FEASIBILITY OF ROOFTOP PHOTOVOLTAIC APPLICATIONS IN RESIDENTIAL BUILDINGS IN SAUDI ARABIA

BY

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This thesis, written by **AMMAR HAMOUD AHMAD DEHWAH** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN ARCHITECTURAL ENGINEERING.**

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DEDICATED TO
MY BELOVED PARENTS
AND ALL FAMILY MEMBERS

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I would like to begin with appreciation and gratitude to Almighty Allah, the most beneficent, and the most merciful, who has given me the ability to accomplish this work and complete my degree.

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LIST OF ABBREVIATIONS

ASTM	**:**	American Society for Testing Materials
B-C	**:**	Benefit to cost ratio
BIPV	**:**	Building integrated photovoltaic
CAGR	**:**	Compound annual growth rate
DHI	**:**	Diffused horizontal irradiation
DNI	**:**	Direct normal irradiation
EVA	**:**	Ethylene Vinyl Acetate
FIT	**:**	Feed in tariff
GCC	**:**	Gulf Cooperation Council
GHG	**:**	Greenhouse gases
GHI	**:**	Global horizontal irradiation
GIS	**:**	Geographic Information System
HVAC	**:**	Heating, Ventilating, and Air Conditioning
IEA	**:**	International Energy Agency
IRR	**:**	Internal rate of return
KACST	**:**	King Abdul-Aziz City for Science and Technology
KAPSARC	**:**	King Abdullah Petroleum Studies and Research Center
KAUST	**:**	King Abdullah University of Science and Technology
KSA	**:**	Kingdom of Saudi Arabia
LCC	**:**	Life cycle cost
LCCA	**:**	Life cycle costing analysis

LCOE	**:**	Levelized cost of electricity
NOCT	**:**	Nominal operating cell temperature
NPV	**:**	Net present worth
O&M	**:**	Operating and maintenance
PV	**:**	Photovoltaic
RHI	**:**	Reflected horizontal irradiation
RS	**:**	Remote Sensing
SA	**:**	Saudi Arabia
SEC	**:**	Saudi Electricity Company
STC	**:**	Standard testing conditions
$\mathbf{T_a}$	**:**	Ambient air temperature
$\mathbf{T_c}$	**:**	Cell temperature under real conditions
$\mathbf{T_{ref}}$	**:**	Cell temperature under STC (T_{ref} = 25 °C)

ABSTRACT

Full Name : AMMAR HAMOUD AHMAD DEHWAH

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Globally, the building sector consumes about 40% of the total energy consumption, whereas it is 80% in the Kingdom of Saudi Arabia. Utilizing renewable energy technologies in buildings can help in reducing load on the national grid and hence can contribute to considerable environmental benefits. The Kingdom of Saudi Arabia is endowed with a huge intensity of solar energy estimated by 2,200 kWh/m^2/year, considered as one of the highest direct normal irradiation globally. KSA has set future plans to meet the increasing energy demand targeting a diverse and sustainable sources of fuel for energy use rather than depending only on fossil fuels as per vision 2030. An integral part of the vision is to generate 9.5 GW of electricity from renewable energy resources. This research aims to develop a general framework for evaluating the feasibility of PV in building applications. It also supports the framework with a case study for PV applications on residential rooftops at urban scale. High resolution satellite images, GIS tools, PV design and energy simulation software were employed to carry out the analysis. Based on the collected samples, and as an average, 16% of apartment rooftops and 20% of villas' rooftops can be utilized for PV applications. At a city scale, the analysis showed that the total roof area (RA) for the residential units in Al-Khobar equals to 14.2 km^2 which in turn provides a total of 3.2 km^2 PV area (PVA). It also showed that the total energy potential for tilted and flat panels equals to 675 GWh and 394

GWh respectively. The study also concluded that with proper rearrangement of rooftop service components the energy potential can be increased by 34%. Considering a typical villa, the total on-site generation when tilted PV panels are installed within the utilizable area (UA = 0.15) can substitute 10% of the total consumption. Further increment in the utilizable area up to 40% of the roof, increases the percentage of savings up to 29%. High reductions in GHG emissions were also obtained at the city scale. Considering the current conditions, and from economic point of view, it is easier for end users to depend on the grid-supplied electricity. However, considering financial incentives helped in reducing the gap between LCOE and Electricity tariff especially for villas. Recommendations were introduced in order for policy makers and regulators to set rules that will help to utilize the roof more efficiently and hence harvest more solar energy.

ملخص الرسالة

الاسم الكامل: عمار حمود احمد دحوه

عنوان الرسالة: دراسة جدوى استخدام الخلايا الكهروضوئية على أسطح المباني السكنية في المملكة العربية السعودية

التخصص: الهندسة المعمارية

تاريخ الدرجة العلمية: يونيو 2017

يستهلك قطاع البناء حوالي 40٪ من إجمالي استهلاك الطاقة على الصعيد العالمي، في حين أنه يستهلك 80٪ في المملكة العربية السعودية. من الممكن أن يساعد استخدام تكنولوجيات الطاقة المتجددة في المباني في الحد من الحمل على الشبكة الوطنية، وبالتالي يسهم في تحقيق فوائد بيئية كبيرة. تمتلك المملكة العربية السعودية امكانات هائلة من الطاقة الشمسية تقدر ب 2.200 كيلوواط ساعة / م2 / سنة، والتي تعتبر واحدة من أكثر المناطق استقبالا للاشعاعات الشمسية. وقد وضعت السعودية خططا مستقبلية لتلبية الطلب المتزايد على الطاقة مستهدفة مصادر متنوعة ومستدامة للوقود بدلا من الاعتماد فقط على الوقود الأحفوري وفقا لرؤية 2030. حيث تهدف الرؤية لتوليد 9.5 جيجا واط من الكهرباء من مصادر الطاقة المتجددة كطاقة الشمس والرياح. يهدف هذا البحث إلى دراسة جدوى استخدام التكنولوجيا الكهروضوئية على أسطح المنازل السكنية لإنتاج الكهرباء وفق الظروف المناخية والاقتصادية في المملكة العربية السعودية. واعتمد البحث على تقنيات متعددة منها صور الأقمار الصناعية عالية الجودة، وأدوات نظم المعلومات الجغرافية، وبرامج محاكاة الطاقة **(PVSOL, Design Builder)** لإجراء التحليل والتصميم للألواح الكهروضوئية. واستناداً الى العينات التي تم جمعها وتحليلها، توصل البحث الى انه يمكن الاستفادة من 16% من اسطح العمائر السكنية و20% من اسطح الفلل في استخدامات الطاقة الشمسية، وعلى مستوى المدينة، أظهرت الدراسة أن المساحة الكلية لاسقف الوحدات السكنية في الخبر تساوي 14.2 كم مربع، مما يوفر بدوره مساحة 3.2 كيلو متر مربع صالحة لاستخدام الطاقة الشمسية. وأظهرت أيضاً أن تطبيق الألواح الكهروضوئية المائلة والأفقية على اسطح المباني في مدينة الخبريمكن ان ينتج 675 جيجا واط ساعة لكل سنة و 394 جيجاواط ساعة لكل سنة على التوالي. وخلصت الدراسة أيضا إلى أنه مع إعادة ترتيب وتنظيم الاسطح يمكن زيادة إمكانات الطاقة بنسبة 34٪. وبالنظر الى وحدة سكنية من نوع (فيلا)، فان اجمالي توليد الطاقة من الخلايا الكهروضوئية المركبة في المساحة المتاحة من الممكن أن تغطي 10% من احتياج الفيلا السنوي للكهرباء. ويمكن أن ترتفع هذه النسبة الى 29% اذا ما تم زيادة النسبة المتاحة للتركيب الى 40% من مساحة السطح وذلك عن طريق تنظيم وترتيب سطح المبنى. كما تم تخفيض معدلات إنتاج غاز ثاني أكسيد الكربون بشكل كبير على نطاق المدينة. ومن الناحية الاقتصادية وفي الاوضاع الراهنة، فانه من الاسهل لمستخدمي المباني السكنية الاعتماد على الكهرباء المتوفرة عبر الشبكة. ومع ذلك، فإن الحوافز المالية ساعدت على تقليص الفارق بين تكلفة انتاج الكهرباء من الخلايا الكهروضوئية وتعرفة الكهرباء من الشبكة.

CHAPTER 1

INTRODUCTION

1.1. Background

Energy has become one of the top concerns in developed as well as developing countries. According to the International Energy Agency (IEA), 81% of the world total energy is primarily supplied by fossil fuels which are deplete-able resources, whereas the share of renewable energy is only 14% (IEA, 2015). Globally, the building sector consumes about 40% of the total energy consumption and is responsible for releasing 33% of the total Green House Gases (GHGs) emissions (UNEP, 2012).

Considering the situation in the Kingdom of Saudi Arabia (KSA), the country depends heavily on oil and natural gas as primary fuels for electricity generation. Buildings share 80% of total electricity consumed out of which 52% accounts for the residential sector as shown in Figure 1 (Iskandar, 2015). According to recent published data, the total amount of sold energy to the residential sector is 135,908 GWh, with 6.7% average annual growth rate, being one of the highest growth rate compared to other sectors (SEC, 2014).

The world total energy consumption has grown by 31% and CO_2 emissions by 34% from the period 2000 to 2013 (IEA, 2015). Predictions show that this trend will continue to grow driven by developing economies. Continuing at this rate, burning fossil fuels to meet the rapid energy demand will result in environmental crisis. Global warming and in sequence climate change are serious environmental issues which requires immediate actions (Shi et al, 2010). Many of the developed countries have moved toward clean sources of energy and are heavily investing on advanced technologies aiming to harness the power from sustainable resources.

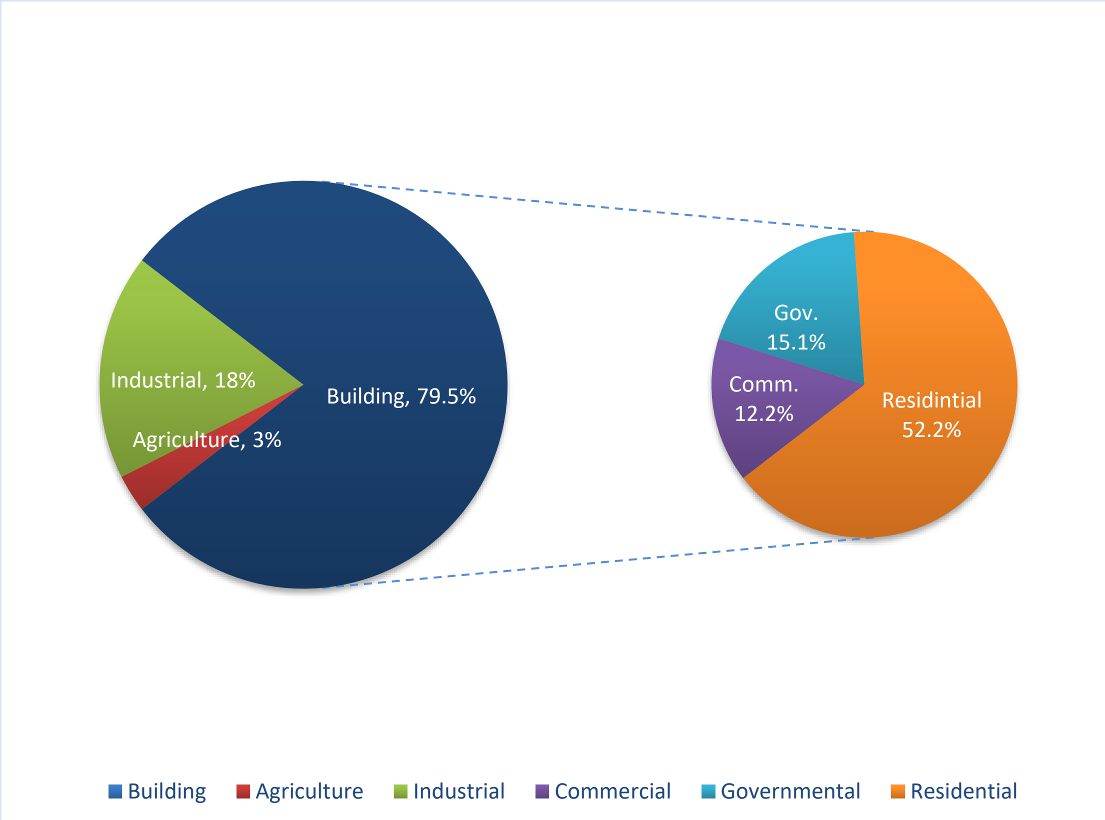


Figure 1: KSA Electricity Share by Sector (Iskandar, 2015)

Renewable energy depends on natural resources such as solar which is an abundant energy source that provides free and clean energy. One of the developing technologies that harvests solar energy is Photovoltaic (PV) or solar cells, which can convert sunlight into electricity. Solar PV market experiences records at every year since 2012. As revealed by REN21, the overall global capacity of solar PV is 227 GW as by 2015, in which about 70% was added over the past four years (REN21, 2016).

KSA has moved recently toward energy efficiency in all sectors including the building sector. Solar energy has a great potential in the kingdom (Shaahid and El-Amin, 2009), this is because it is blessed with a huge intensity of solar energy estimated by 2,200 kWh/m^2/year, considered as one of the highest direct normal irradiation globally (Liu, 2015). In addition to that, SA has in general a clear sky and there is a low probability of precipitation. However, there are also undesirable aspects to be considered in which it is likely to present a challenge to the PV adoption in this climate (Alajlan and Smiai, 2013). Such aspects include high ambient temperatures, dust and humidity which can negatively impact the performance of PV systems (Touati et al., 2013).

PV technology can be used in large scale industrial applications or even for domestic applications. Utilizing electricity generated from PV technology to supply building loads have shown effectiveness in major parts of the world (Sadineni et al., 2012; Ordenes et al., 2007; Bansal and Goel, 2000; Radhi, 2010). PV can be incorporated into buildings in various manners these include; roof mounted, wall mounted, roof integrated, wall integrated and integrated or coated on glazing systems. Currently, most of PV building applications worldwide have PV modules installed on rooftops. The reason behind this is that the built environment in cities offers vast areas of unused rooftop spaces. In addition to the fact that rooftops usually provide an optimal and suitable location for capturing solar light with minimum shade interruptions.

Assessing the potential of solar energy through installing rooftop PV systems has been the interest of many countries. For instance, a study showed that rooftop PV panels can generate 39% of total national electric-sector sales in the United States (US) (Gagnon et al., 2016). Moreover, 79% of all residential energy requirements in Andalusia, can be supplied by installing PV on all available residential rooftops (Hong et al., 2014). In order to assess the potential of solar energy for an urban scale, all rooftops areas should be estimated initially. Furthermore, estimating the solar energy potential from rooftops PV is a multifaceted process in which many parameters should be considered relating to the amount of solar radiation received (latitude, sky conditions, time of the year), roof structure (slope, free spaces, shading) and PV technology (efficiency, response to temperature, humidity and dust).

1.2. Statement of the Research Problem

The kingdom of Saudi Arabia (KSA) is amongst the highest countries worldwide in terms of per capita energy consumption (9.4 MWh) and CO_2 emissions (16.4 tons) (IEA, 2016). It is highly expected that electricity demand will increase significantly due to the rapid population growth (2.54% - annual growth rate (GAS, 2016) as well as economic development. KSA depends completely on oil and natural gas as primary fuels for electricity generation. Bulk of the generated electricity is dedicated to supply buildings. Buildings consume around 80% of the total electricity in Saudi Arabia with the residential sector alone comprising 52% of this share (Iskandar, 2015).

The kingdom is currently investing on renewable energy seeking diversity of energy resources. It has already set targets for renewable energy utilization, as to generate 9.5 GW of power from solar and wind energy by 2030 (Jurgenson, 2016). Therefore solar PV technologies within the building scope are a valid option for Saudi Arabia to reduce the load on the national grid and in sequence to help in reducing the negative environmental impacts.

1.3. Significance of the Research

KSA depends mainly on fossil fuels while the share of renewable energy, up to date, is negligible. The kingdom has set future plans to meet the increasing energy demand targeting a diverse and sustainable source of fuel for energy use rather than depending solely on fossil fuels. These investments are primarily targeting large scale projects such as the existing power plants while neglecting the potential from building applications. This study addresses the potential of solar energy at urban scale, through the application of PV being mounted on building rooftops rather than being installed on land. This research involves economic considerations as well as environmental assessment to evaluate the PV feasibility. This type of detailed study was not conducted in any part of the GCC region, hence this work will add a valuable contribution to the solar industry in the region and will benefit regulators and policy makers.

1.4. Research Objectives

This research aims to evaluate the feasibility of PV utilization in building applications given Saudi Arabia's climatic and economic conditions. This is achieved through the following key objectives:

1) Developing a framework for evaluating the feasibility of PV in building applications.

