elevation and Azimuth for simulation date and location (sunearthtools.com)

Date:	15/08/2021 GMT4	
coordinates:	25.0703717, 55.1805595	
location:	25.07037170,55.18055950	
hour	Elevation	Azimuth
06:53:10	-0.833°	74.08°
7:00:00	0.65°	74.81°
8:00:00	13.93°	80.84°
9:00:00	27.42°	86.68°
10:00:00	41°	93.06°
11:00:00	54.47°	101.35°
12:00:00	67.39°	115.53°
13:00:00	77.54°	152.22°
14:00:00	75.97°	219.07°
15:00:00	64.78°	248.26°
16:00:00	51.68°	260.55°
17:00:00	38.15°	268.25°
18:00:00	24.57°	274.42°
19:00:00	11.09°	280.24°
19:54:02	-0.833°	285.73°

Simulation setup data (figure 4.3) includes location coordinates and period. The geographical location and sun trajectory is illustrated in figure 4.4 for the chosen simulation period as presented by TracePro. The solar source will be at its estimated position as per latitude and relative noon hour. TracePro simulation design is based on a Lambertian scatter model of a 0.55° scatter angle, equally scattering incident illumination in all directions.

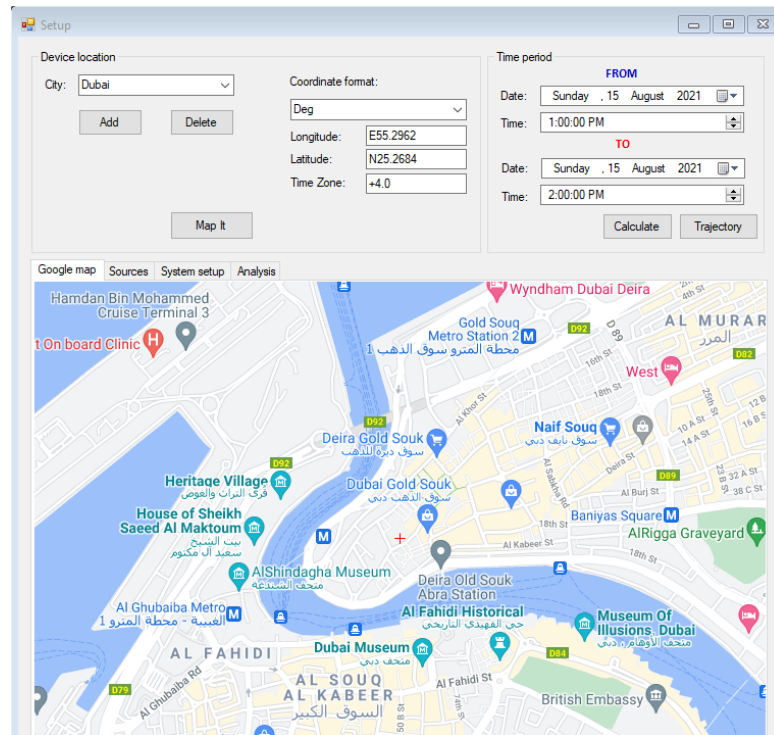


Figure 4.3: Location, date, and time setup of solar emulator simulation (TracePro 2021)

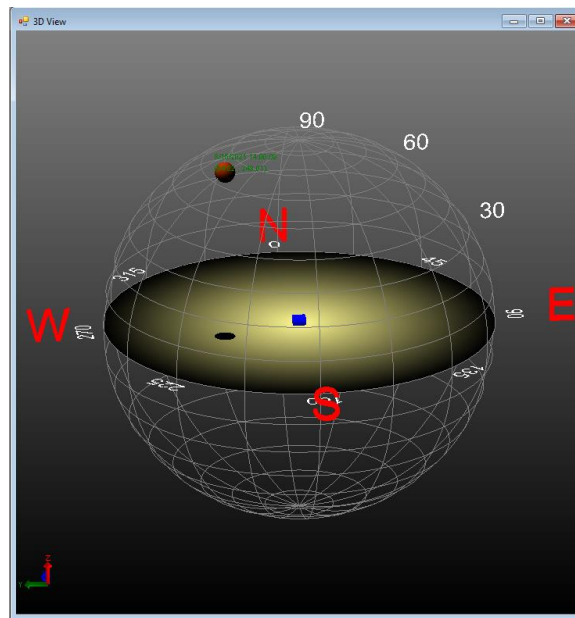


Figure 4.4: 3D representation of sun trajectory (TracePro 2021)

The second step in setting up the solar emulator is determining the solar model. As recommended in software manual the Igawa all-sky model was chosen with clear sky conditions. All values in the Sources window are auto calculated by TracePro (Figure 4.5) most of which can be altered upon request, here I have adjusted the number of rays to 10000 for clear simulation results.

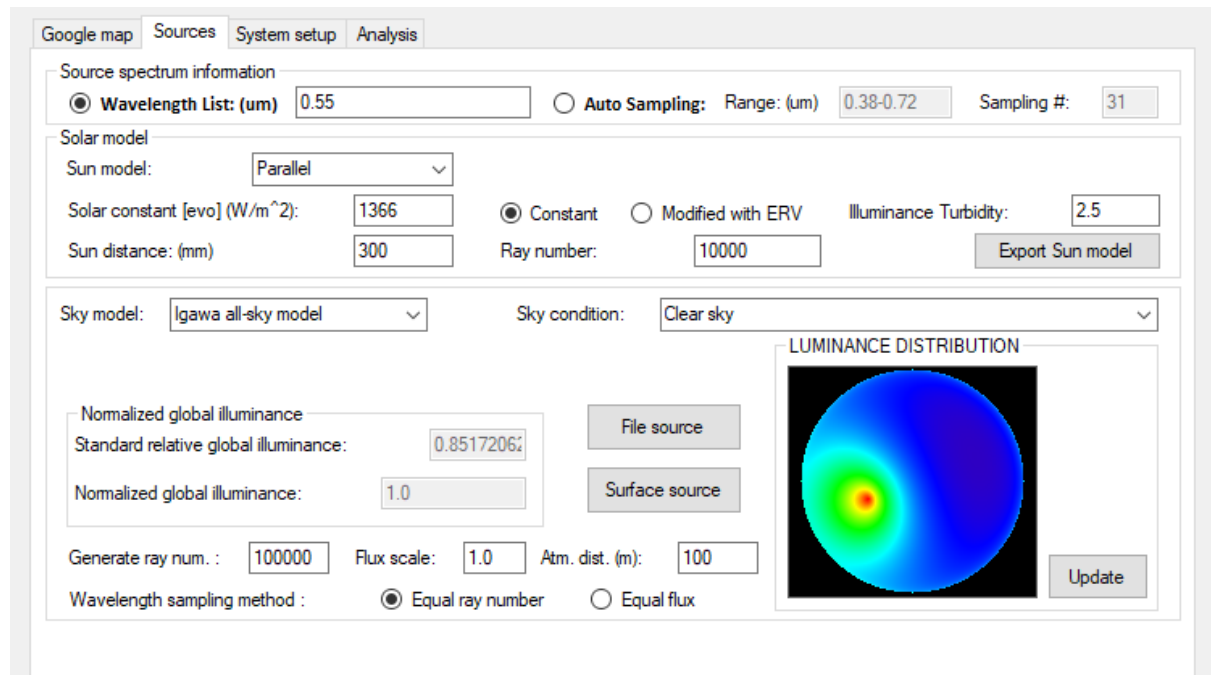


Figure 4.5: Solar emulator sources details (TracePro 2021)

4.2 Modelling façade schematics

The next step is the system setup, here the localized coordination's are determined to control the dimensional relation between irradiance source and object of study, display luminance distribution and determine sun tracking features (figure 4.6). TracePro is designed to simulate relatively smaller objects, therefore, modelling the entire façade is not possible. Moreover, the objective of this study is to examine the amount of light incident to the back side of bifacial panel with the effect of different façade material, this can be analyzed per meter square of the double façade system. Hence, a 1 x1 m sample of both components of the building integrated bifacial PV double skin façade was modeled within TracePro as per chosen simulation matrix to facilitate comparison of results and disregard diffracted rays from adjacent façade component and focus on normal to surface solar irradiance path. Figure 4.7 shows the model setup and all specified surfaces.

Following TracePro recommendations, for the bifacial PV represented by the blue sheet, both front and back surfaces are assigned as exit surfaces with a perfect absorber property to focus the research on the reflected, diffracted and absorbed rays from the inner façade skin. As for the façade (grey sheet) only the outer pane is an exit surface and material changes based on the façade schematics specified in the simulation matrix. Indicated model represents the glassed inner façade with a 1 m distance between the two skins. The green circular object represents the solar irradiation source, the sun, with emitting irradiance of 1034.44 W/m^2 , as illustrated in figure 4.1.5. the value of the emitting irradiance is a product of the solar emulator simulation.

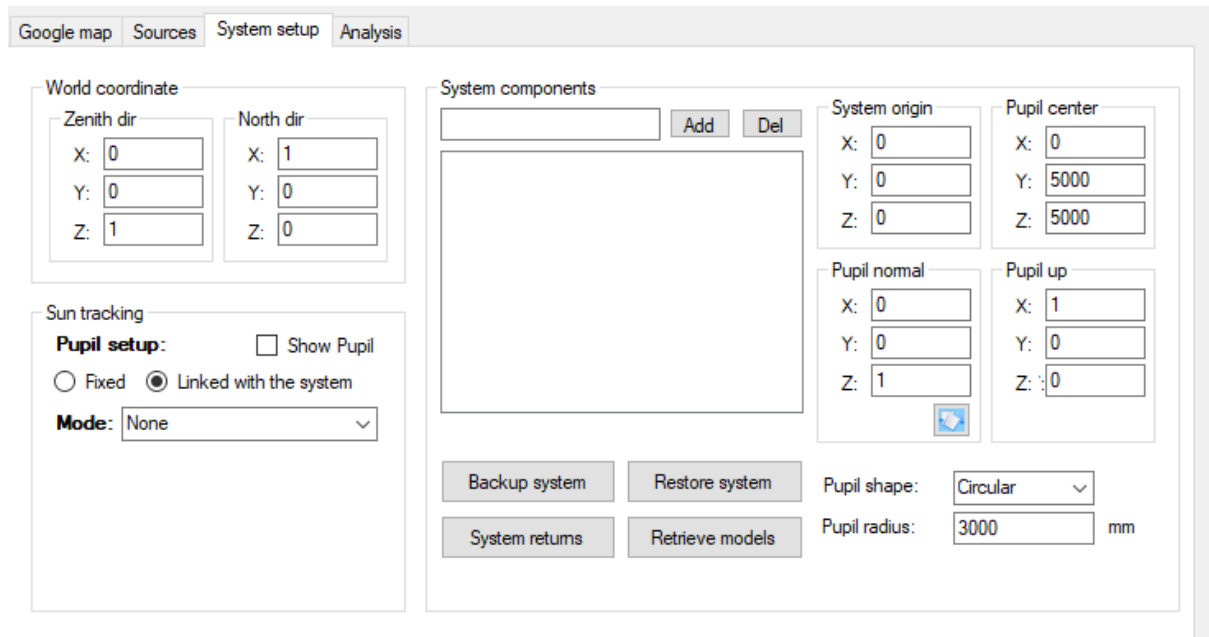


Figure 4.6: System setup window (TracePro 2021)

After launching the solar emulator analysis, the results are represented as both graph and table for total flux on the facade surface for each simulation interval, here it is 15 minutes as seen in figure 4.8. The façade total collected energy is 223171.75 Wh with a peak irradiance flux of $3.37 \times 10^5 \text{ W/m}^2$. In the result viewer table, the incident angle with its corresponding flux value is given for each simulation interval (figure 4.9). These results are the same for all 16 simulated schematics.