2) Implementing the framework to estimate the utilizable rooftop areas for PV applications for existing buildings.

3) Investigating the performance of solar PV pertinent to power generation and energy savings.

4) Conducting economic and environmental assessment for the designed PV system.

1.5. Scope and Limitations

This research focusses on incorporating PV technology into existing buildings to reduce load on the national grid. It is important to note that energy conservation measures (ECMs) pertaining to envelop, Heating Ventilating and Air-Conditioning (HVAC) as well as lighting systems should be considered for newly constructed buildings in order to make sure that building energy consumption is reduced as much as possible. Incorporating renewable energy technologies for building applications comes as a further step to be considered for meeting reduced energy demands. On the other hand, retrofitting existing buildings for energy saving purposes is expensive and sometimes not viable especially if replacements or new elements are introduced to the buildings.

The proposed framework is implemented to investigate the potential of rooftop solar PV for the two most common residential types i.e. apartments and villas. The case study is also limited to:

- Hot-humid climates representing the weather generally in the eastern region of Saudi Arabia.
- PV rooftop applications as the use of building integrated photovoltaic (BIPV) may require in depth investigation about their impact on building's energy performance.
- A suitable number of samples, due to the large scale considered in this study.
- A case by case analysis for the economic assessment as many factors can impact the analysis in which they vary from one building to another.

1.6. Research Methodology

The research approach set to achieve the stated objectives involves five main stages as outlined below:

Stage-One: Literature Review

- Addressing the concepts and parameters pertaining to Photovoltaics (PV) technology such as PV system components, incident solar radiations and PV sensitivity to atmospheric factors.
- Examining the existing literature in the field of PV applications in the building sector.
- Shedding some light on the concepts of Remote Sensing (RS) and Geographic Information System (GIS) technologies as they are used in different stages of this research.

Stage-Two: Data Preparation and Analysis

- Developing a general framework for the purpose of evaluating the feasibility of PV utilization in building applications.
- Collecting required data about land usage from Eastern Region Municipality to identify residential zones.
- Collecting high resolution satellite images for the area of study to provide a better and clear picture of rooftops and their components.
- Carrying out field visits to a suitable sample of building rooftops to be able to understand the situation (components and dimensions) more clearly.

- Computing gross and utilizable roof area for each building sample.
- Computing the ratio of utilizable to gross roof area.

Stage-Three: Energy Analysis

- Modelling of energy yield from PV systems considering orientation and inclination optimization using PV simulation tool.
- Estimating building energy savings from PV rooftop application using an energy performance modelling tool.

Stage-Four: Results and Conclusions

- Discussing rooftop area assessment for villas and apartments.
- Comparing villas and apartment buildings in terms of utilization factor and PV electricity production.
- Discussing the overall potential of electricity generation from PV systems installed on rooftops in the selected urban area.
- Conducting economic and environmental assessment for the designed PV system.
- Summarizing and highlighting the main results and findings from the study.
- Recommendations to the policy makers and for future work.

Figure 2 summarizes the methodology in a graphic format.

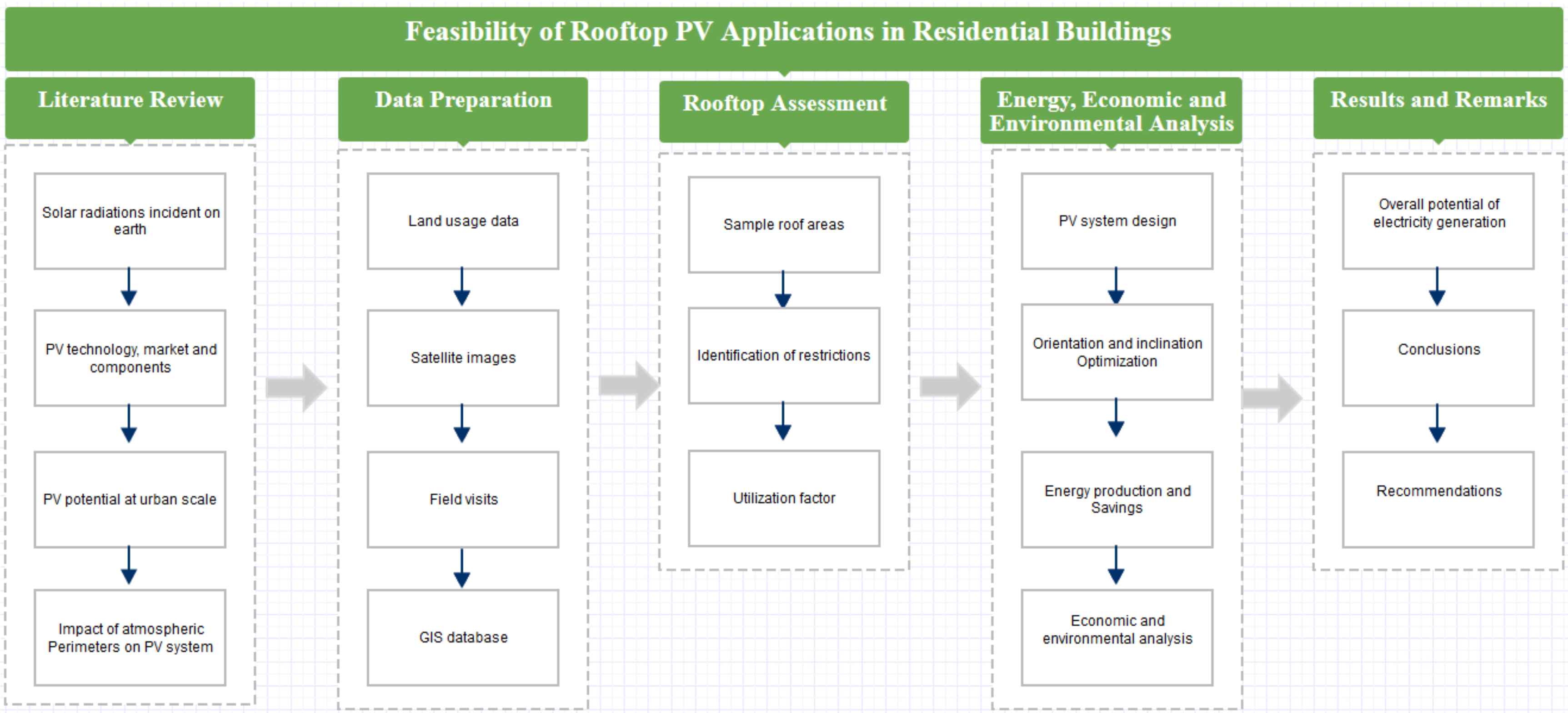


Figure 2: Research Methodology

CHAPTER 2

LITERATURE REVIEW

The literature in this research work addresses the concepts and parameters pertaining to Photovoltaics (PV) technology. It examines the existing literature in the field of PV applications in the building sector. As other technologies such as Remote Sensing (RS) and Geographic Information System (GIS) are also involved in order to conduct this study, this review of literature will shed some light on their concepts. Economic feasibility is considered as an integral part of this research, hence methods and parameters involved in published research studies pertaining to PV economics are also covered in this chapter.

2.1. Solar Radiations Incident on Earth

The earth is blissed with a huge amount of solar radiations incident on its surface around the clock. The average yearly solar irradiation that is received at the atmosphere layer is called solar constant, which is equivalent to 1365 W/m^2 (NASA). This makes the total solar irradiations received on the edge of earth's atmosphere equals to 1.73×10^{17} W, which is equivalent to 10,000 times the world's total energy consumption (DOE). When this vast amount of radiations enters the atmosphere, part of it is reflected (30%) by atmosphere, clouds and land. Another portion of the radiations is absorbed by atmosphere and clouds (19%), leaving 51% of the radiations to be absorbed by the earth's surface (Figure 3) (Ahrens, 2009).

The solar radiations that reaches normal to a surface on earth is called the Global Horizontal Irradiations (GHI) which can be classified into three categories; Direct Normal Irradiations

(DNI), Diffused Horizontal Irradiations (DHI) and Reflected Horizontal Irradiations (RHI) or Albedo. The term *Albedo* represents the reflectivity of a surface and is defined in the literature as the ratio of the reflected radiations by a surface to the initial amount of radiations striking the surface.

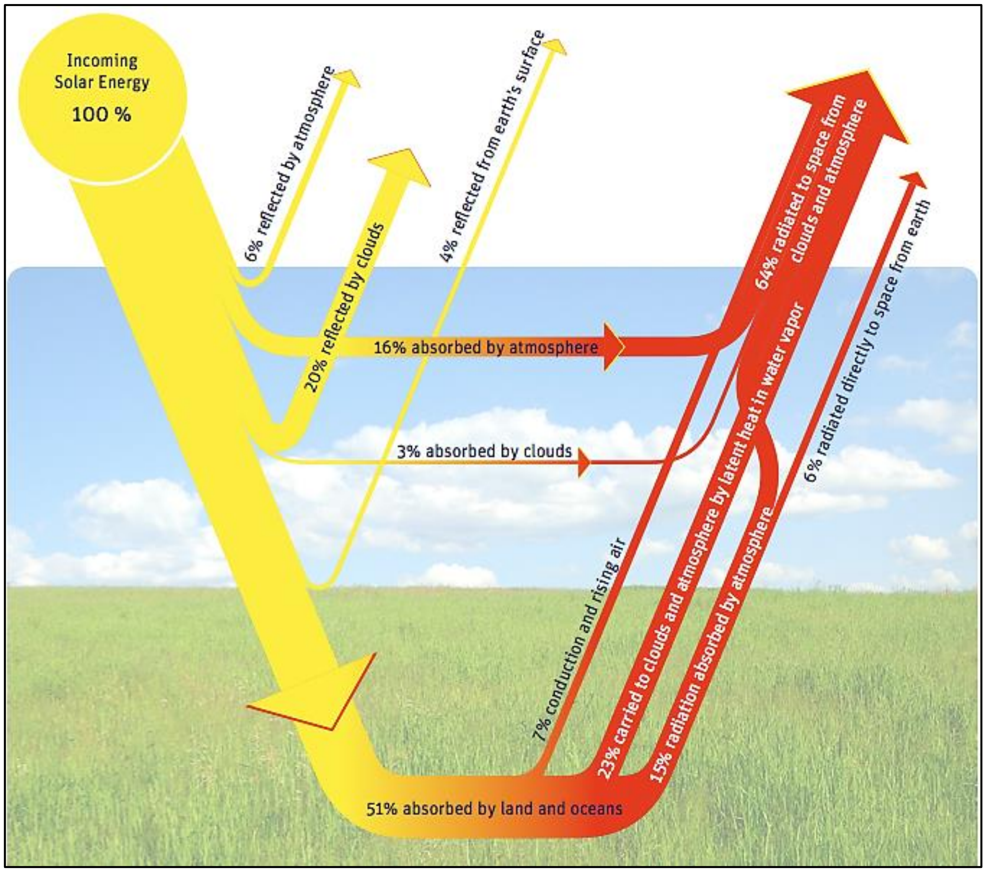


Figure 3: Solar Radiations Incident on Earth ((Kipp & zonen)

2.2. World Distribution of Solar Radiations

Looking at the global scale, Middle East and Northern Africa regions have the highest annual average solar energy potential with a value equivalent to 5736.2 ExaJoules. Sub-Saharan Africa and Former Soviet Union come next with a value of around 4950 and 4427 ExaJoules respectively. The rest of regions that are following are North America, centrally planned Asia, Latin America and Caribbean as shown in Table 1 (Ahrens, 2009).

Table 1: Solar Radiations Distribution Worldwide

Region	Min (EJ)	Max (EJ)	Average (EJ)
North America	181.1	7,410	3796
Latin America and Caribbean	112.6	3,385	1749
Western Europe	25.1	914	470
Central and Eastern Europe	4.5	154	79
Former Soviet Union	199.3	8,655	4427
Middle East and North Africa	412.4	11,060	5736
Sub-Saharan Africa	371.9	9,528	4950
Pacific Asia	41.0	994	518
South Asia	38.8	1,339	689
Centrally planned Asia	115.5	4,135	2125
Pacific OECD	72.6	2,263	1168
Total	1574.8	49837	**25706**

Being at the top of the list, Middle Eastern countries must exploit and utilize this high potential of solar Energy. Figure 4 shows the range of Direct Normal Irradiations (DNI) striking on the Middle East and Africa. KSA which encompasses the majority of the Arabian Peninsula, with an area of 2.15 million km^2, is receiving a range of DNI between 1600 – 2500 kWh/m^2. It is also noticed that cities along the western coastal of the kingdom are entertained more with solar irradiations compared to the other regions. The measurement of solar radiations in Saudi Arabia, using different approaches, was a concern of several studies.

(Rehman, 2009) studied the distribution of solar radiations and sunshine hours over 41 different locations representing Saudi Arabia. It was found that, on a yearly average, Saudi Arabia is receiving more than 2000 kWh/m^2, ranging from 1630 kWh/m^2 in Tabuk and 2560 kWh/m^2 in Bisha. Table 2 depicts the sunshine hours and solar global horizontal irradiation values of 10 selected locations involved in the study. A more recent study analyzed the broadband solar irradiations including GHI, DNI and DHI over the kingdom for a full year, using a new monitoring network. The study concluded that, most stations experience high GHI levels, and a minimum of 1800 kWh/m^2 annual average DNI.

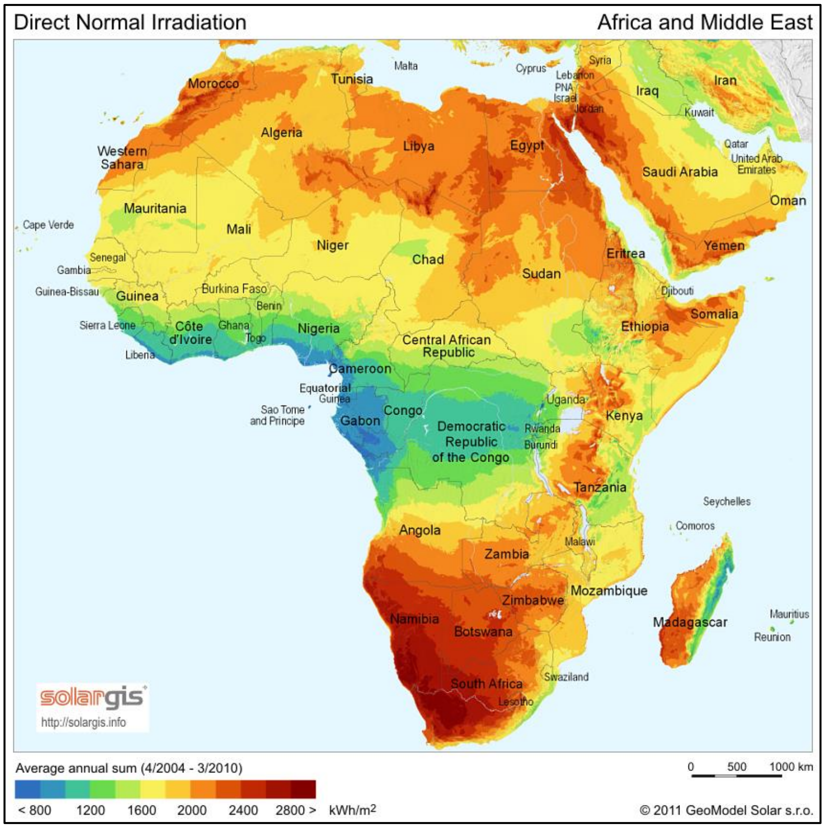


Figure 4: Direct Normal Irradiation Received on Africa and MiddleEast (Solargis)

Table 2: Sunshine Hours and GHR for 10 Locations in Saudi Arabia (Rehman, 2009)

Station	City	Latitude (deg.)	Sunshine duration (h)	Global Horizontal Radiation (kWh/m2)
1	Tabuk	28.38	9.1	1640
2	Hail	27.47	9.4	1910
3	Qatif	26.55	8.4	1730
4	Al-Hofuf	25.5	8.7	2070
5	Riyadh	24.57	9.2	1870
6	Madina	24.52	9.1	2320
7	Taif	21.23	8.9	1980
8	Bisha	20.02	9.2	2560
9	Abha	18.22	8.7	2130
10	Najran	17.55	9.1	2530

This study is targeting Al-Khobar city which is located few kilometers from Al-Dhahran city. There is more available information in terms of weather data in Al- Dhahran compared to Al-Khobar, hence, this research will consider the climatic data of Al-Dhahran. Al-Dhahran is a city in the Eastern Region of Saudi Arabia, located 62 m above sea level and lies between a latitude of 26.32° and a longitude of 50.13°. (Shaahid and Elhadidi, 1994) concluded that the attainable yearly solar potential for Dhahran city is 2030 kWh/m^2. (Elhadidy and Abdel-Nabi, 1991) analyzed the diffuse fraction of GHI over Dhahran city concluding with a value of 0.11 on a typical clear day and 0.91 on a dusty day. Table 3 and Figure 6 show the monthly solar irradiation data for Al-Dhahran city.

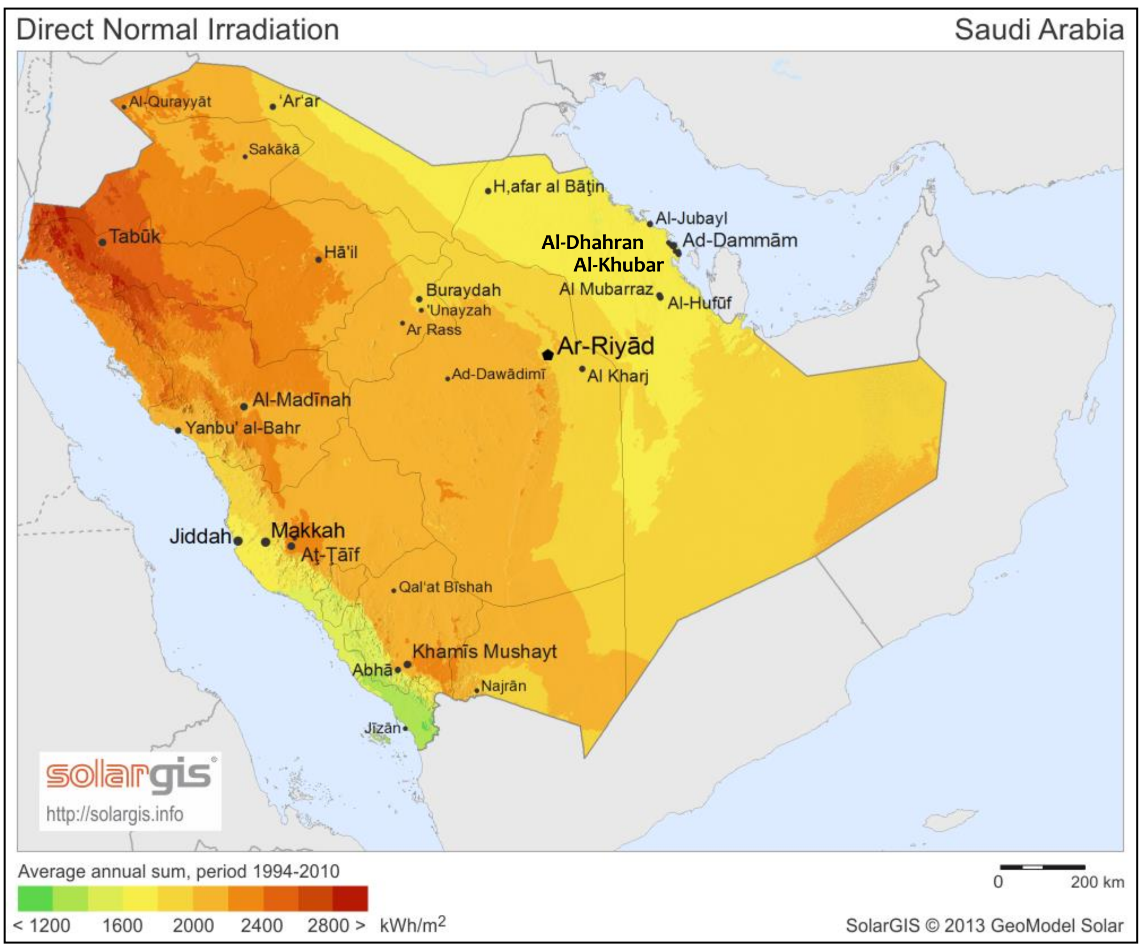


Figure 5: Direct Normal Irradiations Received in Saudi Arabia (Solargis)

Table 3:Monthly Global and Direct Normal Irradiation Data for Al-Dhahran, Saudi Arabia (JRC)

Month	H_h	H_{opt}	DNI	I_{opt}
Jan	3880	5080	4330	51
Feb	4800	5820	4770	43
Mar	6060	6720	5520	30
Apr	6600	6680	5520	14
May	7790	7340	6720	1
Jun	8320	7530	7690	-6
Jul	7860	7270	6770	-3
Aug	7450	7320	6610	9
Sep	6910	7450	6880	25
Oct	5750	6870	6330	40
Nov	4160	5310	4390	49
Dec	3720	5020	4390	54
Year	6110	6540	5830	24

Where:
H_h: Irradiation on horizontal plane (Wh/m^2/day)
H_{opt}: Irradiation on optimally inclined plane (Wh/m^2/day)
DNI: Direct normal irradiation (Wh/m^2/day)
I_{opt}: Optimal inclination (deg.)

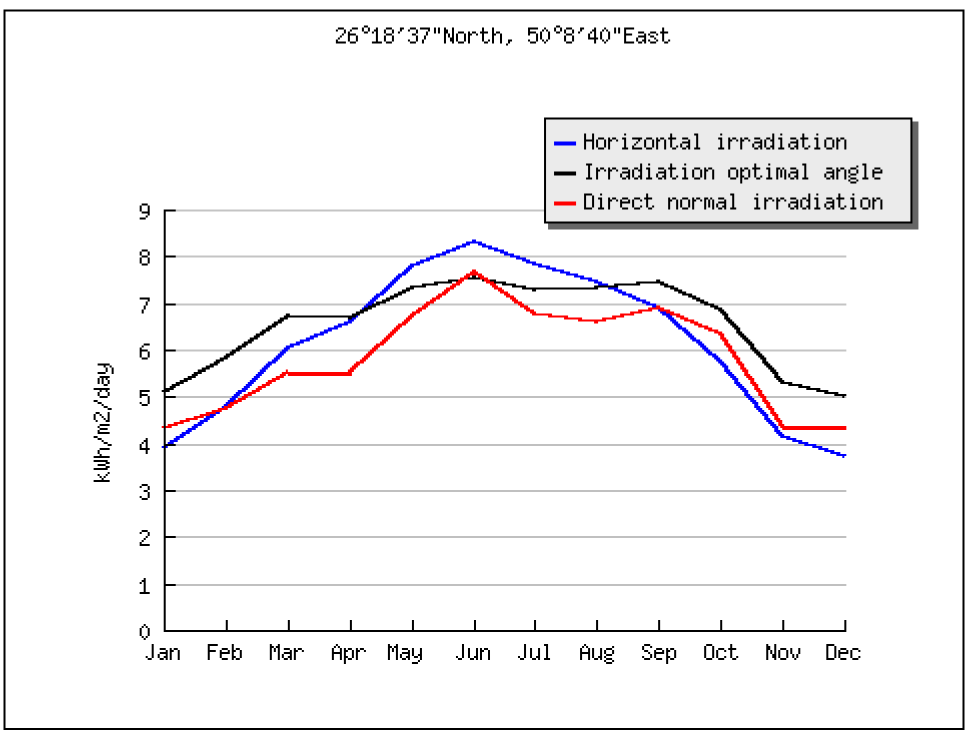
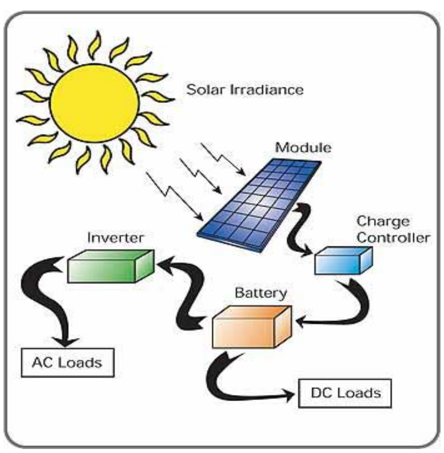


Figure 6: Monthly Solar Irradiation Data for Al-Dhahran, Saudi Arabia (JRC)

2.3. Photovoltaic (PV) Technology

PV is simply a technology that converts sunlight into electricity. There are three common types of PV cells including mono-crystalline, poly-crystalline and amorphous thin films with 15%, 13% and 5% efficiency respectively. Solar PV systems are mainly either standalone (off-grid) or grid-connected systems. The obvious difference is that stand alone systems require thermal storage (batteries) for usage when sun light is not available, while in grid connected systems building loads can be supplied by the grid during sun unavailability times. The basic components of a PV system include the PV module, charge controller, invertor, and batteries in case of off-grid systems (Figure 7-a) and smart meter in case of grid-connected systems (Figure 7-b).

The main advantages of PV systems are its low running cost, low maintenance requirements and its clean production while the main cons are the high capital cost, intermittent load, and that it cannot support heavy loads such as HVAC system.



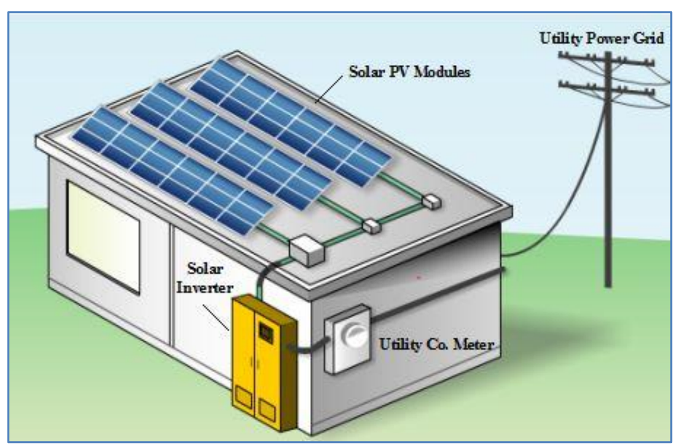


Figure 7: (a) Components of Standalone PV system, (b) Components of Grid Connected PV system (SWES)

2.4. World PV market

PV technology is leading the renewable energy market right after hydro and wind as shown in Figure 8 (IEA, 2017). The total installed capacity of PV worldwide was 277GW in 2015 with China, Germany, Japan and US as the main contributors as shown in Figure 9 (REN21, 2016). PV market includes large scale utility and small scale or rooftop applications. KSA is mainly investing on large scale projects as those already existing in the country such as the 0.5 MW PV power plant installed by Saudi Electricity Company (SEC) in 2011, 10 MW PV power plant installed by Aramco in 2011, 3.5 MW PV power plant installed at King Abdullah Petroleum Studies and Research Center (KAPSARC) in Riyadh and a 2 MW PV power plant installed at King Abdullah University of Science and Technology (KAUST). Although the utility scale projects are constituting the larger share of the solar market in most part of the world, small scale applications are growing rapidly and are encouraged through incentives for the end users. The share of installed rooftop PV is about 60% of the total PV market in Germany, with 35% installed on small to medium residential and commercial buildings (BSW solar, 2012). Small scale solar market in India has grown dramatically with a 90% Compounded Annual Growth Rate (CAGR), and with a total installed capacity of 0.740 GW as by March, 2016 (India Solar Handbook, 2016). Australia's solar market witnessed a significant increase in the number of small-scale solar power systems as more than 1.64 million were installed by December, 2016. This represented about 16% of Australia's renewable energy power generation and 2.8% of the total electricity produced in the country (Clean Energy Council, 2016).

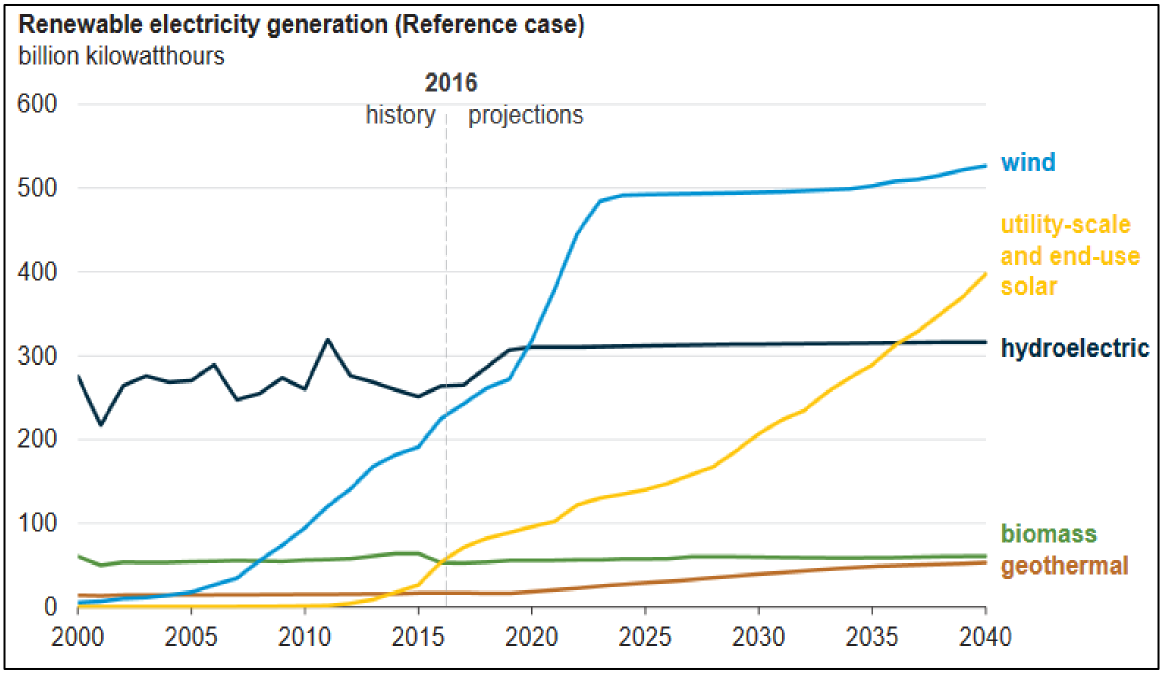


Figure 8: Renewable Energy Generation in Billion kWh (REN21, 2016)

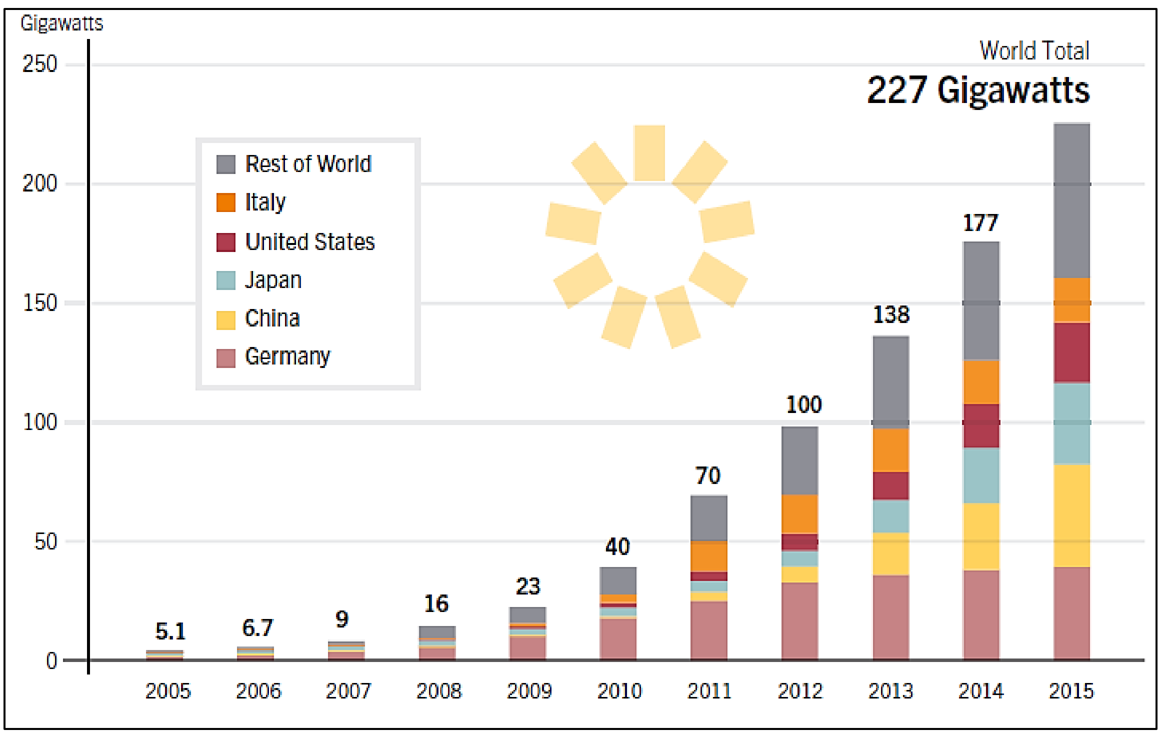


Figure 9: PV Installed Capacity Worldwide (REN21, 2016)

2.5. Impact of Atmospheric Parameters on PV system

The weather conditions are very critical when designing for photovoltaic system. PV modules are normally rated by their power and efficiency measured under particular lab conditions (Standard Testing Conditions or STC). STC is defined as 1000 W/m^2 solar irradiance, 25°C cell temperature (T_{ref}) and 1.5 Air mass. These factors are sensitive toward some of air properties including ambient air temperature (T_a) and humidity which will differ under various climatic conditions such as cloudy skies, rainy and dusty weathers. Therefore, weather parameters affecting PV efficiency are addressed in the next section along with the weather conditions of Dhahran.