As clarified in chapter 3, the simulations are bundled in a 4x4 matrix, four different façade finish material based on the common industry material and previous literature related to optimizing optical performance of bifacial PV panels. The first bundle is testing clear glass façade envelope for four different spacing between inner façade skin and bifacial PV acting as a second skin. (0.5,1,2 and 3 m). The research objective for these spacings is to investigate the effect of ray path length between the two façade skins in terms of lux and ray numbers that reach the back surface of the bifacial PV which consequently affects the electrical generation from the back panel. The second simulation bundle is for highly reflective glass which is highly

used in medium to high rise buildings, the idea is that the mirrored surface of the façade acts as reflectors for the back panel of bifacial PV, the theory was tested for all four specified gap distances. Third façade material was flat white painted façade cladding and last one was reflective glossy white cladding. All material used are available in TracePro material data base.

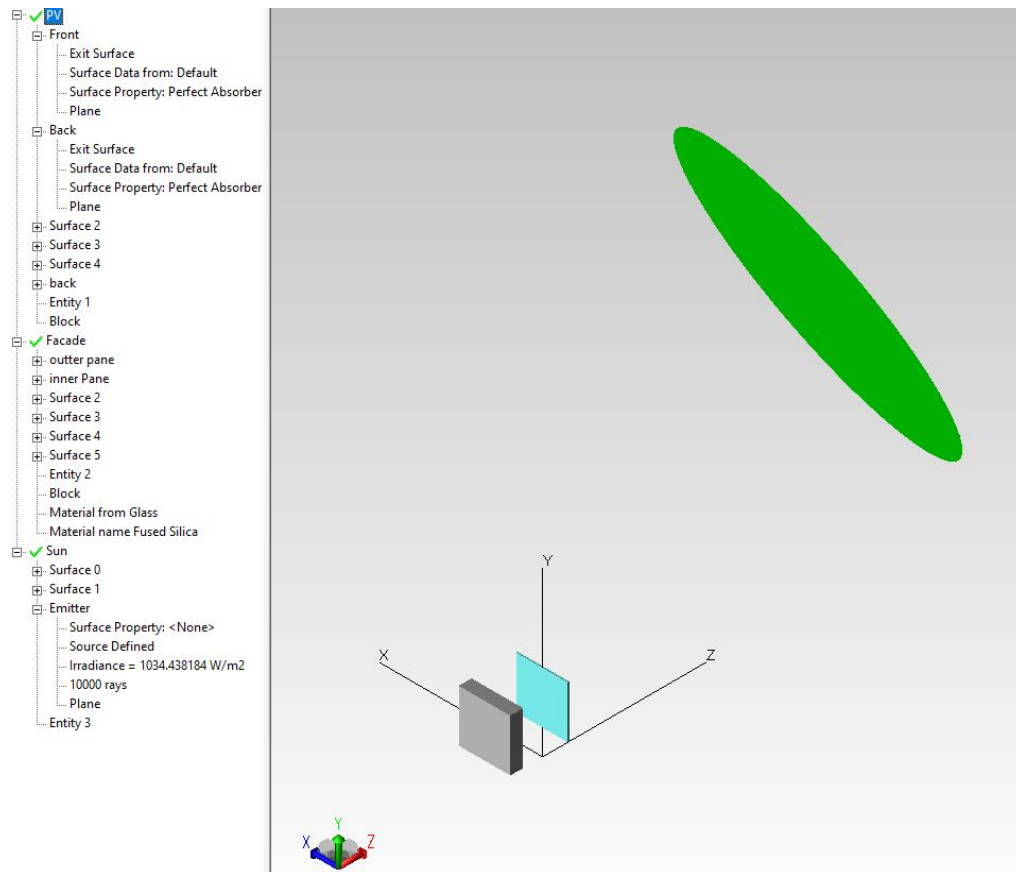


Figure 4.7: Simulation model setup as per simulation matrix (TracePro 2021)

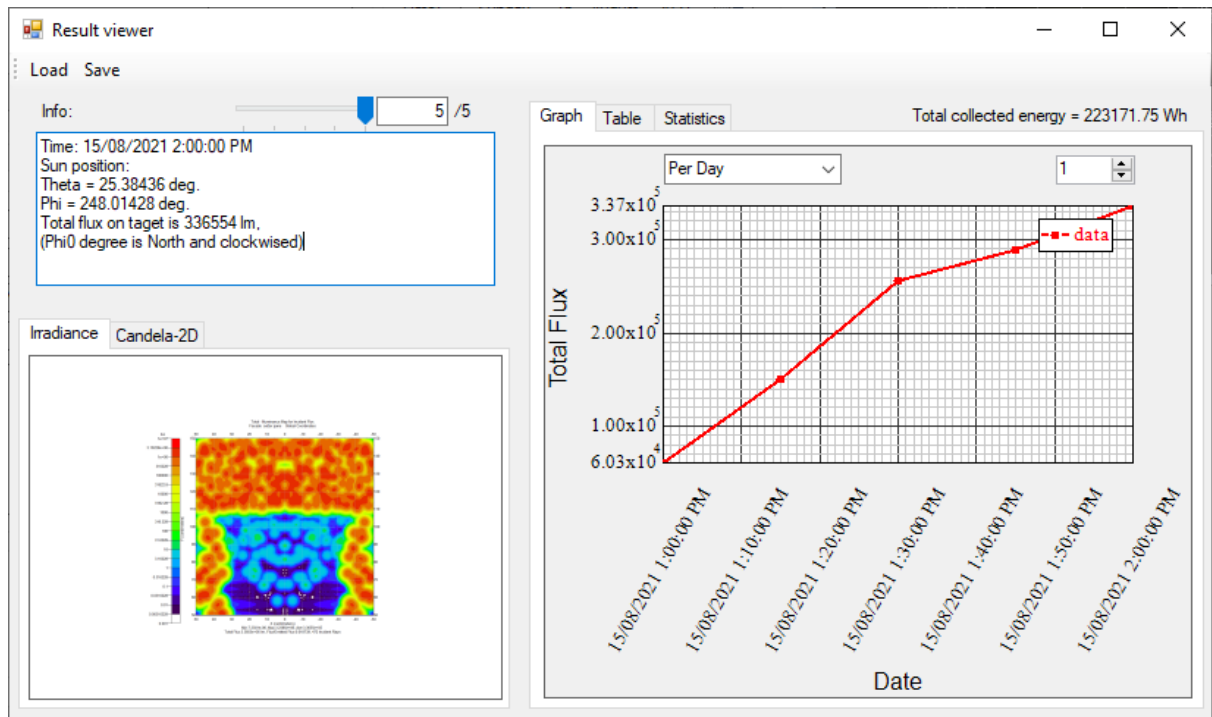


Figure 4.8: Solar emulator result viewer graph (TracePro 2021)

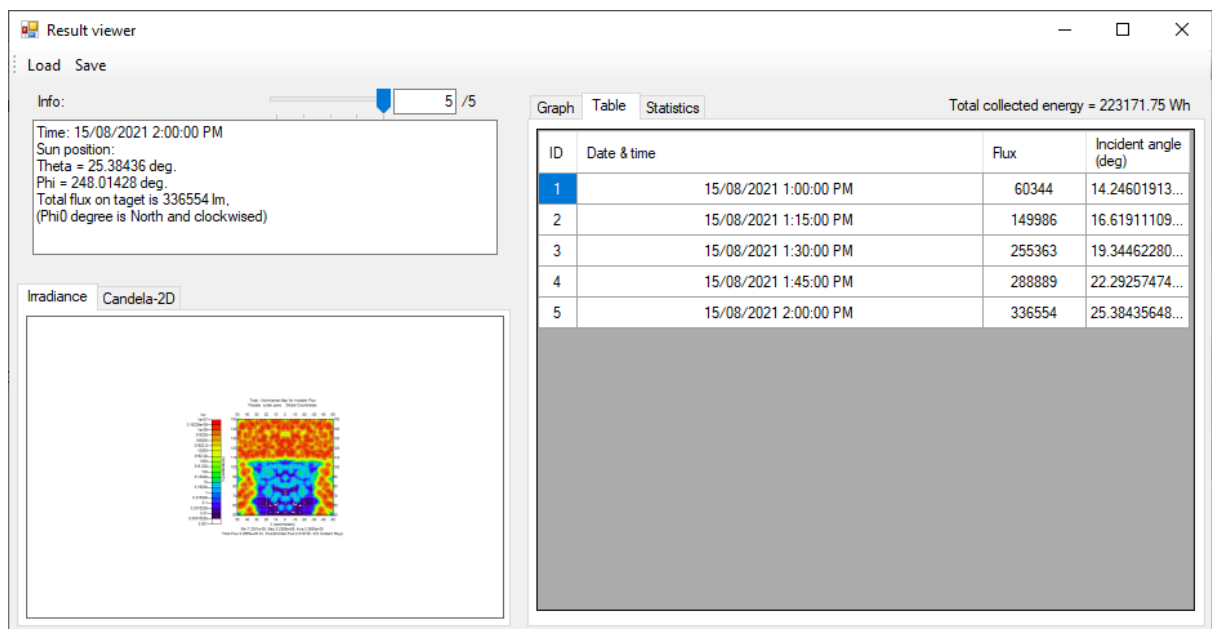


Figure 4.9: Solar emulator result viewer table (TracePro 2021)

CHAPTER 5

RESULTS AND DISCUSSION

This chapter provides the details of simulation results and discuss study findings for each scenario within the four-group bundle as detailed in chapter 4 and summarized in table 5.1 below. The total number of simulations carried out is 16, each simulation is referred to by the letter S and the number of the simulation (S1, S2...., S16). Individual results are presented and detailed in this chapter followed by a comparative analysis of all results collectively in form of a table and graph to highlight the scenario with the most optimal results. The comparison is based on irradiance incident flux on second façade, exiting flux from façade and the incident flux on the back of bifacial panel which represents the subject of the analysis.