2.5.1. Temperature

As mentioned before, PV cell efficiency show best performance under STC conditions. Cell temperature is one of the main factors considered when measuring its efficiency. Figure 10 shows current – voltage (I-V) and power – voltage (P-V) curves for different temperatures. It is noticed that as the temperature increases above the reference temperature (25°C), the voltage drops which in turn decreases the power output while the current is slightly impacted. Cell temperature (T_c) is significantly impacted by ambient temperature in addition to the long exposure to sunlight. In the literature, several models were developed pertaining cell temperature correlations. Mathematically, these correlations are either in an explicit form, in which T_c can be directly computed, or in an implicit form in which other variable are dependent on T_c. Such implicit correlations considers wind speed, cloudiness factor, material related properties (e.g. module emissivity), mounting conditions and other heat transfer characteristics (Schott, 1985; Del Cueto, 2000; Skoplaki and Palyvos 2009; Dubey et al., 2013). On the other hand, explicit mathematical equations can bring the model to a much simpler form by relating T_c with T_a and solar irradiance using normal operating cell temperature (T_{NOCT}) (Myers et al., 2002; Skoplaki et al., 2008). NOCT is defined as the temperature that describes normal operating conditions and constitute of 800 W/m^2 irradiance, 20°C air temperature and 1 m/s wind speed. A standard procedure for determining NOCT was developed by the American Society for Testing and Materials (E 1036-08) (ASTM, 2008). One of the common methods used to determine T_c for non-roof integrated modules is provided as follow (Ciulla et al., 2013):

$$T_c = T_a + \frac{(T_{NOCT} - 20) \times G}{800}$$

Where G is the solar Irradiance.

Hence, one must notice that it is very important to consider the mounting condition in which the PV array is installed. Cells within building integrated photovoltaic (BIPV) require different procedure to determine T_c as the impact of temperature on the modules composition differs from non-roof integrated panels. Davis et al. addressed cell temperature model development and proposed a new method for computing T_c within BIPV modules. The authors also noted that using the NOCT equation can underestimate T_c by 20K (Davis et al., 2001).

The impact of the temperature deviation from T_{ref} on PV efficiency was demonstrated in previous studies. Table 4 shows the efficiency correlation with elevated temperature for different PV technologies.

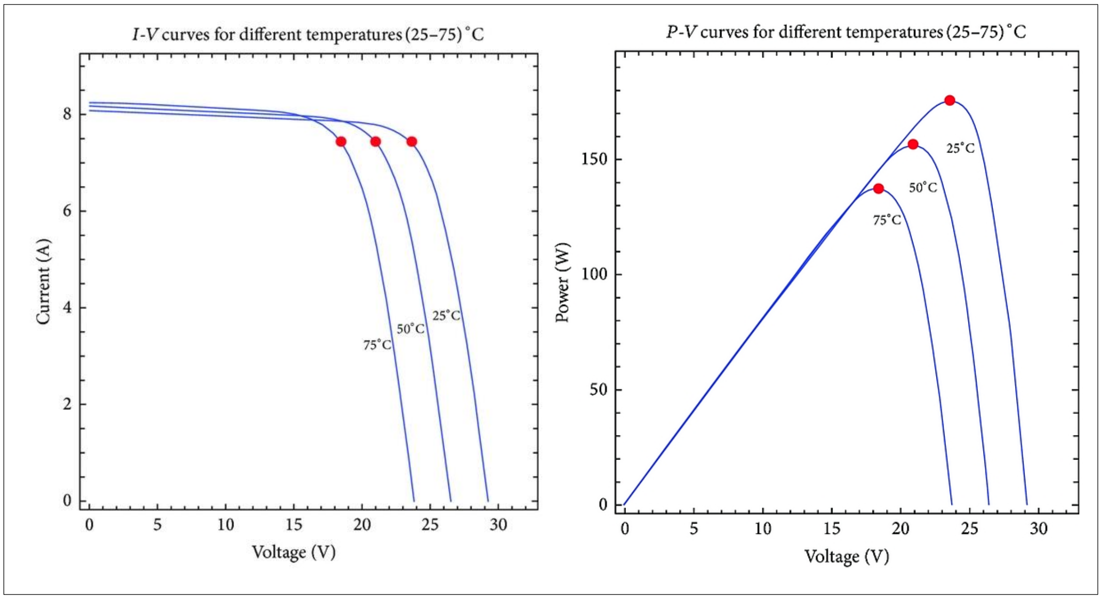


Figure 10: (a) I-V Curves for Different Temperatures; (b) P-V Curves for Different Temperatures

Monocrystalline PV, which are the most common type around the globe, have the highest temperature coefficient (-0.45%/°C) compared to poly crystalline (-0.4%/°C) and a-Si thin film (-0.2%/°C).

Table 4: Efficiency Correlation with Elevated Temperature for Different PV Technologies.

PV Technology	Temperature Coefficient (%/°C)	Reference
Mono Crystalline (Mono-C-Si)	-0.45,-0.5	(Makrides et al., 2012; Kannan et al., 2006)
Poly-Crystalline (Multi-C-Si)	-0.4, -0.38	(Makrides et al., 2012; Dash And Gupta, 2015)
Thin Film (a-Si)	-0.2, -0.23	(Kaldellis et al., 2014; Dash And Gupta, 2015)

Considering real performance of PV modules in hot climates, Touati et al. reported different behavior of monocrystalline and Amorphous PV in terms of temperature resistant. The authors concluded that monocrystalline cells are less affected by temperature compared to thin films (amorphous cells) as illustrated in Table 5 (Touati et al., 2013). As reported by Alshakhs, a recent research addressed the environmental parameters impact on a polycrystalline type PV module under Dhahran climates. A loss in the module efficiency from 11.6% to 10.4% was noticed as the temperature increased from 38 °C to 48 °C, which corresponds to a temperature coefficient of -11 ΔE/°C. (Bahaidarah et al., 2015) conducted numerical and experimental analysis of a monocrystalline hybrid PV system to investigate its electrical and thermal performance against temperature in Dhahran. They found that the efficiency of the module decreases by 0.06% for every 1°C increase in temperature.

Table 5: Temperature Coefficient for Monocrystalline and Amorphous Silicon (Touati et al., 2013)

Technology	**ΔEffeciency/°C**
Mono-crystalline silicon	−0.010
Amorphous silicon	−0.030

Dhahran has a desert climate with very hot-humid summers and mildly cool winters. Figure 11 describes the average temperature conditions in Dhahran collected over a 38 year period. The summer period lasts from May to September with at least 38°C as the average daily high temperature. The hottest month is July with an average high temperature of 43°C, but temperatures can reach as high as 49°C. The winter period lasts from December to March with an average daily low temperature above 11°C. The coldest month is January with an average low temperature of 11°C.

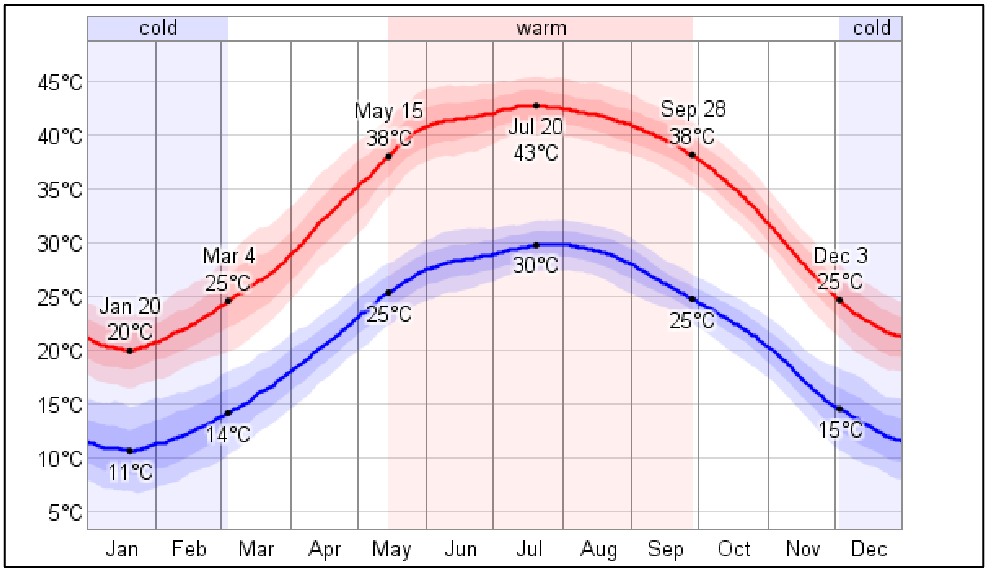


Figure 11: Average Temperatures in Dhahran Over the Year

2.5.2. Relative Humidity (RH)

PV modules are manufactured to prevent moisture from penetration. PV cells are encapsulated between two Ethylene Vinyl Acetate (EVA) sheets for moisture protection. As moisture penetrate the EVA sheet it can result in either delamination, loss of passivation or corrosion of solder joints (Park et al., 2013). However, this is not the only impact of humidity on the performance of PV, as the impact of vapor particles on the incoming irradiations is also accounted for. Generally, power output of PV modules are noticed to be high at low relative humidity periods (Ettah et al., 2012). Rahman et al. experimentally investigated the impact of several operating parameters including humidity on the solar module performance. Figure 12 shows the results, at 800W/m^2 irradiation level, in which the power decreased by about 1.6W for 10% increase in RH and 3.16W for 20% increase in RH (Rahman et al., 2015). (Touati et al., 2013) investigated the sensitivity of monocrystalline and amorphous PV cells under the climate of Qatar (Table 6). The analysis showed that amorphous cells

(0.043 ΔE/%RH) has a sharper decrease compared to monocrystalline types (0.015 ΔE/%RH).

Table 6: Humidity Coefficient for Monocrystalline and Amorphous Silicon (Touati et al., 2013)

Technology	ΔEffeciency/%RH
Mono-crystalline silicon	-0.015
Amorphous silicon	-0.043

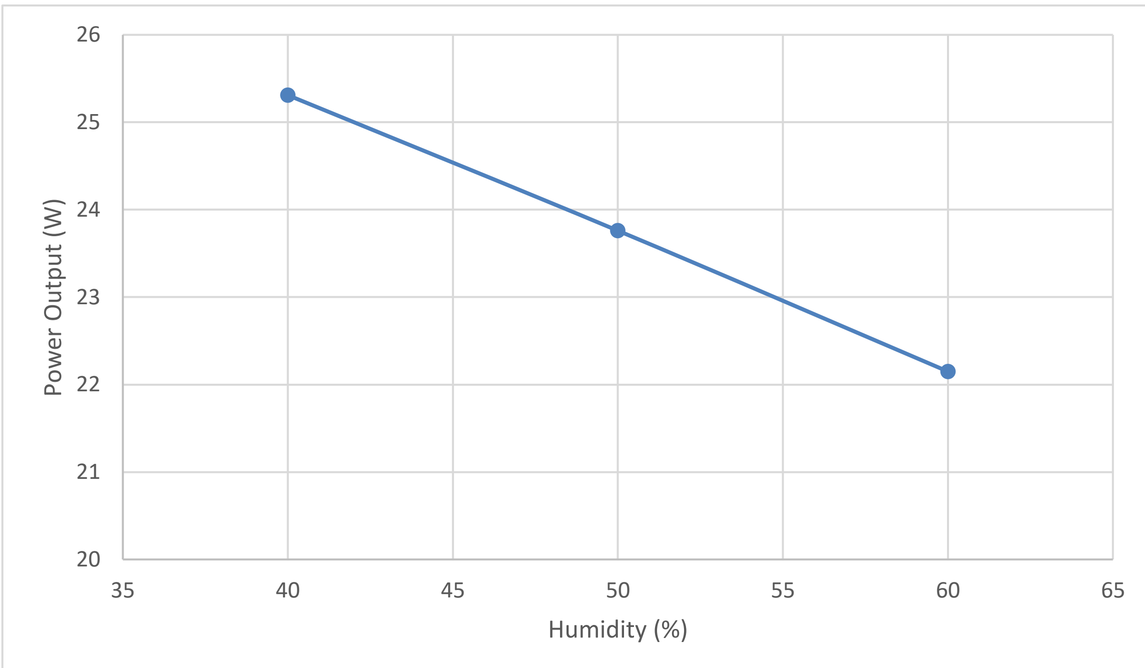


Figure 12: Humidity Vs. Power Output (Rahman et al., 2015)

Summers in Dhahran are considered very humid, as the average daily high Relative Humidity (RH) ranges between 61% and 90%, while the average daily low RH ranges between 15% and 46% throughout the year (Figure 13).

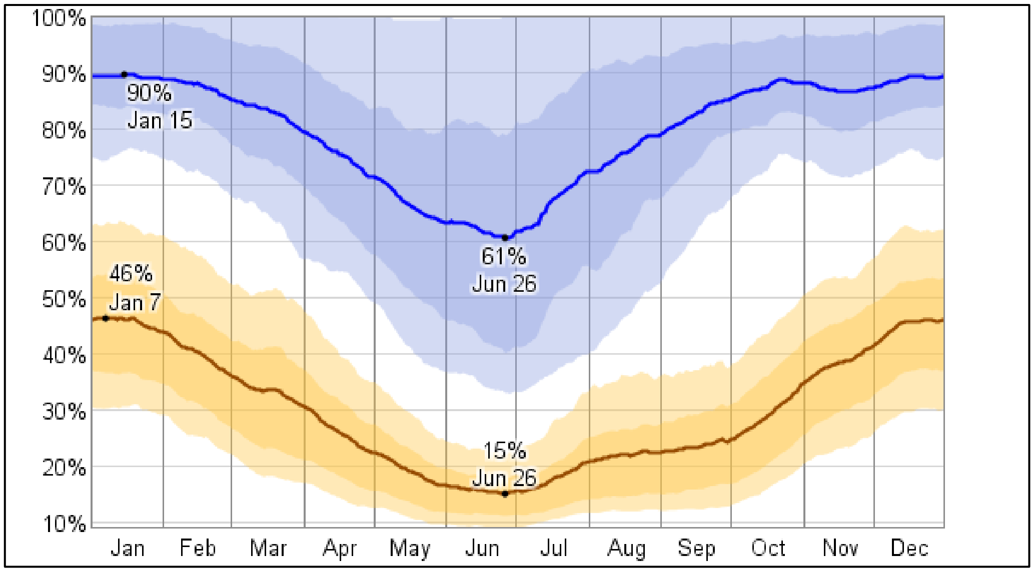


Figure 13: Average Relative Humidity in Dhahran Over the Year

2.5.3. Clouds

Solar irradiance is the major source of input to the PV cell, hence it is a very important factor to consider. In fact, a study showed that the greatest impact on PV's power output occurs due to solar irradiance levels (Makrides et al., 2012). Figure 14 depicts I-V curves in response to different irradiance levels influenced by variable sky conditions. It is clear from Figure 14 that voltage is slightly affected by solar irradiance, while current changes dramatically with varying levels of irradiance. (Rahman et al, 2013) reported an increase of 2.9W in the solar module power as the level of irradiation increased by 100 W/m^2 but raising the PV cell temperature by a 4.9°C.

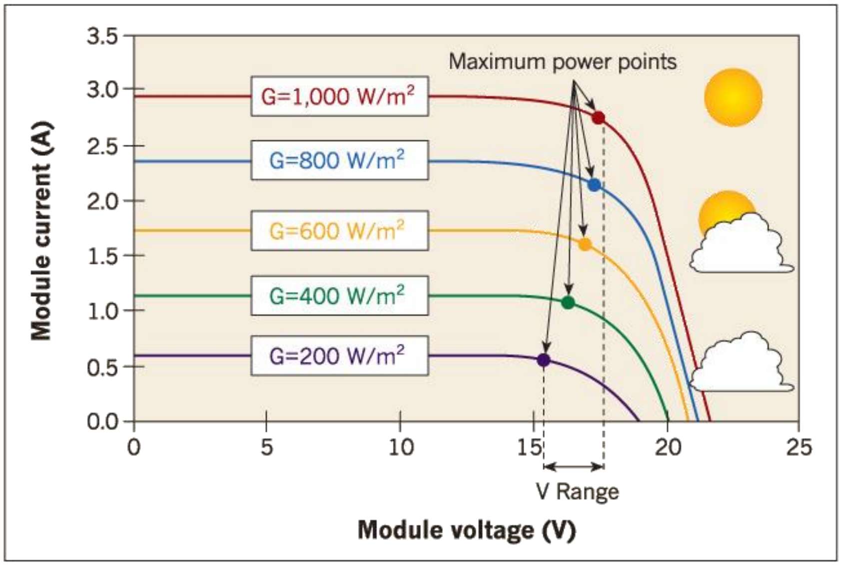


Figure 14: I-V Curve for Different Irradiation Levels (ecmweb.com)

In general, Dhahran has a clear sky conditions throughout the year, despite that clouds coverage can reach 25% in the winter season as shown in Figure 15. The sky is pretty clear during summer months with an average of 0% cloud coverage, while it can reach 25% in the winter season.

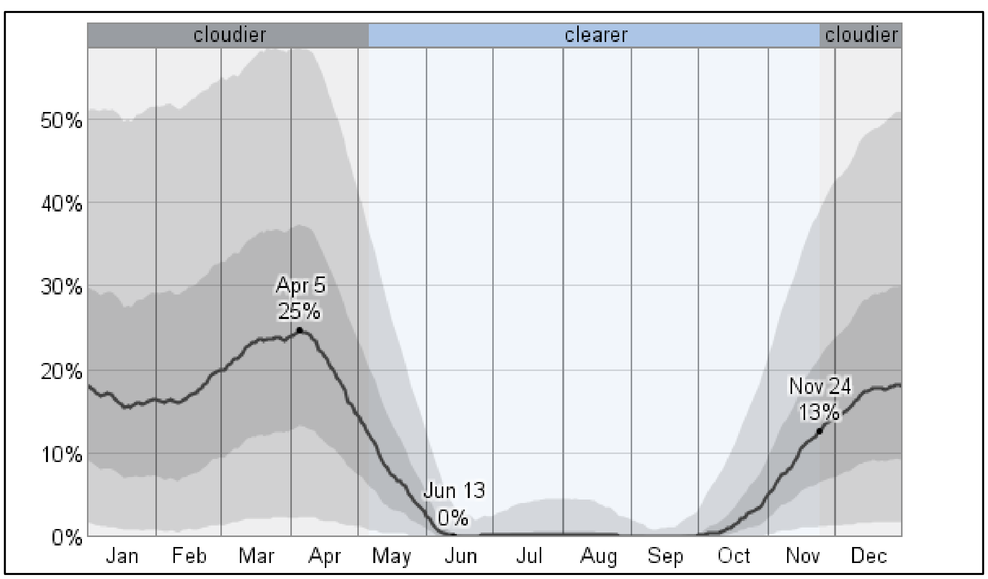


Figure 15: Clouds in Dhahran Over the Year

2.5.4. Dust

Dust particles have a significant and an adverse impact on the efficiency of PV panels (Bahaidarah et al., 2015; Mani and Pillai, 2010; Mejia et al., 2014) especially in desert regions where dust storms are frequent while rain is less expected. The accumulation of dust on PV panels hence results in a major reduction in the power output. The power output loss depends on various variables such as dust density on the PV outer surface, its tilt angle, orientation to the principal wind direction, length of exposure and location climatic conditions (precipitation and humidity).

Many studies in worldwide and in the GCC region focused on testing the performance of different PV technologies against dust (Cristaldi et al., 2014; Paudyal and Shakya, 2016; Abderrezek and Fathi, 2017). The GCC region in general has a desert climate where dust storm phenomena occurs frequently. (Touati et al., 2013) investigated the performance of two PV technologies against dust under the climate of Qatar. The analysis showed that during a day, dust accumulation caused a decrease of 0.095% and 0.071% in efficiency of monocrystalline and polycrystalline PV respectively. (Karmouch and El Hor, 2017) studied the impact of dust on the performance of roof mounted PV panels in the southern region of Saudi Arabia considering different tilt angles. A 10% loss in efficiency was recorded to be the result of 4 months of dust accumulation on a 30° tilted PV panel. Increasing the tilt angle to 55° reduced the losses by about 1% only. Another study was conducted by (Adinoyi and Said, 2013) to investigate the impact of dust accumulation on the power output of crystalline PV modules after being exposed to the outside conditions in Al-Dhahran city. It was found that a single dust storm can cause a reduction of 20% in the power output while a six month exposure to dust can brings the reduction to as much as 50% when no means of cleaning is performed.

2.6. Relevant Studies of Solar PV Potential at an Urban Scale Worldwide

GIS offers a significant contribution to the field of renewable energy wither for policy makers, planning commissions or for service companies. GIS has been utilized for renewable energy applications in many parts of the world. (Quinonez-Varela et al., 2007) used GIS as a planning tool in combination with power system simulation software for renewable energy assessment. Other applications involved spatial mapping of renewable resources for energy harvesting (Ramachandra and Shruthi, 2007), decision support for biomass availability assessment (Zambelli et al., 2012), wind farm site selection (Latinopoulos and Kechagia, 2015; Wróżyński et al., 2016) and solar/thermal energy potential assessment (Gadsden et al., 2003; Mills, 2004).

Studying the potential of rooftop PV for large scale applications has been the interest for researchers especially with the advancement of solar technologies. A number of researchers have developed methods for estimating the power that can be generated by the employments of PV on available rooftops at an urban scale. Three main procedures were developed including constant value method, manual based selection and GIS based techniques (Melius et al., 2013). Table 7 summarizes the pros and limitations of the three main methods.

Table 7: Summary of the Pros and Limitations of the Main Methods Used for Rooftop Area Estimation

	Pros	Cons
Constant Value	Quick and easy	Assumptions are not based on knowledge of buildings, validation is difficult
Manual Selection	Detailed, assumptions are based on specific knowledge of buildings	Time intensive and not easily replicable
GIS based	Detailed, replicable and can be automated	Time and computer resource intensive

The first method (constant value method) is the simplest as it considers a number of assumptions by simply assuming a percentage of utilizable area for each building category. (Denholm and Margolis, 2008) investigated several approaches to generate supply curves based on rooftop PV deployment. They estimated the potential considering residential and commercial separately due to the relatively high cost difference between the two roof categories. A number of assumptions were included such as number of buildings, percentage of utilizable area, roof type and installation costs. This method gives a quick estimation, however, it has larger errors due to not considering parameters that may affect the arrangement of PV panels (e.g. HVAC, different building heights).

Manual selection method is the most accurate method, however, it is time consuming as buildings are investigated individually. This method utilizes remote sensing techniques (e.g. aerial images) with high resolutions such as Google Earth™ to evaluate the available rooftop areas. (Izquierdo at al.,2008) proposed an approach to estimate the utilizable rooftop areas for PV applications and also determined the range of errors occurred during the estimation. They used different data such as census, land uses and building densities to help in their estimation under the Spain weather conditions. (Ordonez et al., 2010) used satellite images (Google Earth™) along with construction statistics to determine the power capacity of roof mounted PV panels on residential buildings in particular. The digital maps are then exported to AutoCAD® and scaled to measure roof areas as well as to consider roof components that can interfere with PV modules layout. The results showed that about 79% of all residential energy requirements in Andalusia could be supplied by installing PV on all available rooftops. Despite the accurate estimates given by this approach, it is difficult to consider such a strategy for large scales (countrywide) (Gagnon et al., 2016).

Many research available in the literature used remote sensing and GIS to determine the potential for PV installed on rooftops in different parts of the world. (Singh and Banerjee, 2013) developed a strategy on estimating the available rooftops to be utilized for PV panels. The authors used Google Earth™ for satellite imagery which was georeferenced using QGIS software and then rooftop potential was simulated with the help of PVsyst software.

(Hofierka and Kanuk, 2009) established a methodology for the potential of PV in urban areas by developing a 3D model of a city implemented in GIS. The study considered different classification of buildings including residential, industrial and shopping malls. The results showed that PV production can generate two-third of the electricity consumed in the studied area.

(Hong et al., 2013) conducted a sensitivity analysis to assess the impact of rooftop factors on PV generation. The authors then developed a based optimizing model using GIS in which they made decision making easier.

(Bergamasco and Asinari, 2011) proposed an algorithm to explore the available rooftops in the city of Turin, Italy for PV utilization. The methodology considered roof topology and shadows reflected on the rooftops of 60,000 buildings. MATLAB® algorithm was used for consideration of shadows and other roof components (dish antennas, condensers, etc.) and results showed a 90% accuracy level for the examined samples.

2.7. Economic Assessment of PV

There exist different types of assessments including technical, economic, financial, social and many others (El-Sharkawy, 2005). Economic considerations are of utmost importance in any type of study, in fact it is the most important factor in which investors mostly make their decisions based on. Feasibility studies evaluate the potential of an investment or a project for success. A project is said to be viable if the cost indicators are positive or benefits are more than expenditures. Cost indicators include but not limited to net present value (NPV), internal rate of return (IRR) and benefit to cost (B-C) ratio. NPV can be evaluated by considering the present value of all outgoing (expenditures) and incoming (benefits) cash flows of the study period. The sum of all cash flows at their present value is called NPV, in which if it is positive then investment is worth it. The previous indicators are considered as lowest life cycle cost (LCC) which is the most common and simplest measure of economic feasibility.

Life cycle costing analysis (LCCA) assess the total cost of a project by considering capital cost (purchasing and installation), fuel cost, operating and maintenance (O&M), replacements, residual value and any benefits. LCCA is advantageous when comparing different alternatives as to select the lowest overall price of ownership.

Sensitivity analysis can support the study by determining which of a number of uncertain parameters has the paramount impact on a predefined criteria of the analysis. It also helps in examining different "what if" scenarios to identify critical parameters.

Levelized cost of electricity (LCOE) is another popular economic measure being used by most of the scholars in the field of energy. It is one type of LCCA in which it considers the life time costs to give an estimation of the cost per unit energy (e.g. $/kWh). Many studies have considered LCOE as a method for evaluating the feasibility of a newly installed renewable energy systems such as PV technology (Ouyang and Lin, 2014; Mundada et al., 2016; Kang and Rohatgi, 2016). (California Energy Commission, 2010) adopted the method of LCOE in their report to evaluate the feasibility of energy generation systems including those from fossil fuels and from renewable energy sources. The report provides a summary of the LCOE for all 21 technologies for comparison, which can contribute to the energy programs in California. (Adaramola, 2015) conducted a techno-economic study for 2.1 kW small-scale grid-connected PV system in Norway. Many parameters were included in the analysis such as capital cost, operating and maintenance, inflation, interest rate and feed-in tariff (FIT). After performing the calculations, the LCOE was found to be US$0.110/kW h.

2.8. Remote Sensing Technology

Remote sensing is an advanced technology in which information (e.g. images) about earth surface is acquired using sensors usually installed on satellites. The principle behind remote sensing is detecting radiant energy reflected of emitted by materials or objects. This can involve passive or active sensors depending on the method of collection. Passive sensors such as infrared and radiometers rely mainly on sun radiations reflected from objects while the latter works by emitting energy from their own source and then measure the reflected radiations from the target (e.g. RADAR and liDAR). Image processing is required to enhance the image presentation so it can be easily interpreted.

There are many advantages of remote sensing and these include; (1) ability of data collection within inaccessible areas or zones of danger, (2) replacement of slow data collection on ground which can be very costly by providing large area coverage, (3) ability of monitoring dynamic features such as water bodies and (4) an image that is produced can be analyzed for different purposes. Remote sensing has limitations as well; (1) it is an expensive technique when measuring small areas, (2) it requires special training for data processing and analysis, (3) studying dynamic features are costly because repetitive collection are required and (4) instruments often requires calibration, in which it will result in uncalibrated data in case calibration is not done.

Remote sensing is used to provide imagery of the earth, such satellites include *Landsat*, *IKONOS*, *QuickBird* and *GeoEye*. Remote sensing is used in many applications such as agriculture, oil exploration, water resource management and disaster management.

2.9. Geographic Information System (GIS) technology

Geographic Information System (GIS) is a tool that allows users to visualize, analyze, compare, interpret spatial data as well as helping in driving conclusions for decision makers. GIS software are available widely and can display, store and manage georeferenced data. Examples of commercial packages include ArcGIS® (Esri), Geomedia® (Hexagon Geospatial), Maptitude® (Caliper Corporation).

GIS provides a unified database in which it is capable of analyzing spatial data in many ways. It also allows for a better data management by controlling who can access, view and edit the data. It can also help in answering many questions and is able to carry out “what if” scenarios. GIS has drawback as well, it is considered as an expensive software especially for services. It requires huge amount of data input in which it may take a lot of effort or even cost a lot.

GIS has been used for many application including crime mapping, disaster and crisis management, optimum site selection, road networking, wastewater systems management and estimation of renewable energy potential.

CHAPTER 3

FRAMEWORK DEVELOPMENT AND IMPLEMENTATION FOR EVALUATING THE FEASIBILITY OF PV IN BUILDING APPLICATIONS

3.1. Framework Development

Evaluating the potential of renewable energy technologies has a multifaceted process involving technical, economic and social aspects. Figure 16 illustrates a developed framework that can be used to evaluate the feasibility of PV in building applications. The following subsections describe the main elements in the framework.

3.1.1. Technical Viability

The technical part investigates how much of the received solar irradiation can be captured and then utilized for building applications. It involves four main aspects i.e. system performance, area availability and physical positioning, aesthetics and availability of technical assistance. The system performance is defined by the efficiency of the system in converting the solar energy into electricity. PV performance is dependent on the type of technology adopted and the environmental conditions under which the system is operating. Chapter 2 discusses the main types of PV systems and the impact of weather conditions on the system output. Another technical aspect includes area availability and physical positioning of PV panels. In most cases, structural and service components are occupying majority of the space leaving a small area for PV applications. PV layout and orientation can have a direct influence on the system performance by means of harvesting maximum solar irradiation. Furthermore, architectural considerations play a role in the decision making process. PV panels should be well integrated with the building and should not disturb its architectural appearance. Another critical aspect is the availability of technical assistance and support before installation and during operation of PV systems. Technical support teams can help users in customizing the system to fit their needs and to provide periodic maintenance to maintain a good system performance.

3.1.2. Economic Potential

The economic potential describes the feasibility of the PV systems given the resources and technical potentials considering the region's economic situations. Economy is of utmost importance in any type of study, in fact it is the most important factor in which investors mostly base their decisions on. The cost of the technology including the initial investment and the maintenance costs are the main inputs to perform LCA. LCOE is the tool that is used to determine the feasibility given the PV system costs and its energy yield. Chapter 2 discusses the main features used in the economic assessment.

3.1.3. Policy, Regulations and Social Context

The key to promote PV applications is through policy intervention which can include a wide range of direct and indirect incentives. Incentives can encourage building owners to think about adopting this technology and hence will create a demand for PV allowing the PV market to develop. Regulations can also contribute to enhance the feasibility by means of reducing payback period. These include building regulations as to dedicate part of the roof area for PV applications, and energy regulation as to escalate electricity tariffs. Awareness about energy and its environmental impacts can help in community adoption for PV technology.

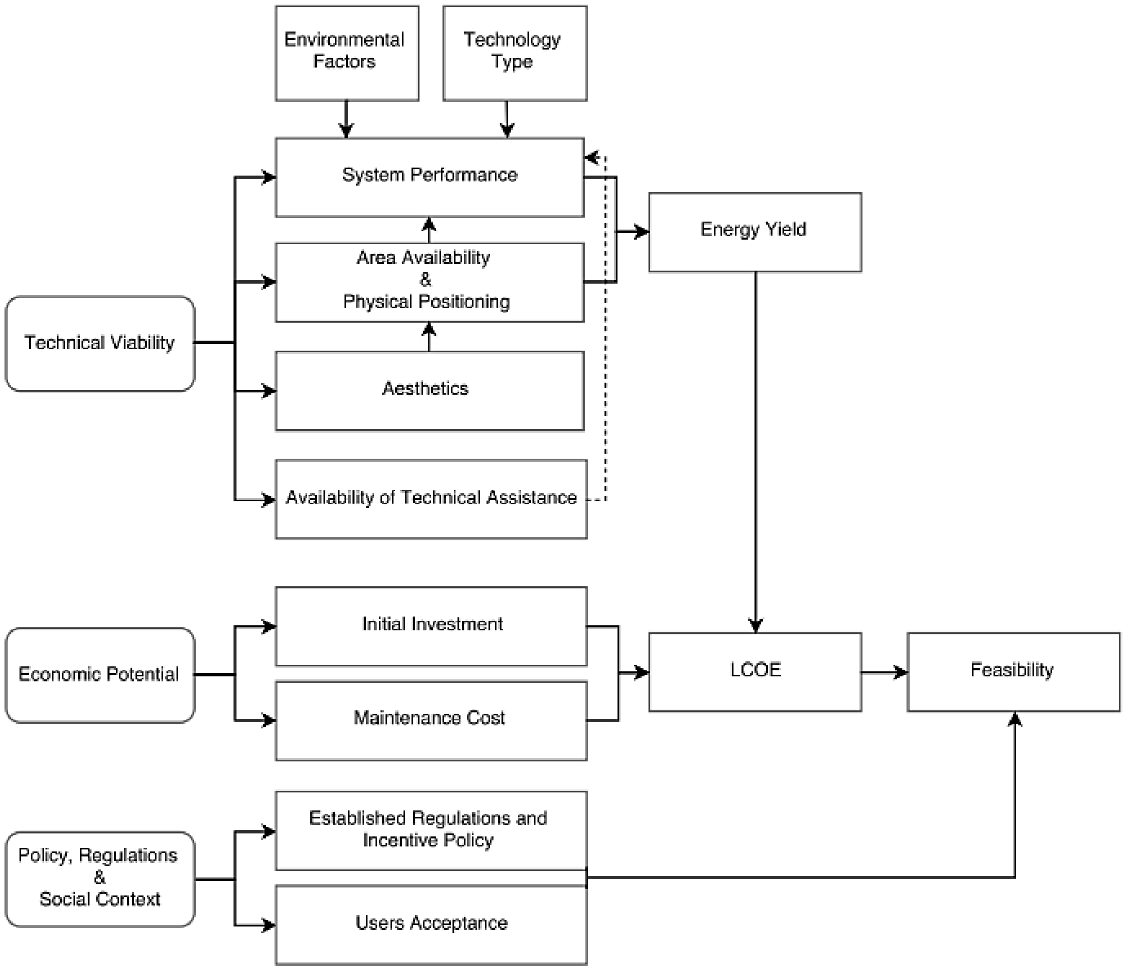


Figure 16: Framework for Evaluating the Feasibility of PV in Building Applications

3.2. Framework Implementation

This section provides a case study that implement the proposed framework without considering the social aspects. The case study considers evaluating the potential of rooftop PV at an urban scale, considering a city in the eastern region of Saudi Arabia. It is very important to conduct rooftop area assessment before analyzing or designing the PV system. Many studies were conducted in different parts of the world aiming to estimate the potential energy from rooftop PV. There is no one specific method to determine the available rooftop area, some of the methods are based on assumptions while others include manual inspection for the rooftops using satellite images or utilizing GIS technology. Table 8 summarizes the findings of residential rooftop area estimation from the main available methods in the literature.