Table 5.1: Simulation Scenarios bundles

Gap Distance (Loncour et.al 2005) (Yusufoglu et.al 2014)		Façade Material (Ming Koh et.al 2021) (Brennan et.al 2014) (Cronemberget et.al 2014)			
		Clear Glass	Reflective Glass	White Paint	Reflective Paint (White)
		Based on commonly used by construction industry		Based on the findings of studies on the effect of spectral albedo on different solar photovoltaic types	
0.5	Gap is regarded as a typical cooling gap between the two elements of a double skin façade.	S1	S5	S9	S13
1	This distance is found in corridor style double façade system. Accessible only for maintenance purposes.	S2	S6	S10	S14
2	Gap distance larger than 2 meters is considered as an atrium accessible by public.	S3	S7	S11	S15
3		S4	S8	S12	S16

5.1 Double skin façade – Clear Glass façade / bifacial BIPV second skin

The first simulation bundle (S1 – S4) represents the double façade system where the façade is clear glass, and the second façade is the bifacial PV panel. This bundle includes four simulations where each represents a gap space between the two façade components. Typically, regular glass has high transmittance of light compared to other material. The effect of that is examined in this simulation bundle.

5.1.1 Gap space of 0.5m (S1)

This scheme is considered as a typical double skin façade with glass curtain walls, for the outer skin however is bifacial photovoltaics to achieve a dual objective of typical double skin façade benefits and generating electricity from both sides of panel. The ray trace simulation was carried out for analysis mode as per irradiance data concluded from solar emulator with 10,000 rays hitting the model surface with an altitude angle based on selected time and date for the simulation. Figure 5.1 display rays after running the ray trace analysis, the model is displayed with reference to predetermined coordinates setup. The flux is displayed in a three default monochromatic colors based on wavelengths (Red, green and blue). Red is the longest wavelength (0.666 to 1), green (0.333 to 0.666) and blue less than 0.333. Figure 5.2 is a closeup of ray display showing the rays within the gap of double skin façade.

Since the front of bifacial PV panel will keep receiving the same solar exposure, not affected by the changes of the different second façade material, results of total flux and number of incident rays are constant for all design scenarios (S1 to S16), results for front side bifacial PV in irradiance map of incident flux shown in figure 5.3. The value of incident flux on front side is 570080 lm with 894 direct incident rays on the surface.

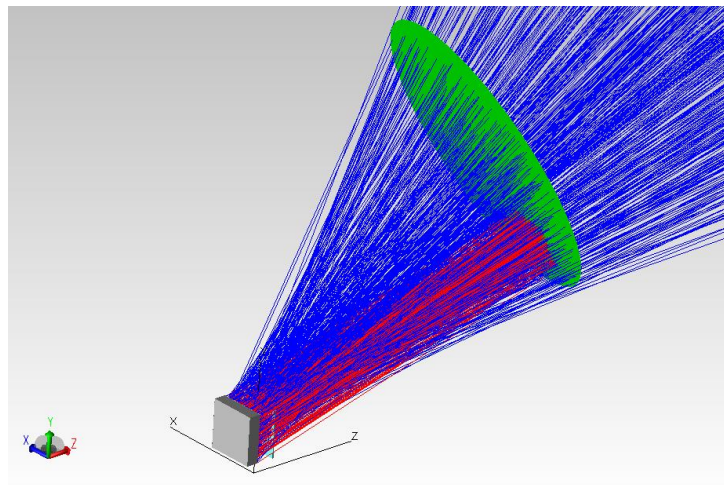


Figure 5.1: Display of rays for S1 simulation analysis (TracePro 2021)

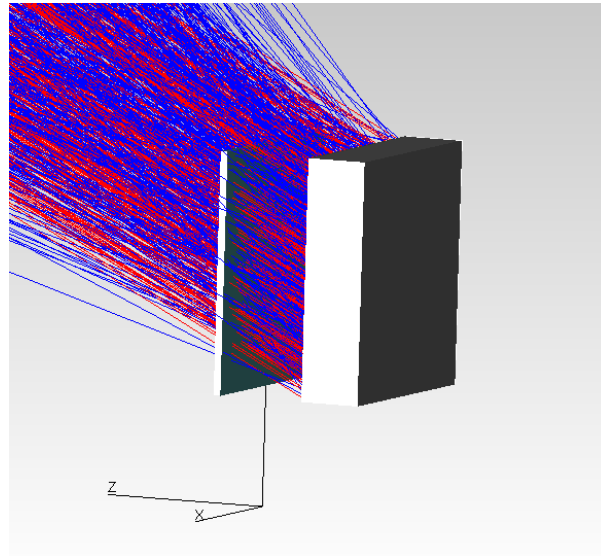


Figure 5.2: Closeup of rays between the two façade surfaces (TracePro 2021)

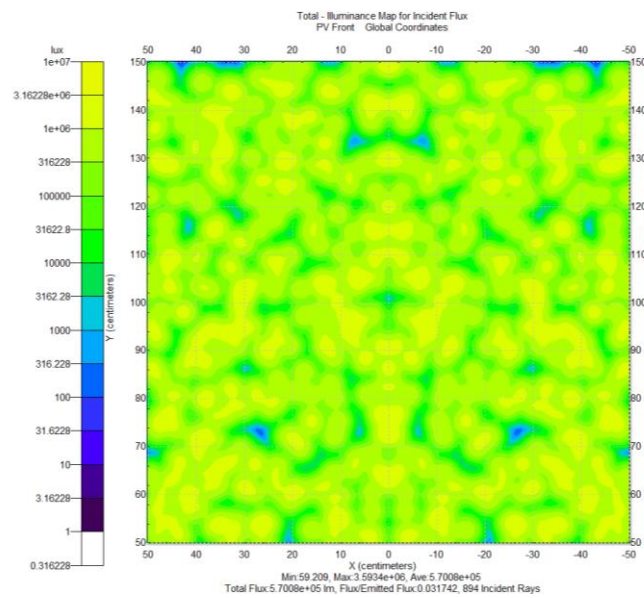


Figure 5.3: Irradiance map of bifacial PV front side (TracePro 2021)

The results for the glass façade (figure 5.4) shows that incident flux (154850 lm) was transmitted through, and the amount of reflected flux within the visible light spectrum is equal to zero (figure 5.5). This complete absence of exiting flux significantly affects the optical

performance of the back side of bi-PV as only few rays reach the surface as seen in figure 5.6, consequently the irradiance map highlights the few areas on the surface with incident flux of 10395 lm 18 rays only reaching the back.

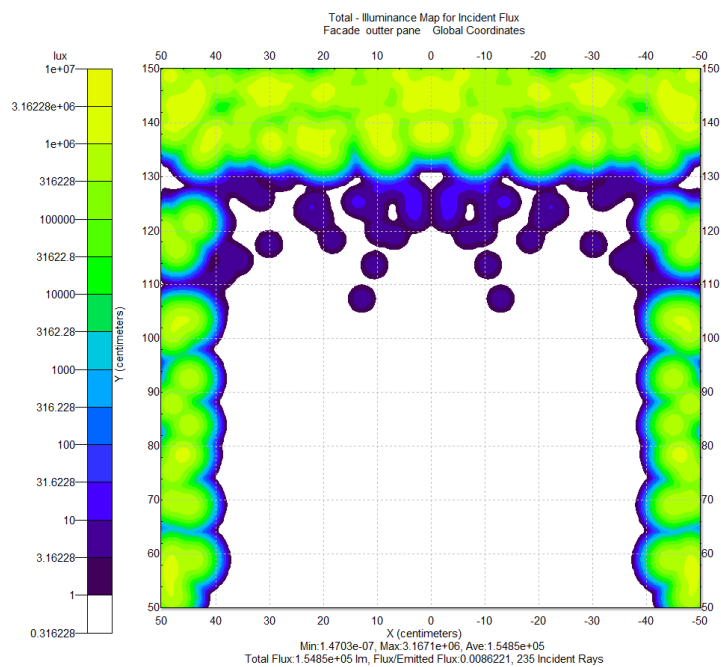


Figure 5.4: Façade irradiance map for incident flux in S1 (TracePro 2021)

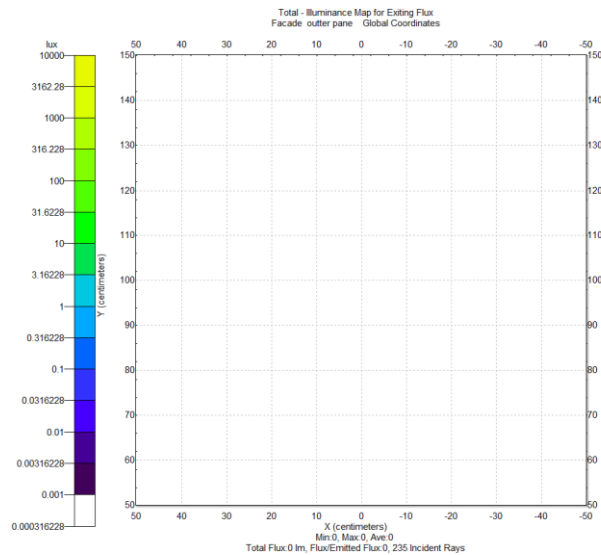


Figure 5.5: Façade irradiance map for exiting flux in S1 (TracePro 2021)

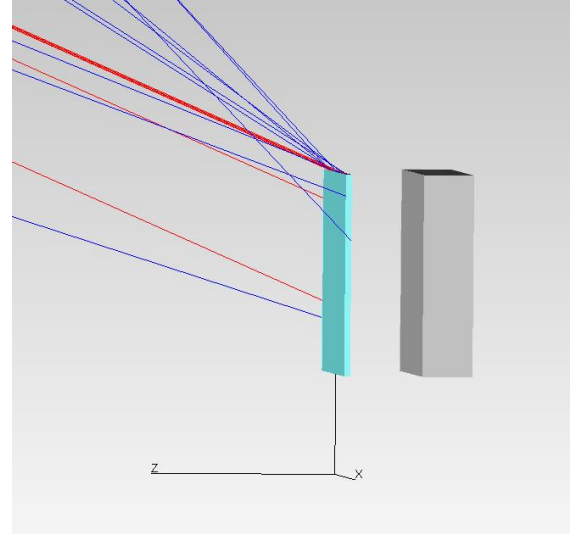
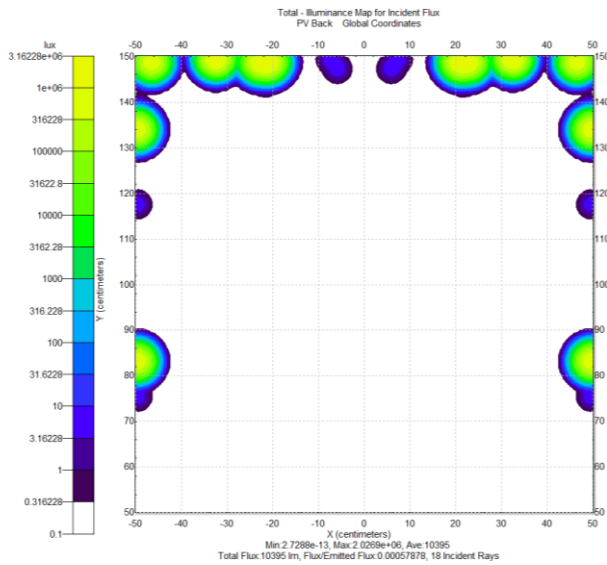


Figure 5.6: Back side of Bifacial PV irradiance map of incident rays in S1 (TracePro 2021)

5.1.2 Gap space of 1m (S2)

In Simulation No.2 the materials of the model are the same, but the space is doubled from 0.5 m to 1 m. The hypothesis is that increasing the gap will allow more rays to come through and reach the second façade surface. The results showed that, although the number of rays did increase as well as the incident flux reaching the façade surface to 299310 lm and 451 rays in total (figure 5.7). The exiting flux remains zero for this type of glazing. This meant the total irradiance flux on the back side of Bifacial PV remains the same as S1 (10395 lm). However, when examining the irradiance map in figure 5.8 it is clear the distribution of the flux is more uniform across the surface.

The same result pattern is displayed in simulations S3 and S4 where the number of rays hitting the façade increase with gap distance increase, as well as the increase of incident flux on façade. However, the exiting flux remains zero, thus the incident flux on the back side of Bi-PV is constant, a value of 10395 lm and 18 rays. Figure 5.9 displays how for S3 and S4 the façade incident flux value is 549380 lm, although number of rays in S3 is 660 and in S4 is 669 rays.

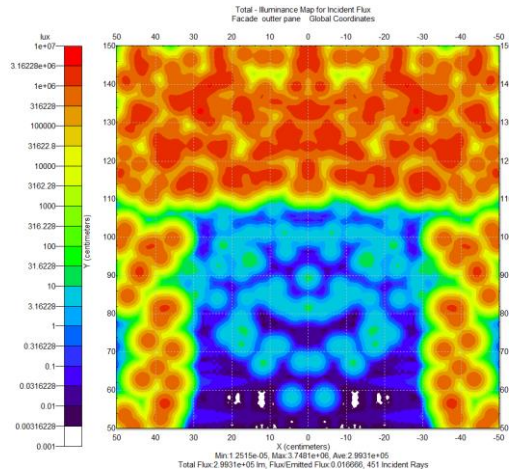


Figure 5.7: Façade Irradiance map of incident flux and rays in S2 (TracePro 2021)

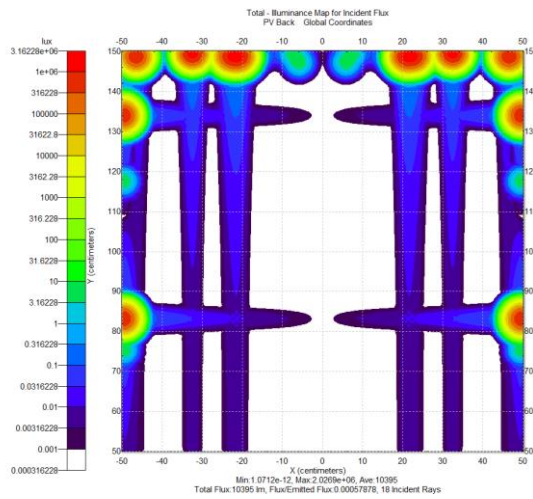


Figure 5.8: Back Bifacial PV Irradiance map of incident flux and rays in S2 (TracePro 2021)

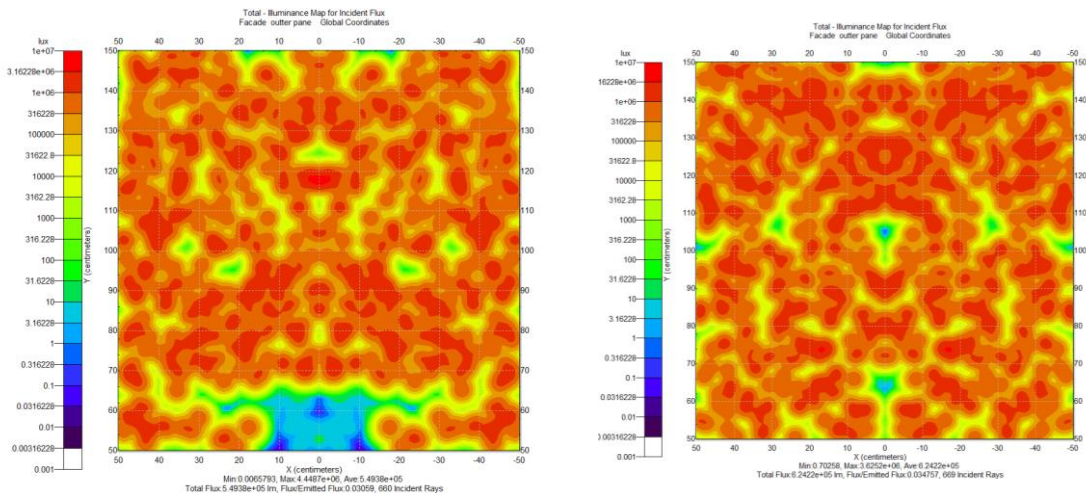


Figure 5.9: Back Bifacial PV Irradiance map of incident flux and rays in S3 and S4 (TracePro 2021)

5.2 Double skin façade -highly reflective Glass façade / bifacial BIPV second skin

The second simulation bundle examines the architectural façade material of reflective glass. Reflective glass is typically used to enhance the thermal performance of building envelope. Furthermore, as the transmittance is less, it is expected that more incident light reflected from the glass reaches the back of bifacial PV panel. As all bundles, four gap distances are modeled and simulated (S5 to S8). Results are shown and discussed in this section.

5.2.1 Gap space of 0.5m (S5)

Simulations 5 analyze the design scheme of highly reflective glass (mirror like) as the façade with four gap distances 0.5 meters. Chosen from TracePro data base, the façade glass has specular reflectivity factor is 0.948 and absorptance of 0.05. Running the ray trace simulation analysis for simulation No.5 the results displayed incident flux to façade surface equal to the value for S1 154850 lm. whereas exiting flux values are a high of 147110 lm. Façade incident and exiting flux is illustrated by irradiance maps in figures 5.10.

The hyped rays reflected from in façade to the back surface of bifacial PV spikes up the incident flux to 78322 lm with 127 number of rays. Figure 5.11 clearly shows the enhanced optical performance on the back surface.

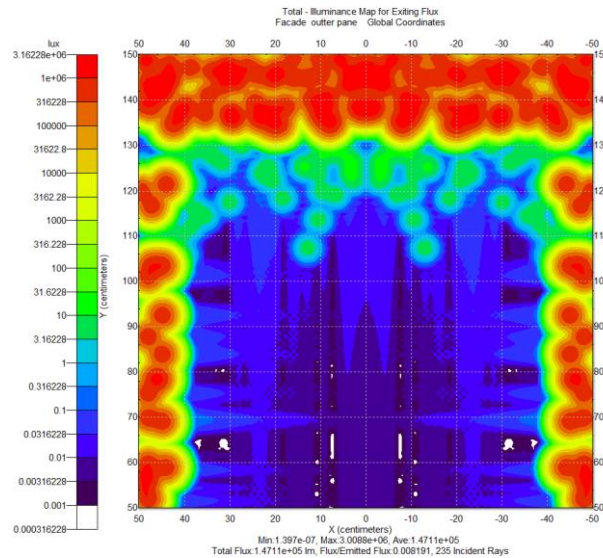


Figure 5.10: Façade irradiance map of exiting flux for S5 (TracePro 2021)

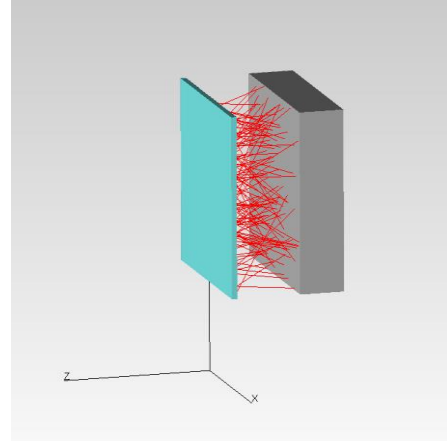
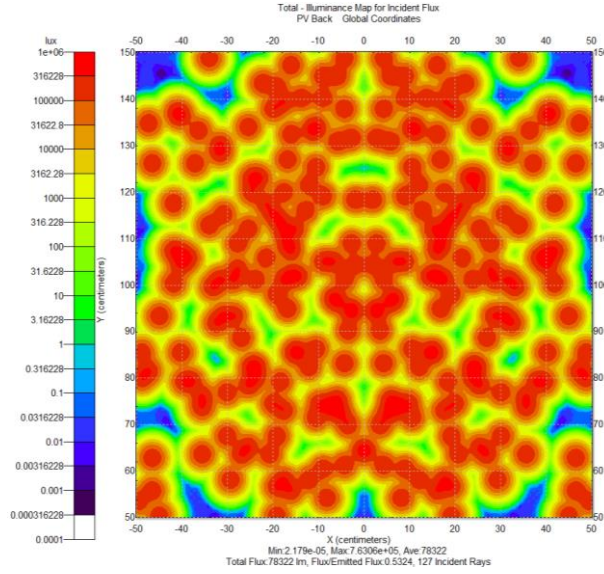


Figure 5.11: Back of Bi-PV irradiance map of incident flux and reflected rays-S5 (TracePro 2021)

5.2.2 Gap space of 1 m (S6)

Analyzing simulation No.6 it is observed that incident irradiance on façade is the same flux value of Simulation No.2 (figure 5.12) the change is in the exiting flux due to the change of surface property from regular glazed façade to highly reflective façade, subsequently increasing the incident flux on the back surface of Bifacial PV. However, by increasing the gap distance that value of incident flux and number of rays decreased as seen in figure 5.13. This is expected since the ray path becomes longer, and some rays get diffracted and absorbed.