Table 8: Summary of Findings of Residential Rooftop Area Estimation from the Main Available Methods

Study	**Area of Study**	**Method**	**Utilizable Area**	**Remarks**
Frantzis et al. 1998	Minneapolis	Constant Value	35-65%	Flat roofs
Chaudhari et al. 2004; Frantzis et al. 2007; Paidipati et al. 2008	United States	Constant Value	22-27%	-
Wiginton et al. 2010	Southeastern Ontario	Constant Value	30%	-
Armanino and Johnson;	Arizona	Manual Selection	1.31-11.6%	-
Nguyen and Pearce 2012	Ontario	Manual Selection	33%	-
Ordonez et al. 2010	Andalusia	Manual Selection	51-55%	Flat roofs
Jofierka and Kanuk 2009	Bardejov, Slovakia	GIS Based	35%	-

This section describes in detail the methodology used in determining the available rooftop area for PV utilization. After reviewing the literature, and despite being time intensive, the manual selection method was selected as the most suitable method for this study. That is because the GIS based method requires intensive data and resources, and because the selected method can provide acceptable results and can serve the research scope. The use of satellite images can be very helpful in surveying buildings' roofs, but Google Earth™ or Bing™ do not have high resolution images for Saudi Arabia as compared to the case in other advanced countries. Hence, site visits were required to get a better picture of the buildings, their surroundings and their roof conditions. Figure 18 shows a flowchart of the procedure followed for rooftop assessment which are discussed in details in the subsequent sections.

3.2.1. Sample Buildings

Investigating all residential buildings in Al-Khobar is impossible and can be very tedious, therefore 22 different samples were selected including 14 apartments and 8 villas. A larger number of samples was proposed initially but due to the difficulties in obtaining the samples, they were reduced to 22. Samples were selected from different zones of the city including north, south, east, west, and middle of Al-Khobar. Majority of samples were taken from the middle because this area has more population density. Figure 17 depicts the locations and distribution of sample within the city. It was important to consider samples from different residential neighborhoods to account for the variation in building characteristics. Privacy and security were the main challenge in conducting field visits. It was not appropriate to select random buildings for the study due to cultural reasons, therefore, friends and contacts were approached to facilitate the work. For the case of apartment buildings, building owners usually do not give the roof key to tenants except for those who stay in the annex (penthouse).

Another point is that, it was necessary for the author to be accompanied by one of the tenants during the visit to avoid problems. Therefore and in order to account for the convenience of the tenants, the process was taking longer time than expected as most of them preferred to be visited during weekends. For the case of villas, most of the villas have the access to the roof through the building so getting inside the building was extremely difficult.

Figure 17: Locations and Distribution of Selected Samples

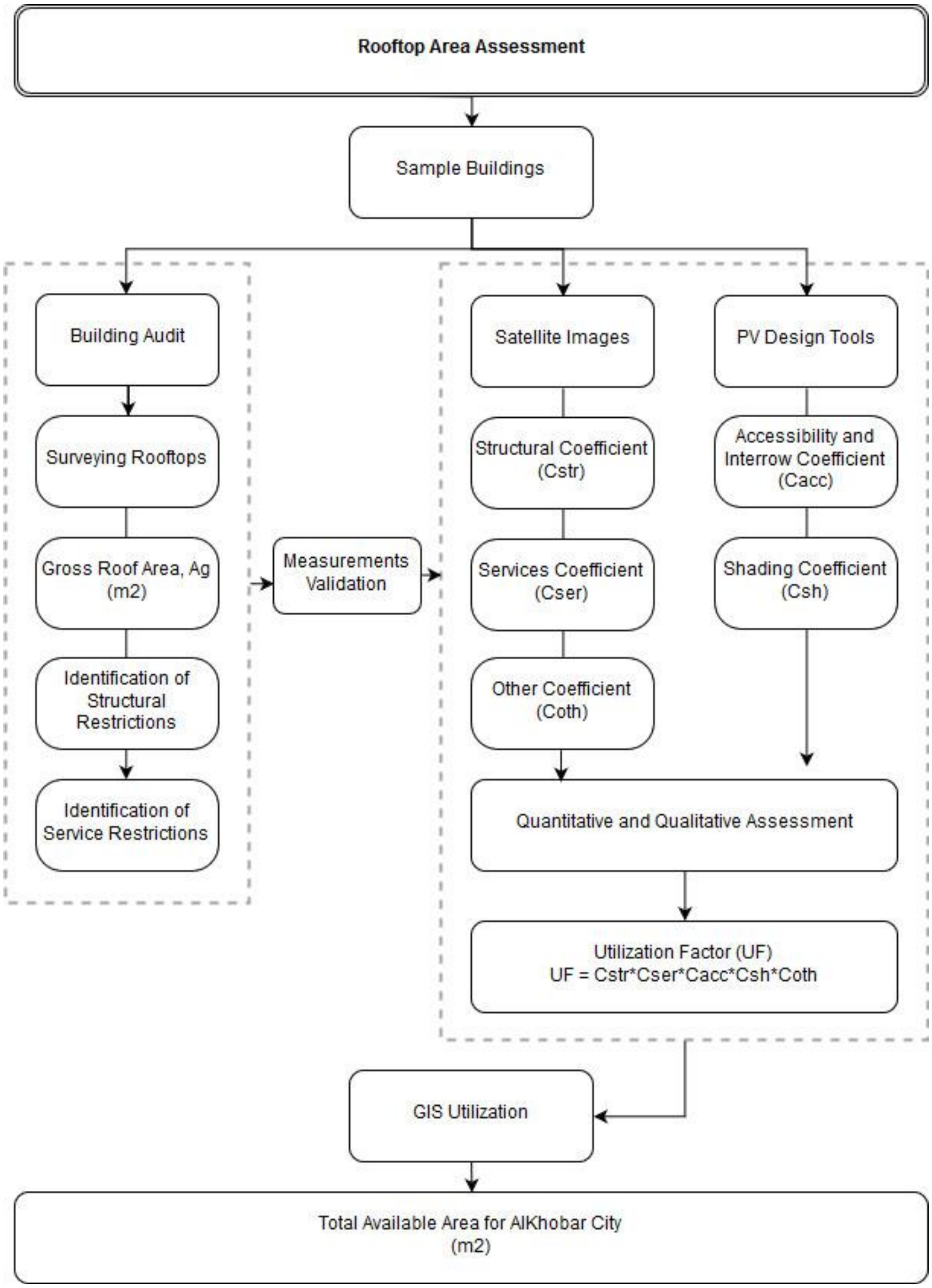


Figure 18: Flowchart Depicting the Approach for Rooftop Area Assessment

3.2.2. Building Audit

A building audit sheet was prepared for the purpose of collecting necessary data for the analysis. All sample buildings were visited and audited at daytime. The audit involved inspection of the surroundings to check for adjacent structures or trees to account for shading. It was noticed that most buildings within the same zone have similar height. It was also noticed that green areas are rare within residential areas and if exist, they do not extend to more than buildings height. Data about the number of floor, number of flats, and floor heights were also collected. Most villas have two floors, some involve an annex (mainly for maid), and they have high parapet walls. Apartment buildings have a number of floors ranging from 2 to 8 floors, and a number of flats ranging from 5 to 16.

3.2.3. Surveying Rooftops

It was necessary to visit samples of rooftops to have a close and clear picture and also to take measurements for validation. Roof geometry measurements were taken to be validated by Google Earth Pro™. All rooftop components were surveyed in term of quantities and dimensions as well as location in reference to the roof. It was noticed that majority of rooftops have a rectangular shape. The main restrictions (hurdles) for installing PV were identified and classified into different groups and are summarized in Table 9. All identified hurdles were classified under the following categories; structural restrictions, services restrictions, accessibility, maintenance and inter-row spacing restrictions, shading restrictions and other restrictions. It is important to note that these classifications were considered based on the purpose of the elements that can be found in a typical rooftop. While during the coefficient calculations of each restriction type, the classification was considered based on the impact of the rooftop components on a PV system.

Table 9:Classification of Main Restrictions

Classification	Components
Structural restrictions	Columns and rebars
Service restrictions	Water tanks, AC package units, dish antennas, atrium shaft area, AC condensers, water boilers
Accessibility restrictions	Nearby accesses; area of 1m adjacent to walls; inter-row spacing
Shading restrictions	Parapet walls, annexes, atrium shafts walls; service components (height);
Other restrictions	Courtyard; clothesline

Pictures were also taken to help in retrieving any information after leaving the buildings as it would not be easy to visit them again.

3.2.3.1. Identification of Structural Restrictions

The first step toward calculating the coefficient of utilization was to identify Structural elements that exist on rooftops. Structural elements include annexes, parapet walls, columns, column rebars, stairwells, atrium shafts (used to provide lighting for multiple of inner spaces) and elevator shafts. In addition to the geometry of the building, as having irregularities would obstruct the installment of PV panels. Moreover, fly roofs, which are light weight corrugated steel sheets covering the whole roof for the purpose of protection from sun and rain. They are common in residential units in specific areas such as Thoqbah and Al-Aqrabiyyah.

It was noticed that mostly building owners tend to build annexes as to gain more profit. Parapet walls are also common due to cultural aspects including privacy and safety reasons. As apartment buildings do not have garden or a courtyard, tenants utilize part of the roof to get some fresh air for themselves or for their children. Hence, high parapet walls are desired to prevent others to look at them and to protect children from falling down. Many apartment buildings have an inner atrium that is open to the sky, in which kitchens' and bathrooms' windows look into. The main purpose of this shaft is to provide natural light and natural ventilation for kitchens and bathrooms. The shaft walls extends above the surface of the roof with one meter height on average. Figure 19 shows a roof full of columns that were kept for long period of time as an example of structural restriction.

Figure 19: Example of Structural Restriction

3.2.3.2. Identification of Services Restrictions

Service restrictions can be defined as any component that provides any kind of service to the tenants. This include dish antennas, water tanks, Air Conditioning (AC) condenser units, central HVAC package systems, vents and water boilers. The aforementioned components exist in different dimensions and different mounting conditions. Almost no residential rooftop would not have dish antenna and water tanks. It was noticed that dish antennas are commonly being distributed randomly over the roof occupying vast areas which, instead, can be used for PV applications. Some apartment buildings had a better organization in distributing dish antennas as they are installed along the perimeter of the parapet wall either on the roof surface or on the parapet wall itself. Water tanks are commonly installed on the highest elevation which is the roof of the annex. In regards to the Heating Ventilation and Air Conditioning (HVAC) system, it was noticed that three types are common including AC split systems and AC window units in apartment buildings while villas can include central AC units as well. Not all residential buildings have AC condenser units installed on the roof, as some have them installed them on exterior walls. Vents are mostly provided through the atrium shafts extending with a similar height to the shaft walls. Surprisingly, water boilers were noticed on rooftops of many of the villa samples in which they are exposed to outdoor conditions. Figure 20 and 21 show a picture of a well-organized roof and a poorly organized roof respectively where both apartment buildings have 3 stories and almost similar roof area.

Figure 20: Well-Organized Roof

Figure 21: Poorly Organized Roof

3.2.4. Measurements Validation

After taking roof measurements and quantifying the rooftop components of all samples, it was necessary to identify the locations of the restrictions to account for the impact of the organization of components on PV suitability. Google Earth Pro™ was used for this purpose. The validation was done on 11 samples by measuring one side of a building on Google Earth Pro ™ and comparing it with field measurements. Table 10 summarizes the results of the comparison and shows that the errors are minimal and the measurements though Google Earth Pro™ are accurate.

Table 10: Measurement Validation

Sample No.	Length 1	Length 2	Length 3	Average (m)	Measured length (m)	Error (m)	% Error
1	13.50	13.40	13	13.3	13.40	-0.10	-0.75
2	12.85	13.10	12.46	12.8	12.85	-0.05	-0.36
3	11.70	12.08	12.23	12.0	12.35	-0.35	-2.81
4	10.78	10.85	10.42	10.7	10.80	-0.12	-1.08
5	13.23	13.92	13.88	13.7	13.70	-0.02	-0.17
6	15.64	16.07	16.85	16.2	16.10	0.09	0.54
7	13.20	13.88	13.72	13.6	13.35	0.25	1.87
8	18.00	18.14	19.00	18.4	18.56	-0.18	-0.97
9	8.10	8.58	8.77	8.5	8.20	0.28	3.46
10	14.90	15.10	14.80	14.9	15.00	-0.07	-0.44
11	15.24	15.64	15.38	15.4	15.30	0.12	0.78

Now that all rooftop components are quantified and their locations are identified, we can determine the coefficient of each type of restriction more accurately and confidently. After determining the areas occupied by services, structural and other components, the total area of the roof is again compared with the actual roof area measured.

3.2.5. Utilization Factor

The utilization factor (UF) is an important indicator for how much space is available on a given rooftop. The utilization factor (UF) is the ratio of the available area for PV utilization to the gross roof area (Ag). To find the utilization factor, structural, services, accessibility, shading and other coefficient must be computed. The classification was considered based on the impact of the rooftop components on PV system. The utilization factor calculations (especially for inter-row spacing and shading coefficients) depend on the selected PV type, tilt angle and orientation, as different types or different mounting conditions can change the results. The following subsections describes the procedure of calculating the various coefficients in sequence and in details.

3.2.5.1 Structural coefficient (C_{str})

The structural coefficient is the ratio of the available area excluding structural elements to the gross roof area. The structural coefficients were calculated based on the impact of structural elements on the PV system in terms of installation, i.e. the area occupied by structural elements. It is to note that the impact of annexes, parapet walls, atrium shaft walls and elevator shafts were considered as part of the shading restrictions due to the shade casted by the components' walls. Columns, columns rebars, irregular geometry and fly roofs were the components considered in the structural coefficient calculations. It is true that fly roofs provide a clean space for PV utilization but they are commonly supported by thin steel columns that are not capable of holding PV modules. Hence, those buildings with complete fly roofs (i.e. covering all roof structure) will have no opportunity of installing rooftop PV considering the current situation. Figure 22 shows a building with fly roof.

Figure 22: Building with Fly Roof

3.2.5.2 Services coefficient (C_{ser})

The services coefficient is the ratio of the available area excluding service elements to the remaining roof area. The impact of the service components on the PV systems is mainly space utilization, however shading can also have an impact especially with large size dish antennas, water tanks and Central AC systems. It was noticed that in apartment buildings, the maximum space is occupied by water tanks (3m^2/tank), followed by large dish antennas (2.6m^2/dish), average dish antennas (1.6m^2/dish) and finally small dish antennas (1m^2/dish) and AC condenser units (1m^2/unit). The space occupied by atrium shafts is used to provide lighting and also for plumbing services, therefore the space was considered as part of the services coefficient. It can was also noticed that in villas, the maximum space is occupied by central AC package units (8m^2/unit), followed by water tanks (3m^2/tank), average dish antennas (1.6m^2/dish), AC condenser units (1m^2/unit), small dish antennas (1m^2/dish) and finally water boilers (0.4m^2/unit). Figure 23 shows a picture of the main hurdles existing on a villa rooftop.