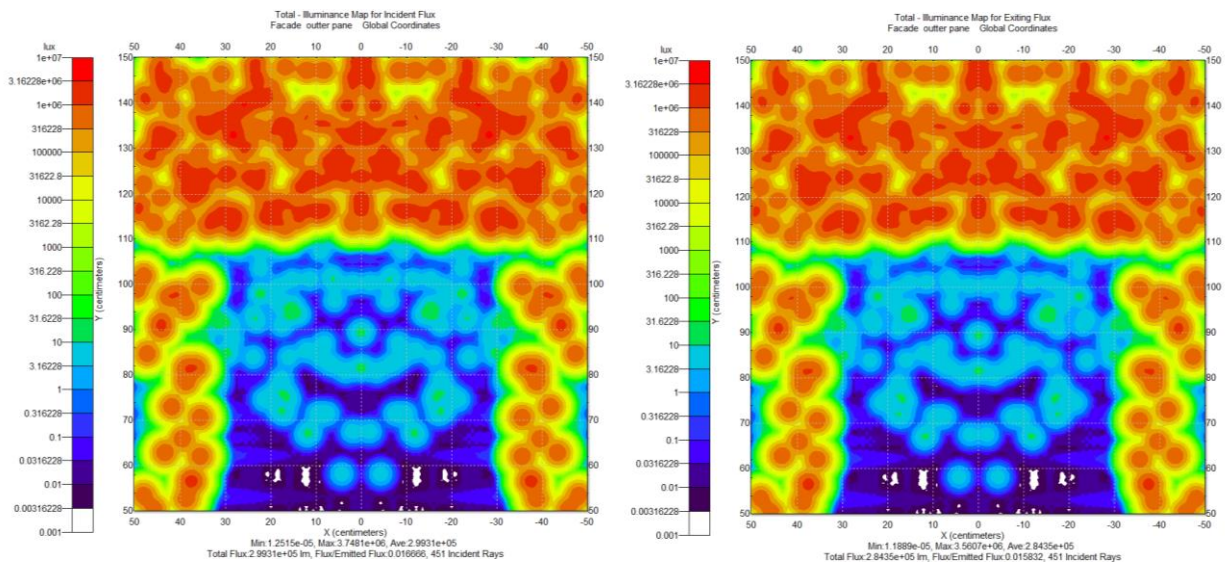


Figure 5.12: Façade irradiance map of incident and exiting flux - S6 (TracePro 2021)

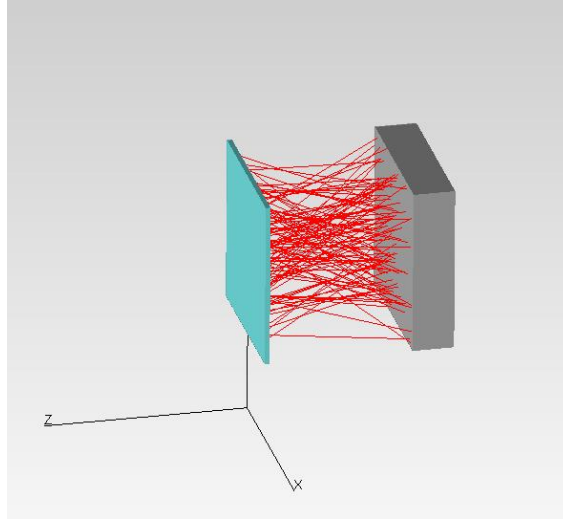


Figure 5.13: Back of Bifacial PV reflected rays-S6 (TracePro 2021)

5.2.3 Gap space of 2 m (S7)

In this design schematic the incident flux on façade surface almost doubles from the 0.5m spacing in simulation No.5, whereas the incident flux on back surface of Bifacial PV almost half value of S5 as illustrated with irradiance maps in figure 5.14. The pattern is recognizable and the relation between gap distance and number of rays reaching back surface of Bifacial PV is clear. Figure 5.15 displays the incident irradiance flux where the distribution of high lux rays decreased from the one in previous two simulations (5 and 6).

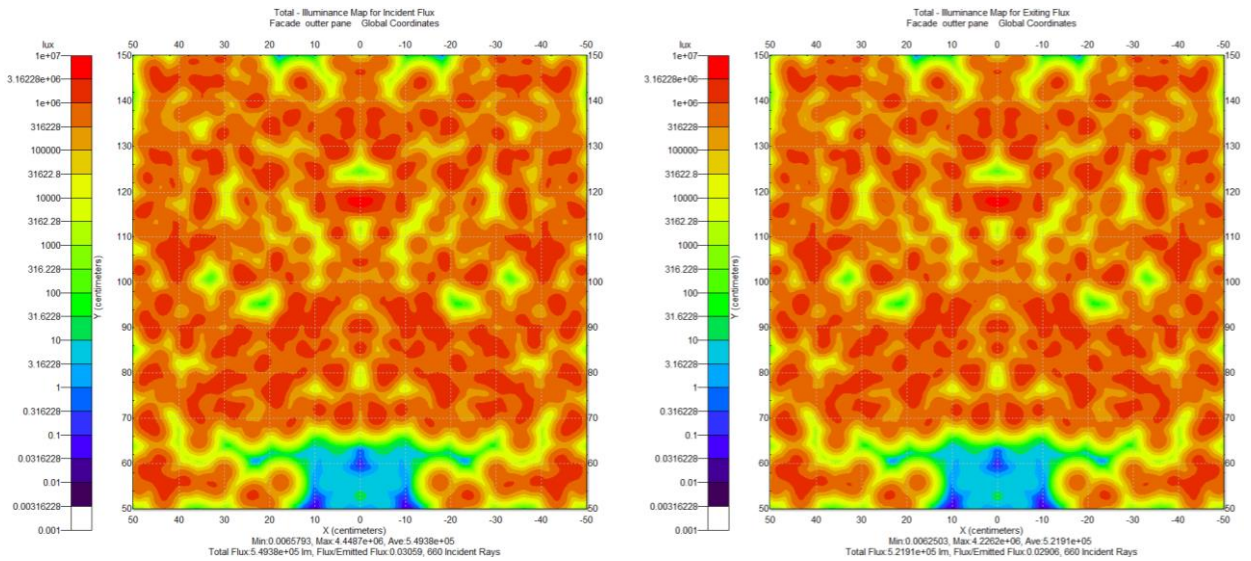


Figure 5.14: Façade irradiance map of incident and exiting flux – S7 (TracePro 2021)

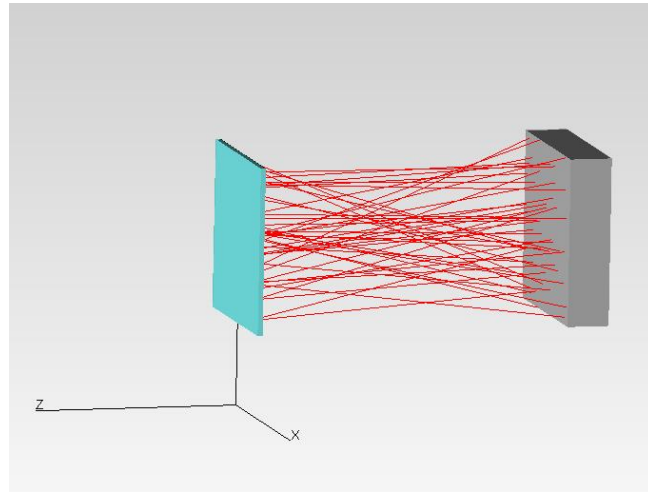
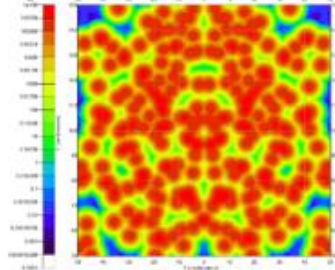
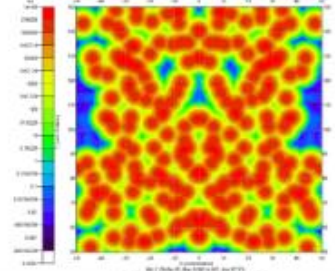
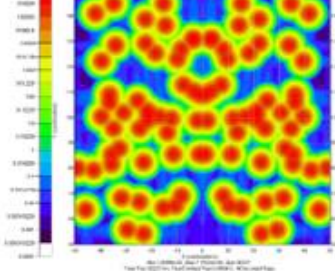
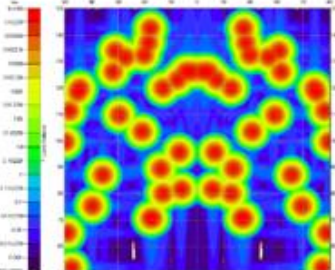


Figure 5.15: Back of Bifacial PV reflected rays-S7 (TracePro 2021)

5.2.4 Gap space of 3 m (S8)

In this simulation the highest value of exiting flux from façade surface is registered a value of 593010 lm and the incident flux increases from equivalent geometry in simulation No.4. Nevertheless, the 3m distance scatters most of the rays and produce lower incident flux on back surface of Bi-PV where the cooler flux colors dominate the irradiance map. Table 5.2 summarize the simulation results for the second bundle in terms of incident irradiance and flux values on back surface of bifacial PV panel.

Table 5.2: back side bifacial-PV panel irradiance maps for S5,6,7 and 8

Sim No.	Gap Distance (m)	Back of Bifacial PV irradiance map of incident flux	Back PV Incident Flux (Lm)
S5	0.5		78322
S6	1		67374
S7	2		36237
S8	3		22439

5.3 Double skin façade -Flat white paint cladding façade / bifacial BIPV second skin

In this section the material investigated is cladding with flat white painting, this material has a level of reflectivity due to its high albedo value 0.5 -0.9 on average. The paint material assigned to the simulations in this section is available in TracePro material data base. This type of cladding paint is commonly used for its thermal performance and cooling effect on the building envelope as discussed in chapter 3. White paint holds an additional benefit of reflecting infrared

waves and maintaining a cooler adjacent around the surface, this results in keeping the façade gap area passively cooled, consequently enhancing the electrical performance of the back side of Bifacial PV.

Ray tracing analysis display in figure 5.16 clearly demonstrate a dynamic optical performance, specially within the double façade gap. All through S9, S10, S11 and S12 simulations the incident flux on surface of façade is equal to its equivalent gap spacing in previous simulations bundle (S5,6,7 and 8). The change however is in the values of exiting flux irradiance from façade surface. These values increase with the increase of gap distance (Figure 5.17). On the other hand, the values of incident flux on back surface of Bifacial PV is inverse with the gap distance. Results as back side bifacial-PV panel irradiance maps for S9,10,11 and 12 are summarized in Table 5.3.

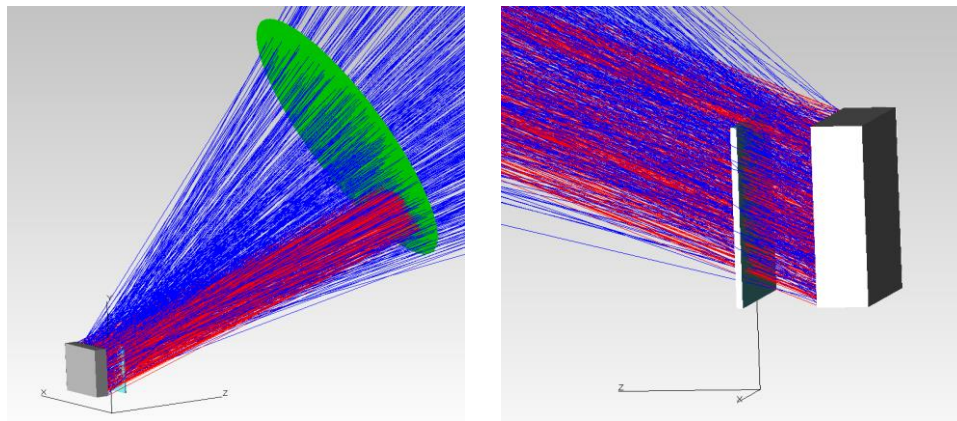


Figure 5.16: Rays display of simulation analysis S9 (TracePro 2021)

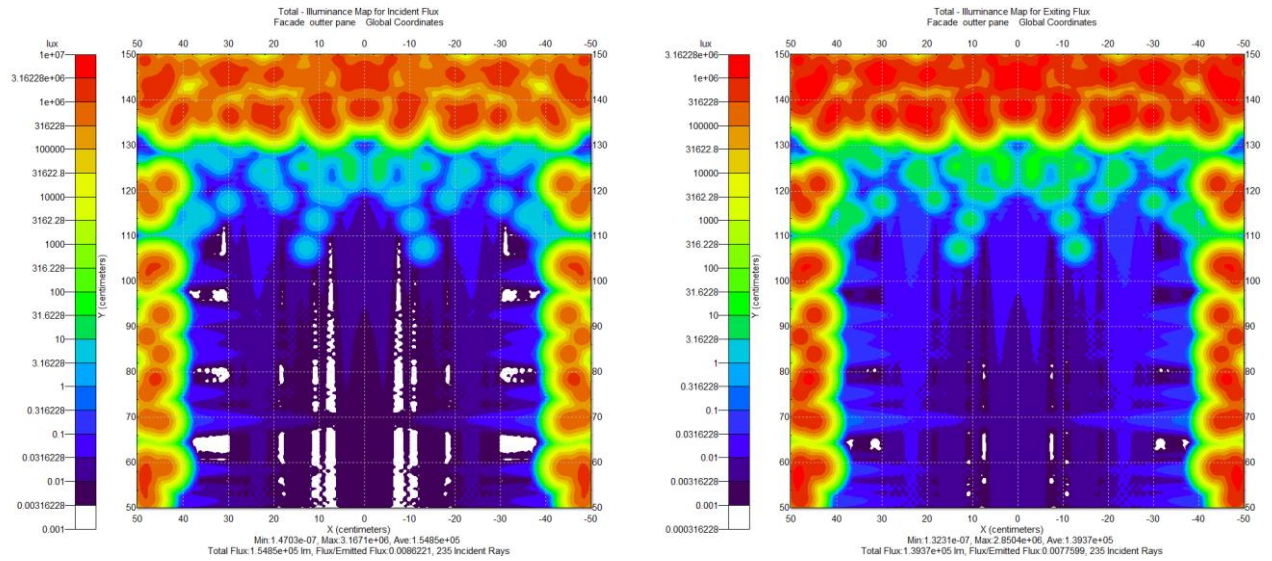


Figure 5.17: Façade irradiance map of incident and exiting flux – S9 (TracePro 2021)

Table 5.3: back side bifacial-PV panel irradiance maps for S9,10,11 and 12

Sim No.	Gap Distance (m)	Back of Bifacial PV irradiance map of incident flux	Back PV Incident Flux (Lm)
S9	0.5		74201
S10	1		63827

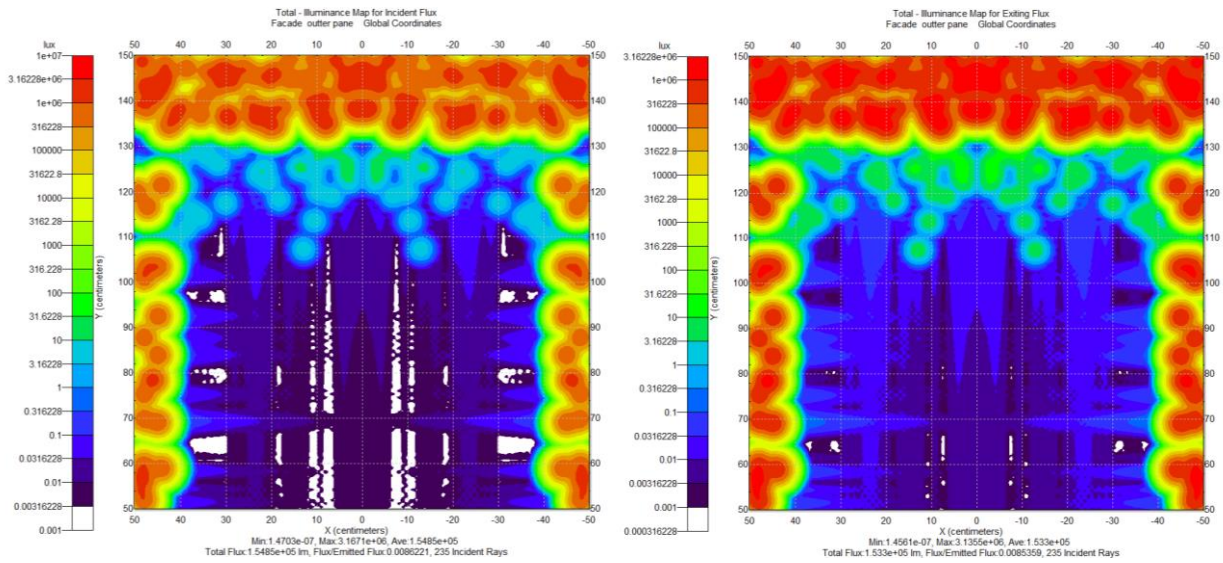


Figure 5.18: Façade irradiance map of incident and exiting flux – S13 (TracePro 2021)

It was observed that the number of rays hitting the surface depends on the spacing between the two surfaces of the double skin façade regardless of the material and surface property. However, the associated energy varied through simulations with regards to the façade material reflectivity parameter. Another noticeable characteristic is the relation between the gap distance and the incident flux on the back surface of the bifacial BIPV, regardless of the façade material, is always an inverse relation. Table 5.4 summarize results of incident irradiance on back side of bifacial PV panel for S13,14,15 and 16.

Table 5.4: back side bifacial-PV panel irradiance maps for S13,14,15 and 16

Sim No.	Gap Distance (m)	Back of Bifacial PV irradiance map of incident flux	Back PV Incident Flux (Lm)
S13	0.5		81617
S14	1		70210
S15	2		37763
S16	3		23384

5.5 Discussion

The objective is to investigate the façade characteristics in a double skin façade system with building integrated bifacial photovoltaics to identify the material that display the highest optical performance in terms of energy/ flux incident irradiance to the back surface of the bifacial PV panel, presented by the ratio of incident irradiance of rear bifacial panel to the irradiance of front side bifacial PV panel.

This ratio is directly related to energy yield of bifacial PV panels. The amount of solar radiation reaching the backside of the PV panels is affected by the reflectivity of material facing it, in this case the façade envelope. Another factor affecting the flux on bifacial rear side is the amount of irradiance reaching the building envelope due to the spacing between the double skin façade system. The two parameters investigated here are, façade material and distance between façade and the Bifacial PV panels integrated into the second skin of the double skin façade system. A simulation matrix was designed to cross both parameters in a 4X4 matrix, the selection of matrix variables is based on previous research and common practice as explained in chapter 3. Four proposed materials with four suggested gap spacings, resulting in 16 design scenarios to be investigated using computer simulation applying the ray tracing software TracePro.

Simulations 1,2,3 and 4 covered double skin facades with a glazed façade and Bifacial PV outer skin with 0.5,1-,2- and 3-meter gap distances. Simulations 5,6,7 and 8 investigate highly reflective glass as the façade for the same gap distances sequence. Third simulation bundle 9,10,11 and 12 simulated flat white paint cladding. Whereas simulations 13,14,15 and 16 explored diffuse white paint cladding façade.

Results for all 16 simulations are summarized in Table 5.5 below. Figure 5.19 is a schematic that illustrates simulation elements. Results are compared in terms of façade incident flux values, façade exiting flux, number of rays on façade, incident flux on back surface of bifacial PV as well as number of rays. Note that the incident flux on bifacial PV front surface is 570080 lumen and number of rays is 894 for all simulations.

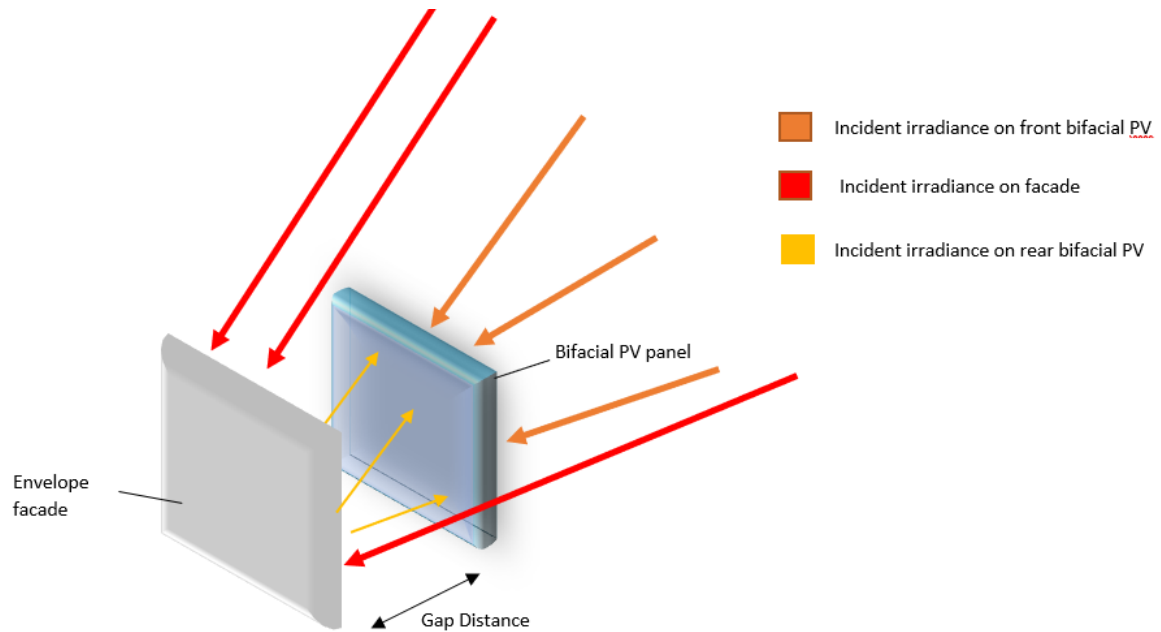


Figure 5.19: Simulation setup schematics

The results displayed that some values depend on the gap distance regardless of the façade material. These values are façade incident flux values and façade rays' number. This is simply because the amount of solar irradiance that lands on the façade is independent from the material of the façade but increase with the increase of the gap distance, hence the larger the distance more rays find its way to the façade surface.