Figure 23: Main Hurdles Existing on a Villa Rooftop

3.2.5.3 Accessibility, maintenance and inter-row spacing coefficient (C_{acc})

The accessibility coefficient is the ratio of the available area excluding areas used for accessing roof, maintenance of services and PV systems as well as the inter-row spacing between rows of PV arrays to the remaining roof area. The impact of the accessibility, maintenance and inter-row paths on the PV systems is only space utilization. This type of restriction was dealt with using PV SOL software. All sample buildings were 3D modelled and standard values of edge distances were considered based on the software to be 1 meter. The inter-row spacing was also optimized using the software which resulted in an area utilization ratio of 0.72. This means if we would like to fit PV modules in 30 m^2 of roof area, we will end up with 21.6 m^2 as the total module area and 8.4 m^2 as inter-row spacing. All the parameters used for the PV design are described in Chapter 4.

3.2.5.4 Shading coefficient (C_{sh})

The shading coefficient is the ratio of the available area excluding the area of PV modules that receives average annual shading of 20% or higher to the remaining roof area. The components that cast shading on PV modules include structural components such as annexes, parapet walls, stairwells, atrium shaft walls and elevator shafts. Annexes usually have an average height of 3.2 m, stairwells have an average height of 2.7 m, walls of atrium shafts have an average height of 1 m and elevator shafts have an average height of 3 m. For apartment buildings, the minimum parapet wall height is 0.2 m while the maximum is 2 m, and the average is 1.3 m. For villas, the minimum parapet wall height is 1 m while the maximum is 3 m, and the average is 1.7 m. The extremely high parapet walls in villas are not understandable as compared to apartment buildings. This is because apartment buildings use parts of the rooftop as sitting areas and for drying clothes (clothesline) while villas rooftops are not usually used in the same way due to the availability of courtyards or garden areas.

Services restrictions also cast shade, considering both types of buildings, water boilers have the maximum height with an average height of 2.2 m, followed by large dish antennas (2 m), water tanks (1.6 m), central AC package units (1.2 m), average dish antennas (0.8 m), AC condenser units and small dish antennas (0.67 m).

3.2.5.5 Other restriction coefficient (C_{sh})

Other restrictions involve any activity that requires permanent space on roofs such as utilizing an area as a sitting area or other purposes (refer to section ***3.2.3.1*** and ***3.2.5.4)***. Other restrictions coefficient (C_{oth}) is the ratio of the available area excluding the area required for other usage to the remaining roof area. The impact of this type of restriction on the PV systems is mainly space utilization. The required space was assessed qualitatively based on some factors such as accessibility, closeness to roof door and total roof area. Few villa tenants use the roof for such purposes while many apartment buildings tenants do. Therefore the coefficient C_{oth} is higher for apartment buildings compared to villas.

After calculating the five classified coefficients, the utilization factor (UF) of each sample was calculated as follow:

$$\boxed{UF = C_{str} \times C_{ser} \times C_{acc} \times C_{sh} \times C_{oth}}$$

Figure 24 illustrates four restriction types used in the study on a typical apartment building. Structural restrictions were not found in this specific case.

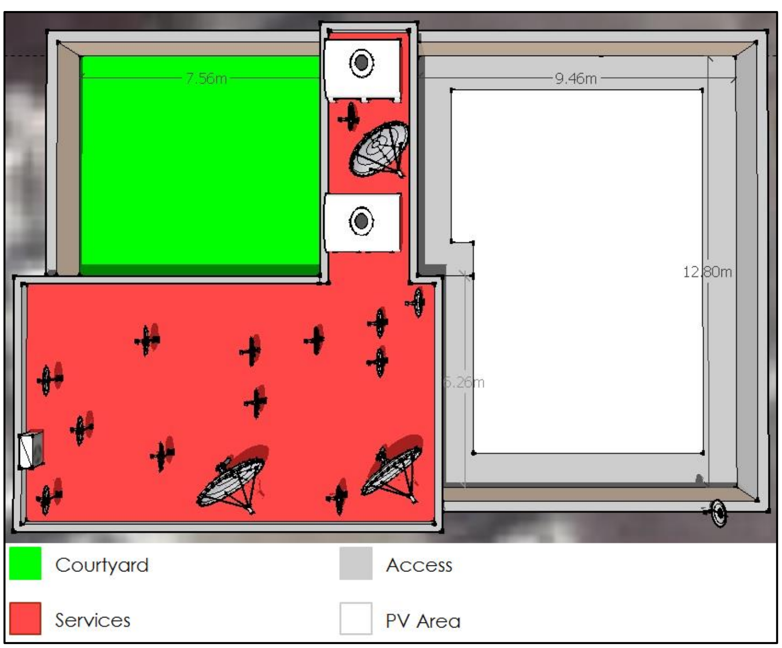


Figure 24: Restrictions on an Apartment Rooftop

The results of the utilization factor are discussed in details in chapter 6.2. In order to extrapolate the utilization factor it was necessary to create a regression model to have a better estimation. A linear regression model was developed for all samples together, and for apartment buildings and villas separately. The linear regression model equations for the existing roof conditions are summarized in Table 11.

Table 11: Linear Regression Model for the Existing Roof Conditions

Samples	Equation	R-Square
Total buildings	PVA= 0.342*RA - 49.55	0.56
Apartment buildings	PVA= 0.365*RA - 62.03	0.56
Villas	PVA= 0.271*RA - 19.4	0.71

3.2.6. GIS Utilization

The main role of GIS in this study is to extrapolate the results found for the rooftop assessment for all samples to the city level. The data was acquired from the General Administration for Urban Planning in the Eastern Region of Saudi Arabia. The data includes shape files of all parcel land of Al-Khobar city with some attributes regarding the status of the land such as the primary usage, secondary usage, allowed built up area, maximum heights, etc.

The attributes within the database provide general information and do not identify apartment buildings and villas as both are describes as residential units. Data management and analysis were done using ArcMap® 10.4.1. The data was used to classify residential parcels into apartment buildings and villas based on the maximum number of floors allowed. After deep investigation, it was noticed from the building regulations that all villas are built on a residential parcel land with 60% built-up area and a maximum of 2 floors. Hence that distinguished villas in this study. An apartment building was defined as any residential building with 2 up to 8 floors. For apartment buildings, it was noticed that apartment buildings can be built on both a residential or commercial parcel lands with 60% and 100% built-up area and a maximum number of 2, 3, 4, 5 and 8 floors.

The calculations of the total PV available area (PVA) or total utilizable area (UA) was conducted for all sample buildings and then for apartment buildings and villas separately. Total roof area was calculated first by multiplying the parcel land area by the built-up area identified by municipality regulations. Furthermore, the PV available area (PVA) for all samples was calculated at the city scale using the regression models shown in Table 11. This study considered a 2 kWp PV system, requiring 20 m^2 PV area, as the average installed capacity for rooftop applications in the residential sector (Hong et al., 2016). In addition, it was calculated that a 2 kWp PV system can provide about 5% of the total energy consumption of a typical villa as discussed later in section (6.3.2). Thus, PV areas (PVA) that are less than 20 m^2 were excluded from the analyses. Figures 25 and 26 depict the area of the analysis and part of the database in ArcMap®.

Figure 25: Area of the Analysis at City Scale

Table

Khobar_Parcels_Only_Res_and_Comm_Excluding_Vacant_Areas_Excluding_very_large_Area1

SHAPE_Leng	SHAPE_Area	Tenant_Nam	Build_Type	BUILT_UP_A	NO_FLRS	MX_HEIGHT	Roof_Area	PRCL_USE	PVA_Comb	PVA_Villa	PVA_Apart
76.720811	351.191375		0	100	3	12	351	Residential	70	0	66
76.503255	350.789483		0	100	3	12	351	Residential	70	0	66
76.22986	351.324395		0	100	3	12	351	Residential	70	0	66
75.773153	351.179985		0	100	3	12	351	Residential	70	0	66
76.467878	351.349174		0	100	3	12	351	Residential	70	0	66
75.513314	351.179734		0	100	3	12	351	Residential	70	0	66
98.258506	585.542762		0	60	2	10	351	Residential	70	76	0
97.017093	584.908384		0	60	2	10	351	Residential	70	76	0
96.81835	585.293956		0	60	2	10	351	Residential	70	76	0
76.266973	351.228047		0	100	3	12	351	Residential	70	0	66
98.159228	585.695215		0	60	3	16	351	Commercial	70	0	66
98.878531	582.979461		0	60	2	10	350	Residential	70	75	0
99.253482	583.021877		0	60	2	10	350	Residential	70	75	0
97.70502	583.123315		0	60	2	10	350	Residential	70	75	0
99.464561	584.0121		0	60	2	10	350	Residential	70	75	0
99.056787	582.992023		0	60	2	10	350	Residential	70	75	0
99.323235	583.109002		0	60	2	10	350	Residential	70	75	0
98.228365	582.522116		0	60	2	10	350	Residential	70	75	0
98.846637	582.506678		0	60	2	10	350	Residential	70	75	0
98.869902	583.857338		0	60	2	10	350	Residential	70	75	0
98.407214	583.582474		0	60	2	10	350	Residential	70	75	0
98.382277	583.57291		0	60	2	10	350	Residential	70	75	0
98.5145	583.66152		0	60	2	10	350	Residential	70	75	0

0 (0 out of 32698 Selected)

Figure 26: Part of the GIS Database Used in the Analysis

The same procedure was applied again but this time considering the potential area on the rooftop. Which means that the impact of services restriction due to the poor arrangement will be reduced. Rearrangement can be done by allowing only one dish antenna per flat in the case of apartment buildings. Then re-installing dish antennas in a way that they are placed in shaded areas where PV installation is not desired. Another option is installing dish antennas on parapet walls especially at the north side as they will not cast much shadows. A much better option is to install central dish antenna which will reduce the number of antennas significantly. An example of different options for rooftop service components rearrangement for the same apartment building illustrated in Figure 24 is shown below in Figure 27.

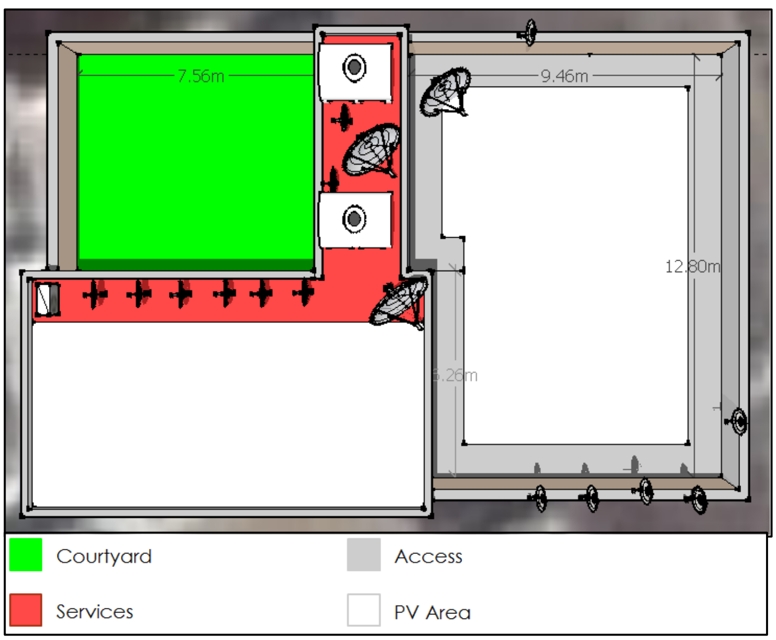


Figure 27: Potential Rooftop Area after Rearrangement of Service Components

The linear regression model equations were also applied again, Table 12 summarizes the equations for the potential roof area after rearranging rooftop service components.

Table 12: Linear Regression Model after Rearrangement of Service Components

Samples	Equation	R-Square
Total buildings	PVA= 0.447*RA - 61.72	0.73
Apartment buildings	PVA= 0.496*RA - 79	0.78
Villas	PVA= 0.195*RA + 15.4	0.61

CHAPTER 4

ENERGY, ENVIRONMENTAL AND ECONOMIC ANALYSIS

4.1. Introduction

This chapter focuses on the energy generated by residential rooftop PV technology at a unit scale (i.e. for each sample building) and at urban scale (i.e. city scale). It also discusses the energy saving due to the PV utilization on rooftop of buildings at a unit scale in terms of meeting part of the building demand and in terms of cooling load reduction.

4.2. PV System Production at Unit Scale

4.2.1. PV System Modelling and Characteristics

The design of PV system was conducted using PV*SOL® premium 2017 software for all samples. However, design builder software was also used to design PV system for one unit. The following subsections describes the systematic approach of PV system design for a sample building in PV*SOL.

4.2.2. Climate and system Data

As mentioned in section 2.2 that the closest available climate data to AL-Khobar city is Dhahran, hence it is used in the simulation. Table 13 summarize the climate data used in the simulation.

Table 13: Climate Data

Parameters	Description
Location	Dhahran
Latitude	26.27°
Longitude	50.17°
Time Period	2000 to 2009
Time zone	UTC+3
Annual sum of global radiations	1985 kWh/m^2
Annual average temperature	27.2 °C
Resolution	Hourly

The selected system type is grid connected PV which is mainly composed of PV array, inverter and net metering. The purpose of selecting grid-tied system is that we want to evaluate the maximum electricity production from PV based on existing roof conditions.

4.2.3. PV System Design and Optimization

PV*SOL software gives users the possibility to work on 2D or 3D model when designing PV systems. When selecting 2D option, the software will require user input for array and inverter details such as the number of modules, mounting conditions, tilt and orientation as well as shading. On the other hand, 3D design option allows users to create a 3D model of building geometry including rooftop components as well as to create PV module formation. First, a satellite image was extracted for the sample building from Google Earth Pro™ and then imported to PV*SOL. The image has to be calibrated to reduce measurements errors. Geometry of the building roof was traced as a polygon on the imported image to guarantee the exact orientation and then the polygon was extruded considering height of the building. Annex was also added as a building component in order for the software to treat its roof as a normal roof and hence allowing components to be added. From the object view tab on the 3D visualization window, all existing rooftop components were modeled including parapet walls, dish antennas, AC condensers as well as water tanks. Noting that water tanks do not exist in the predefined objects library, therefore a water tank was represented as a rectangular 3D object (Figure 28).

The next step involved selection of PV array system including PV module type, orientation and tilt angle. The software then optimizes the inter-row distance or "mounting support clearance" as described in PV*SOL. PV module type was selected based on performance as well as area consideration. The PV module is of monocrystalline silicon type with 16.5% efficiency, 190 W output and a module area of 1.25 m^2. This type was found suitable for residential applications especially with the small area available for installation. Technical specifications of the selected PV module are provided in Figure 28.

Electrical characteristics

	(1) STC 1000W/m²	(2) NOCT 800W/m²
Maximum power (P_{max})	190W	136.8W
Voltage at P_{max} (V_{mpp})	37.1V	33.0V
Current at P_{max} (I_{mpp})	5.12A	4.10A
Short circuit current (I_{sc})	5.56A	4.50A
Open circuit voltage (V_{oc})	45.3V	41.2V
Module efficiency	15.2%	
Tolerance P_{max}	-0/+5%	
Nominal voltage	24V	
Efficiency reduction at 200W/m²	<5% reduction (efficiency 14.4%)	
Limiting reverse current	5.56A	
Temperature coefficient of I_{sc}	0.105%/ ºC	
Temperature coefficient of V_{oc}	-0.360%/ ºC	
Temperature coefficient of P_{max}	-0.45%/ ºC	
(3) NOCT	47±2ºC	
Maximum series fuse rating	20A	
Application class (according to IEC 61730:2007)	Class A	
Maximum system voltage	600V (U.S. NEC) 1000V (IEC 61730:2007)	

1: Values at Standard Test Conditions (STC): 1000W/m² irradiance, AM 1.5 solar spectrum and 25ºC module temperature
2: Values at 800W/m² irradiance, Nominal Operation Cell Temperature (NOCT) and AM 1.5 solar spectrum
3: Nominal Operation Cell Temperature: Module operation temperature at 800W/m² irradiance, 20ºC air temperature, 1m/s wind speed

All solar modules are individually tested prior to shipment; an allowance is made within our factory measurement to account for the typical power degradation (LID effect) which occurs during the first few days of deployment.