Examining the simulation results for the first bundle (S1,2,3 and 4) it is noticed that the glass façade transmitted the irradiance visible light and resulted in zero exiting façade flux. Back surface bifacial PV ray's number was a constant of 18 rays, this is due to the zero value of façade exiting flux. These simulations had a constant back surface bifacial PV incident flux value of 10395 lm, this means all rays were transmitted, absorbed, diffracted but none that reached the back side of bifacial PV and the few rays that directly and indirectly landed on the surface produced the constant flux value.

It was observed that the value of exiting flux as well as ray number of façade surface increase with the increase of gap distance in a coherent pattern. The façade ray's numbers are 235, 451, 660 and 669 for gap distances 0.5, 1, 2 and 3 m consecutively. This confirms that the larger the gap distance between the double skin façade the more rays are allowed to reach the façade surface resulting in higher incident flux thus higher exiting flux. This did not translate to higher incident flux on the back surface of Bifacial PV, in the contrary, the number of rays and incident flux decreased with the increase of façade gap distant. This is because the ray path from façade to back sheet becomes longer and the energy gets dissipated along the way and some of the rays

diffracts away. Since there is a relation between number of rays on façade and number of rays on PV back surface the inverse relation is also consistent as displayed in table 5.3. number of rays are 127, 108, 46 and 26 for 0.5,1,2 and 3 m gaps consequently. This is important because it confirms that the increase of rays on the façade doesn't increase irradiance on back of bifacial PV panel. However, increasing reflectivity certainly does.

Figure 5.20 is a graphical presentation of the incident flux of Bifacial PV back surface for all 16 simulations. Gap distance of 0.5 m displayed higher flux value than all other distances, this of course varied from simulation to another depending on the material of façade. The highest flux was in simulation 13 for diffuse white paint cladding at 0.5 m from bifacial PV, the lux in S13 is 81617 lm which is 119.16 watt/m² on back surface alone. The second highest flux was S5 for reflective glass façade at 0.5m from Bifacial PV. Followed by S9, flat white paint façade at 0.5 m gap distance.

Garcia et.al (2019) This work outlines the indoor performance testing of c-Si bifacial modules under different module mounting setups including open rack, Garcia tested mirrors, glass and reflective coatings on walls behind the bifacial panels and they compared the results against results for black painted sheet panels. white painted background produced 2.7% more electrical power than black painted background. This supports the findings of my research as the simulation results show higher bifaciality for white paint (flat and reflective) over glass. Research by Yusufoglo et.al (2014) analyzed annual yields for standalone bifacial modules under different mounting circumstances, tilt angle, elevation and ground reflectivity. Results established that for the same tilt angle and elevation but with a ground cover of reflective paint (Albedo value of 0.5) increased the annual electrical yields by 15% than mat ground cover. Another simulation-based research using computational analysis for by Alam et.al (2021) where the findings present the effect of ground reflectivity and uniformity on the ground view factor for standalone field bifacial modules. The same results were established in a previous study using mathematical modeling by Shoukry et.al (2016). Although research investigated tilted standalone systems, the same would be expected for vertical bifacial modules.

Table 5.5: Simulation Results for 4 X 4 simulation matrix

Façade Type Simulation No. Distance between Façade and Bifacial Panel	Glazed Façade				Reflective glass Façade			
	S1	S2	S3	S4	S5	S6	S7	S8
	0.5 m	1 m	2 m	3 m	0.5 m	1 m	2 m	3 m
Façade Incident Flux (Lm)	154850	299310	549380	549380	154850	299310	549380	624220
Façade Exiting Flux (Lm)	0	0	0	0	147110	284350	521910	593010
Façade Rays number	235	451	660	669	235	451	660	669
Back PV Incident Flux (Lm)	10395	10395	10395	10395	78322	67374	36237	22439
Bifacial PV Rays number	18	18	18	18	127	108	46	26
Front PV Incident Flux (Lm)	570080	570080	570080	570080	570080	570080	570080	570080
Front PV Rays number	894	894	894	894	894	894	894	894
Façade Type Simulation No. Distance between Façade and Bifacial Panel	White Paint Façade				Diffuse White Paint Façade			
	S9	S10	S11	S12	S13	S14	S15	S16
	0.5 m	1 m	2 m	3 m	0.5 m	1 m	2 m	3 m
Façade Incident Flux (Lm)	154850	299310	549380	624220	154850	299310	549380	624220
Façade Exiting Flux (Lm)	139370	269380	494440	56180	153300	296320	543890	617980
Façade Rays number	235	451	660	669	235	451	660	669
Back PV Incident Flux (Lm)	74201	63827	34330	21258	81617	70210	37763	23384
Bifacial PV Rays number	127	108	46	26	127	108	46	26
Front PV Incident Flux (Lm)	570080	570080	570080	570080	570080	570080	570080	570080
Front PV Rays number	894	894	894	894	894	894	894	894

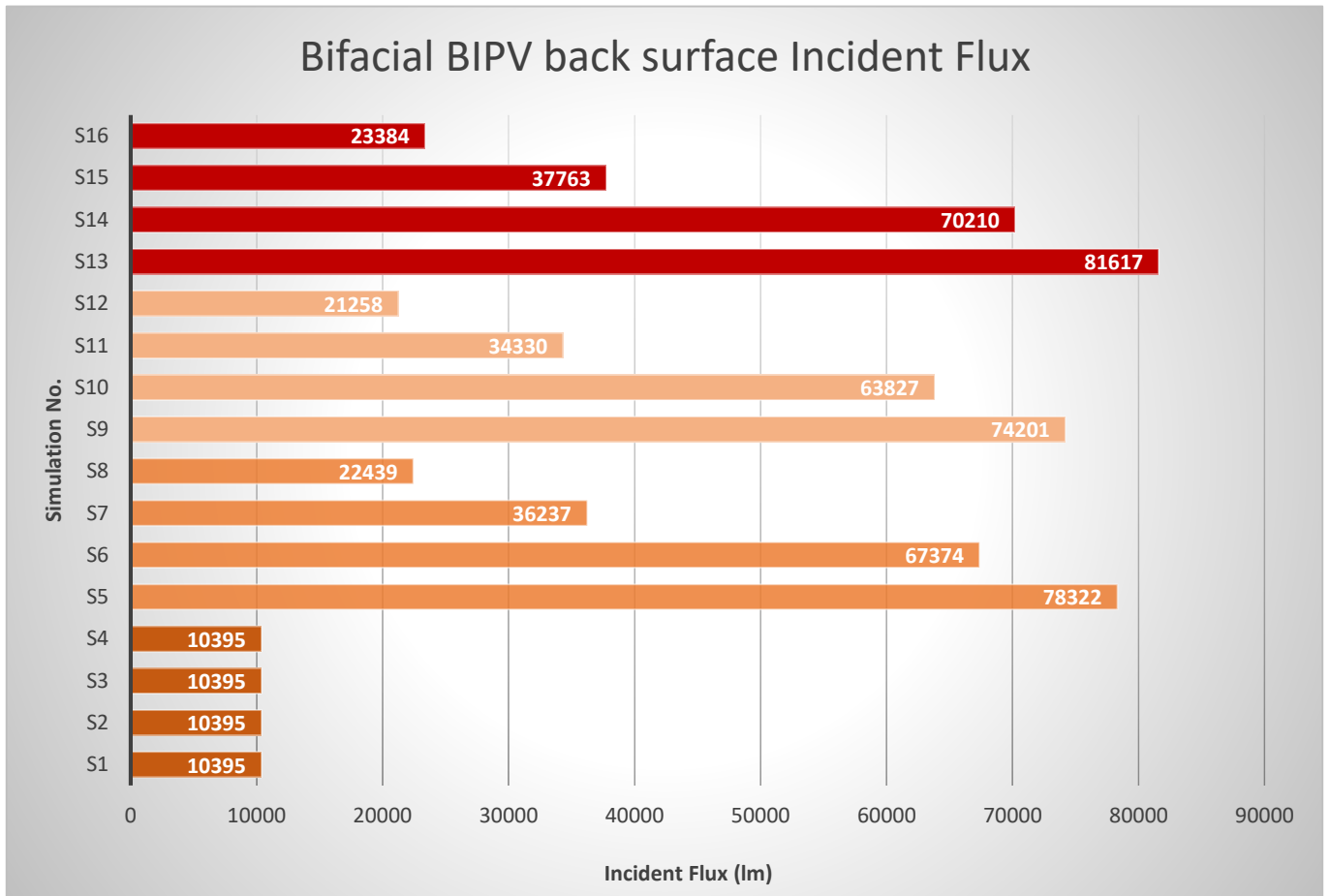


Figure 5.20: Bifacial BIPV back surface incident flux for all 16 simulations

The highest difference in flux levels for all façade material was between spacing gap 1m and 2m, across three simulation bundles, the difference was 46.215% drop of flux value. the drop was significantly less between 0.5m and 1m a percentage of 13.98%. As for 2-3 m gap distance the drop of lux was 38.07% across all bundles (Different façade material).

Furthermore, the change of incident flux levels for the similar gap distance across different façade material was consistent. For example, the difference of flux levels between reflective glass and flat white paint at 0.5, 1,2 and 3m is a 5.26% drop. And between flat white paint and diffused white paint it is a 10% increase for all four gaps.

Table 5.6 highlights the relation between the façade incident flux and the back of bifacial panel incident flux as a percentage value. The Bifaciality factor calculated for each simulation. The percentage reflects how much of the irradiance that finds its way to the façade will also reach the back of the bifacial panel based on the different simulation schemes, hence, electricity yields.

The key parameter when calculating the electrical yield power of a bifacial PV panel is the Bifaciality factor; the ratio of back panel to front panel irradiation. Gostien et.al (2021) modified a traditional metric to count for bifacial outputs in mathematical equations (1,2 and 3), The ratio ($G_{back}:G_{front}$) determines the bifacial irradiance factor that is key to calculate the output power of a bifacial PV panel. It is clear that, the higher the ratio (bifacial irradiance factor) the higher the electricity output power. Therefore, examining simulation results, S13 hold the highest bifaciality factor, hence the highest energy yields.

$$P = G_{eff} \cdot P_0 \cdot (1 + \gamma \cdot (T - T_0)) \quad (5.1)$$

$$G_{eff} = G_{front} + G_{back} \cdot \partial_{pmax} \quad (5.2)$$

$$G_{eff} = \left(1 + \partial_{pmax} \cdot \frac{G_{back}}{G_{front}}\right) \cdot G_{both} \quad (5.3)$$

P: Power output

G_{front} : Front PV irradiance

G_{eff} : effective irradiance

G_{back} : Back PV irradiance

γ : temperature coefficient of power

∂_{pmax} : Bifaciality factor

T: Temperature

T_0 : Reference temperature

Table 5.6: Incident irradiance for façade and bifacial PV back surface and Bifaciality factor

	Sim	Façade Incident Flux (Lm)	Back PV Incident Flux (Lm)	Back PV/ Façade Incident %	Bifaciality Factor $\frac{G_{back}}{G_{front}}$ %
Bundle 1	1	154850	10395	6.713	1.823
	2	299310	10395	3.473	1.823
	3	549380	10395	1.892	1.823
	4	549380	10395	1.892	1.823
Bundle 2	5	154850	78322	50.579	13.739
	6	299310	67374	22.510	11.818
	7	549380	36237	6.596	6.356
	8	624220	22439	3.595	3.936
Bundle 3	9	154850	74201	47.918	13.016
	10	299310	63827	21.325	11.196
	11	549380	34330	6.249	6.022
	12	624220	21258	3.406	3.729
Bundle 4	13	154850	81617	52.707	14.317
	14	299310	70210	23.457	12.316
	15	549380	37763	6.874	6.624
	16	624220	23384	3.746	4.102

CHAPTER 6

CONCLUSIONS

6.1 Overview

Humanity is witnessing a revolution in renewable energy technologies, one that rose from the need for a more sustainable source that could power the rapidly advancing industrial evolution and neutralize the negative impact of fossil fuel on the environment and climate change. Moreover, the advancement in science and research facilitated the development of sustainable energy. Solar energy specifically has witnessed a fast growth in terms of variations and usage expansion. Photovoltaics presented an attainable and flexible source of renewable energy that can be both centralized for mass production via solar parks, and as local production at end user location for direct usage in many applications means. However, the challenges facing this technology stands in the way of energy optimization, therefore, many researchers and developers work to overcome and enhance photovoltaics performance to boost energy production where it becomes completely feasible to apply on all scales.

Building integrated photovoltaics as part of the envelope façade faces many challenges for output maximization. some of which requires technological solutions and others can be solved through optimization of architectural design. Bifacial photovoltaic is a type of PV panels that take advantage of incident light on both front and back surface of the panel, therefore, maximizing energy production for the same unit area. This research studies some of the factors that affects the amount of incident irradiance on the back of the bifacial panel in a double façade schematic where the bifacial panels form the second skin. These factors are the material of the façade behind the bifacial PV panels and the gap distance between the double skin façade components.

Looking into four proposals for each factor, four material types for the building envelope façade and four different gap spacings between double façade components. Resulting in 16 scenarios that were modeled and simulated to examine the behavior of solar irradiance, specifically incident irradiance on the back bifacial PV panel. TracePro software was used to carry out the ray tracing simulations. The results are presented by irradiance maps and analytical tables and graphs of irradiance values for all scenarios.

6.2 Conclusions

For the objective of this research, the technical properties of the bifacial PV panels were not an influencing factor as it is the same throughout all simulation scenarios. However, the variable

factors are related to the double skin façade schematics in terms of reflectivity of the material and the distance from the envelop façade to the bifacial panels. The ray tracing simulation is based on the Monte Carlo ray tracing method, where it calculates the probability of optical behavior for each ray immitted from the source, which in this case is the sun at a location in Dubai-UAE. The software provides the amount of ray's incident or exiting a chosen surface in ray numbers or lumen flux, Irradiance maps containing these information are produced for any selected surface within the simulation.

Parameters chosen for the simulation were selected to provide comprehensive results, such parameters are the date and time of the simulation to be when the sun is at high solar position and angle in the sky, 15th of August 2021 between 1pm and 2pm. Clear sky with no cloud obstruction is another parameter preset for the simulations.

Simulation variables were arranged in a way that the effect of different combinations of façade material and distance between the double skin façade can be examined. Thus, each bundle represents one type of envelope façade material, which will include four simulations, each representing a gap distance scenario. For the first bundle, the façade material is clear glass, across the assessed four gap distances 0.5,1,2 and 3 meters. The second bundle is for reflective glass façade across same gap distances. Third simulation bundle is regular white paint cladding. Lastly, fourth bundle examines diffused white paint.

The simulation results indicate that there are significant effects of façade's material properties on the amount of incident flux on bifacial PV back surface, when coupled with optimizing the distance between the double skin façade elements, and the reflectivity of the façade material to maximize incident flux, thus maximizing the potential power output from BFPVs. The ratio of back panel to front panel irradiation referred to as bifacial irradiance factor has significant effects when it comes calculating the output power of a bifacial PV panel. The higher the bifacial irradiance factor, the higher the electricity output power from the bifacial panel.

Analyzing simulation results it was observed that the higher the gap distance between façade components the higher the value of exiting flux of façade surface. The façade ray's numbers are 235, 451, 660 and 669 for gap distances of 0.5,1,2 and 3 m, respectively. Due to the increase in rays' accessibility, the larger the gap distance between the double skin façade the more rays reach the façade surface resulting in greater incident flux thus greater exiting flux.

More incident flux on the façade did not compensate the larger distance the rays had to travel from façade to the back of bifacial panel, therefore, even if the higher gap distance resulted in higher exiting flux irradiance. The incident irradiance to the back of bifacial panel decreased with the increase of gap distance, since the ray path from façade to back sheet becomes longer and the energy gets dissipated along the way and some of the rays diffracts.

The highest difference in flux levels for all façade material was between the spacing gaps of 1m and 2m, across all simulation bundles; the difference was 46.215% drop of flux value. The

drop was significantly less between 0.5m and 1m at 13.98%. As for the spacing gaps of 2 and 3 m, the drop of lux was 38.07% across all bundles.

Change of incident flux levels for the similar gap distance across different façade material was consistent. For example, the difference of flux levels between reflective glass and flat white paint at 0.5, 1,2 and 3m is a 5.26% drop. And between flat white paint and diffused white paint it is a 10% increase for all four gaps.

The results show that diffused white paint at distance of 0.5m provided optimal incident irradiance to the bifacial PV back surface, followed by simulation of highly reflective glazed façade for the same distance. It was also concluded that the change of result values within the same bundle for different gap spacings is consistent across all material simulations for that specific gap distance, excluding the first bundle for clear glass façade because the light was transmitted through the glass and not reflected.

Diffused white paint presented the optimal results in terms of enhancing bifacial PV panel power output by increasing back side incident irradiance, consequently increasing the bifacial irradiance factor. The material with the second-best performance was reflective glass. This could provide another design options where both materials can be part of envelope design to optimize bifacial PV panels in a double skin façade design setting. The use of the right material with the right spacing can passively increase efficiency of bifacial building integrated PV.

6.3 Research limitations

The objective of all research is to answer a question and filling a gap within the topic of research. Therefore, this requires facing several unknowns and uncertainty. In the case of this research specifically, it was the research methodology that challenged the scope of the study. As explained in Chapter 3, computer simulation was chosen for practicality and resource availability. Afterwards, it was the matter of the proper software. Bifacial Photovoltaic panels have a different setup than Monofacial panels, bifacial PV is more affected by ambient structure and material. This introduced different set of variables to analyze, hence, PV simulation software won't apply on bifacial PV, certainly won't address the variables of ambient setups. Whereas softwares that address the surrounding material, structure and light reflectivity don't provide PV power generation data. Given that the objective of the study is to analyze the effect of façade material on the back side of the bifacial PV panel, the choice was to use the software that accounts for light reflectivity, specifically, TracePro.

TracePro is ray tracing software, it accounts for light reflectivity and optical behavior of different materials and give an accurate ray trace analysis, the limitations of the software however are intertwined with the limitations of the research. For example, up scaling the

simulation setup is not applicable, as the structure modeling is in millimeter with no capacity to model a full building or façade. Consequently, this limited the research to a sample size of the façade, therefore not accounting for architectural design factors. Secondly, the software does not include CFD analysis, which would have been an added value to study the effect of façade gap and material thermal behavior on cooling the PV panels. Moreover, examining the possibility of conducting such analysis on another software like IES reached a dead end, because IES does not account for the thermal behavior of material (heating effect) and its effect on air flow. Further research on a software that applies both is required.

CHAPTER 7

FURTHER RESEARCH

It is clear when examining the literature that the subject of bifacial photovoltaics is currently rich in content and interest is increasing of the matter within the research and development community. Research methodologies varied between field testing and computer simulation, but exclusively as standalone roof mounted systems and no research was found, up to the date of this research, that covered building integrated bifacial photovoltaics. The subject of bifacial PV is not new in concept but very new to the commercial consumption market, but with the continuous decrease of photovoltaic system's cost, the market will pick up on novel technologies and innovative concepts, therefore, further research is required for building integration applications for different type of photovoltaic systems including bifacial PV panels.

In this research the optical analysis was examined through computer simulation where partial section of the façade was analyzed for examining the optimal material at the back side of Bi-BIPV. Further work is planned to be done for a full envelope analysis to investigate the effect of the whole structure geometry on optical performance, thus on electrical yields. Additionally, mixed materials which usually found in double skin façade will be simulated to examine the compound effect of different reflectivity. Computer simulation is a convenient cost-effective research methodology, however, the research plans to conduct field testing for the bifacial panels in form of building integrated double façade systems in same design schemes carried out in current research simulations. As comparing simulations with field or laboratory tested data to further validate the investigation findings.

One of the major efficiency losses in photovoltaic systems is temperature losses, therefore, further investigation should be carried out to investigate the heat build up within the double façade gap that will affect the performance of the Bifacial PV back surface due to both radiative and conductive heat. Façade material heat conductivity and emittance analyzed additionally to potential design solutions such as ventilation and/or heat sinks that could potentially decrease the heat buildup within façade gap and cool down the back side of BIPV consequently cooling down the entire PV system which will lead to increased electrical leads due to controlling cell temperature losses.

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