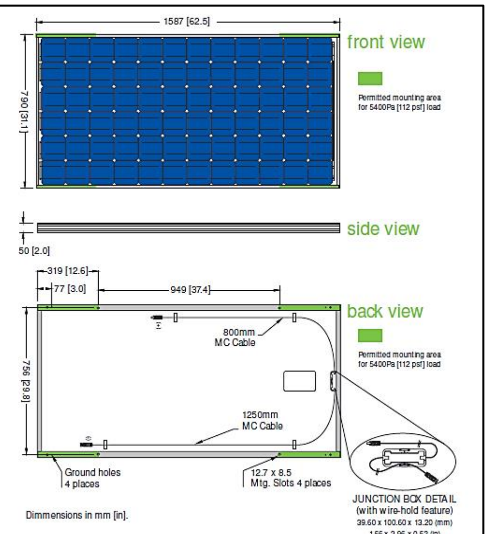
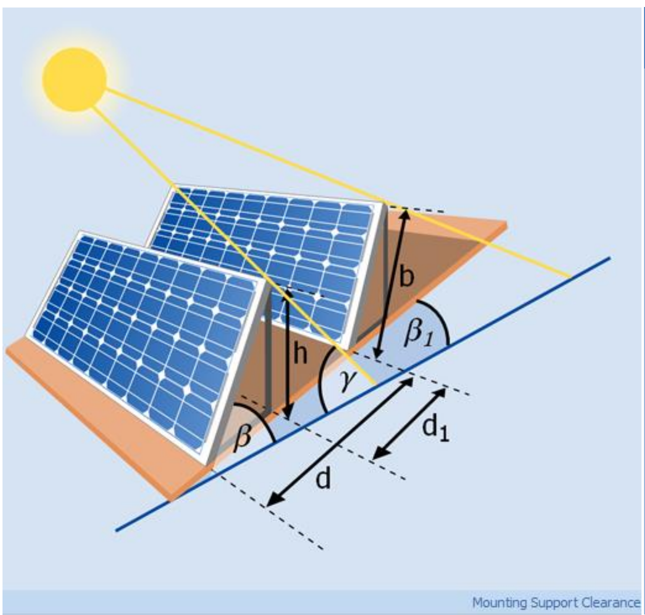


Figure 28:PV Module Technical Specifications

The first option was to consider a 24° tilt angle for the PV array due south, hence assigning these parameters allow the software to optimize inter-row spacing. Figure 29 shows a detailed description of all parameters in regards to dimensions within the PV array. It is noticed that the optimization of the inter-row spacing was calculated based on shadings casted on 21 of December at 12:00 noon where the sun elevation angle is equal to 40.29°. The mount height (h) is 0.32 m, Depth of row ($d-d_1$) is 0.72 m and row spacing (d) is 1.1 m. The mount support clearance (d_1) which is the distance from the front edge of a module in one row to the front edge of a module in the next row, was optimized to be 0.4 m.



Reference	Value
Module mount width (b)	0.79 m
Mount height (h)	0.32 m
Module inclination (ß)	24°
Module orientation	180°
Solar elevation angle	40.29°
Solar elevation angle time	21/12 - 12:00
Depth of row ($d-d_1$)	0.72 m
Mounting support clearance (d_1)	0.4 m
Row spacing (d)	1.1 m

Figure 29: Design Parameters for the PV system

The area of utilization was calculated in the previous chapter (3), therefore courtyard and services areas were excluded (services are located on the annex in this case). An edge distance of 1 m was also considered from all directions for accessibility, maintenance and to avoid closeness to parapet walls. Figure 30 shows the developed 3D model with rooftop components and PV array installed.

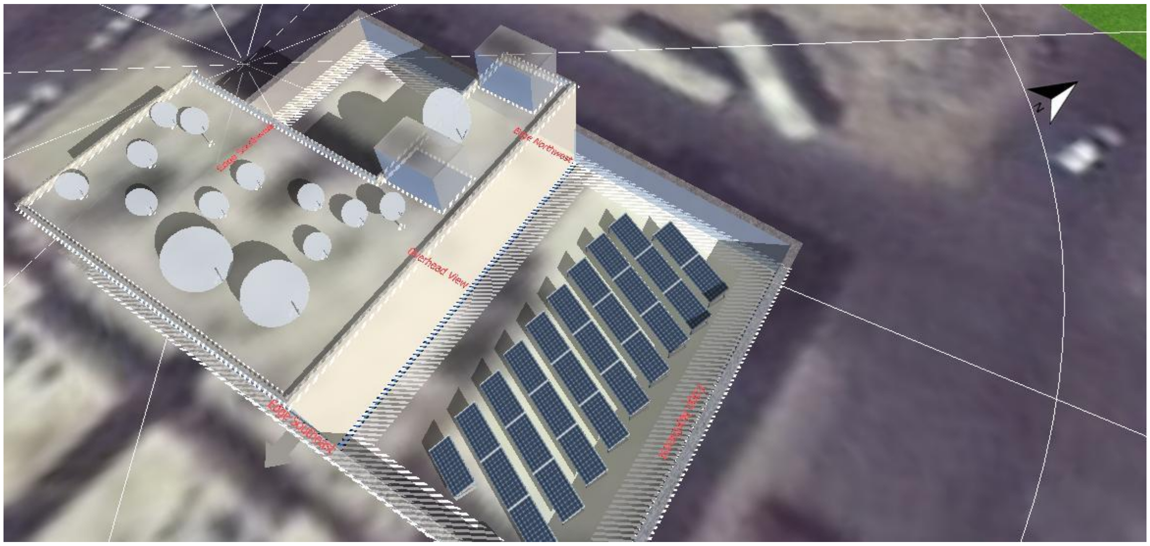


Figure 30: Developed 3D Model with Rooftop Components and PV Array Installed

After placing the PV array system, shading frequency analysis was run to determine the amount of reduction in annual direct irradiance on the basis of the seasonal shade frequency on the areas covered with PV panels. The percentages shown on PV panels in Figure 31 represents the annual average irradiance reduction at each panel due to shading. It was decided to exclude modules that have 20% or higher irradiance reduction as this will negatively impact the system performance and also because of economic consideration. In the next step, all existing panels are configured by assigning inverters to the array system.

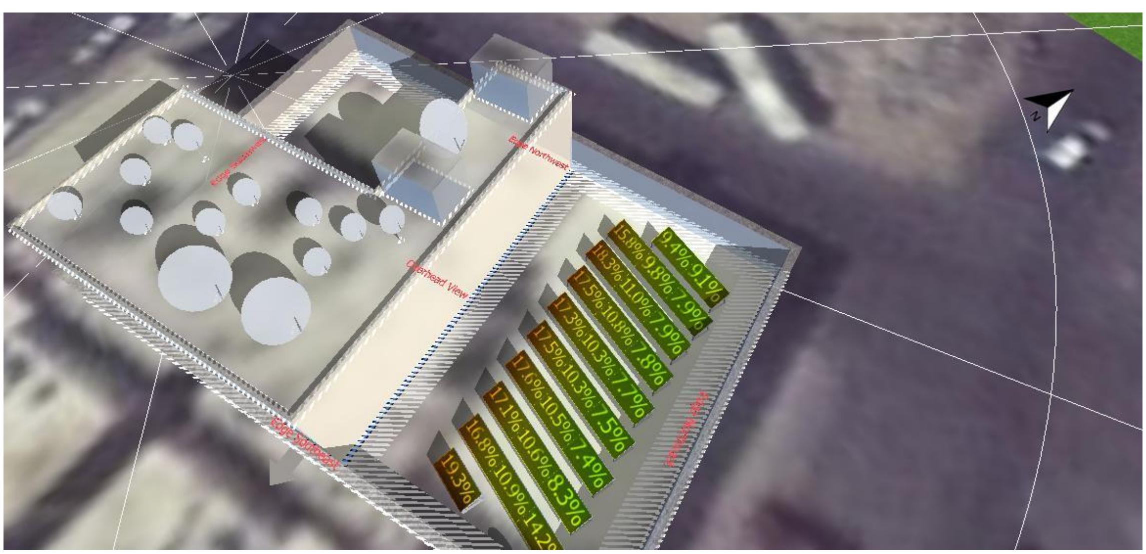


Figure 31: Annual Average Irradiance Reduction

PV*SOL offers the option of optimizing PV module configuration as to select the arrangement that will result with the maximum output. The shade frequency analysis done in the previous step plays a key role in the module configuration. Because shading has a major influence on the array characteristic, it decisively affects the optimum configuration of the modules in strings. The optimized configuration divide modules into strings with a color indicator for each as shown in Figure 32. A system check can be done after the configuration which indicates any existing errors. Cable losses are considered also which was given a value of 3% based on the literature.

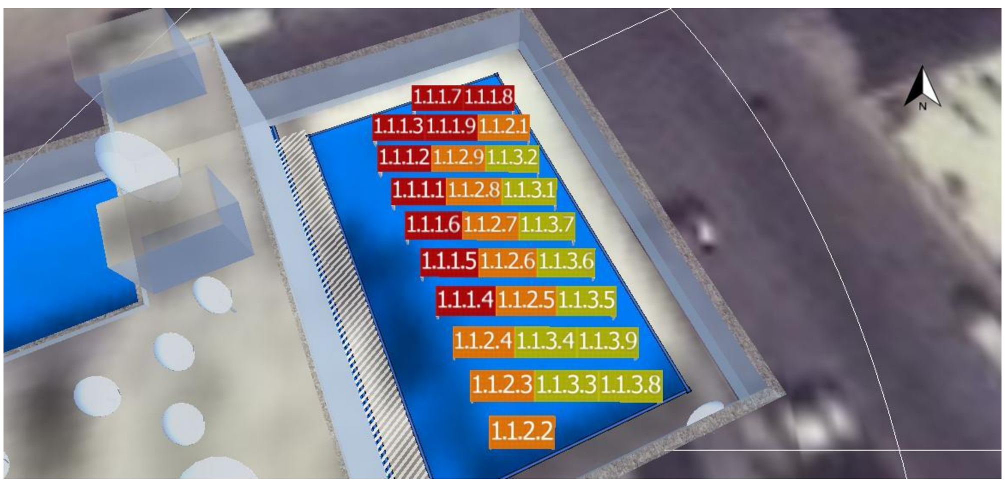


Figure 32: Configuration of PV Panels

4.2.4. Simulation Results

PV*SOL runs the simulation to design the modeled PV system over the year in an hourly bases. The PV generator capacity equals the output rating per module multiplied by number of modules and it is 5.1 kWp in this example. The output electricity generation was found to be 6,625 kWh considering an annual yield reduction of 20.3% due to shading. The specific annual yield is 1291.51 kWh/kWp and the performance ratio is 65.1%. Based on the area covered by modules (34 m^2), the output generation per unit area is equal to 195.4

kWh/m^2/annum. Similarly, a second simulation was run but this time considering a flat PV system. A flat PV system does not require spacing between module rows as the case in tilted systems. Hence a flat PV array system encompasses more PV panels in the same area as compared to a tilted array system. The PV generator capacity for the flat system increased to 6.8 kWp. The output electricity generation is also expected to increase, it was found to be 8,200 kWh considering an annual yield reduction of 21.3% due to shading. It was noticed that the percent yield reduction due to shading is more in Flat PV systems compared to tilt systems in all samples which is due to the panel mount height. The mount height is constant in horizontal Panels (0.3 m) while it is the same for the front edge of a tilted panel only. The tilt angle increases the height of the back edge in a direct proportion allowing less shadows to reach the cells. A summary of the simulation results is shown in Table 14. The detailed results of all samples are provided in the next chapter (5.1)

Table 14: Summary of Simulation Result

24° Tilt angle			
Sample 1	**PV System**	**Value**	**Unit**
	PV Generator capacity	5.1	kWp
	Global Radiation at the Module	1,983.5	kWh/m²
	Electricity Generation	6,079	kWh/year
	Spec. Annual Yield	1185	kWh/kWp
	Performance Ratio (PR)	60	%
	Yield Reduction due to Shading	20.1	%/year
	Total Modules Area	33.75	m^2
	Geometry Area	73.78	m^2
Flat PV (0°)			
Sample 1	**PV System**	**Value**	**Unit**
	PV Generator capacity	6.8	kWp
	Global Radiation at the Module	1,843.7	kWh/m²
	Electricity Generation	7,380	kWh/year
	Spec. Annual Yield	1,078.92	kWh/kWp
	Performance Ratio (PR)	58.5	%
	Yield Reduction due to Shading	21.4	%/year
	Total Modules Area	45.1	m^2
	Geometry Area	73.78	m^2

4.3. Power Generation at an Urban Scale

The objective is to estimate the energy potential at a city scale, so extrapolating the results obtained from the unit scale energy production simulation is required. The simulation was conducted for all sample buildings and then it was normalized to provide an indicator in terms of kWh/m^2 of both geometry area and module area. PV sub-areas were introduced for each building as convenient (total of 42 PV sub-areas), this is believed to provide more accurate results. Figure 33 shows a sample villa with 4 PV sub-areas. This is because each PV sub-area represents a unique case in terms of geometry or the amount of shading being casted on it. The reason for providing the total energy per geometry area (kWh/m^2) is to consider the variation of geometry from building to another as geometry will impact the number of panels to be installed. In the same manner, the reason behind determining total energy per module area (kWh/m^2) is to account for the variation in shading as it will impact the output of the panels. The average area per module was considered for the city level.

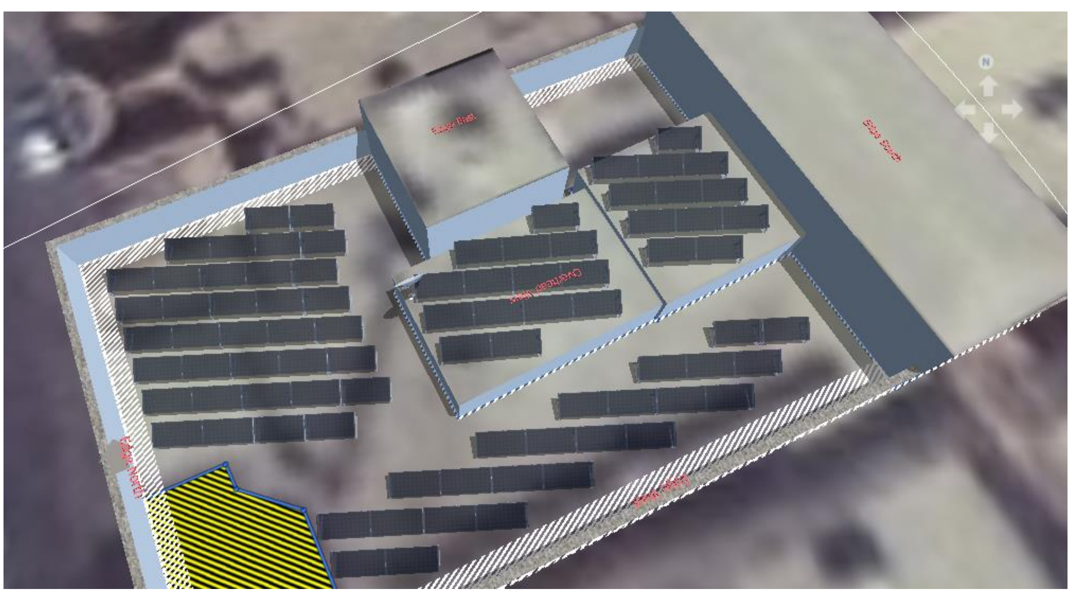


Figure 33: Sample Villa with 4 PV Sub-Areas

4.4. Energy Savings from PV Implementation

One important aspect to look at when considering PV applications in buildings is its impact on building energy consumption. Savings can be achieved in the form of direct electricity reduction or in the form of cooling load reduction due to the shadows being imposed on the roof by PV panels. This research considers the savings at a unit scale rather than at the city scale due to the difficulties in obtaining electricity consumption data for the entire city. It was decided to use DesignBuilder software for this purpose as it has the capabilities to evaluate the energy performance of building integrated PV. DesignBuilder is a powerful software and has a comprehensive user interface to EnergyPlus simulation engine. The forthcoming sections describe the systematic procedure followed to evaluate the energy performance and saving of a typical villa in Al-Khobar city.

4.4.1. Building Energy Savings

DesignBuilder was used to simulate the energy performance of an existing villa as a sample building. It was very difficult to obtain drawings, building characteristics and electricity bills for the building samples. In addition to the unpracticality of modelling all building samples. Therefore, different scenarios are considered to try covering the wide range in the utilization factor (UF) results. To illustrate this, the modelled villa represents the lower range with a utilization factor of 0.16. The same villa will be modelled different times to represent the average and high range in the utilization factor (UF) values.

4.4.1.1. Base case model Formulation

The studied villa is an existing single family residence constructed in 2005 and located in Al-Rakah Court, Al-Khobar, Saudi Arabia. It consists of two floors with a total area of 506

m^2. The roof is rectangular in shape with a gross area of 240 m^2 and a parapet wall height of 3 m. The building in its size, function and construction generally represents a typical villa in that neighborhood. However, as mentioned earlier there is no typical arrangement of rooftop components as each building can be considered as a unique case. Building drawings including structural, architectural and lighting were collected from the building owner as hard copy. A lot of information was not available because generally there is no practice of documentation or keeping records. Therefore, other information needed for the simulation was obtained by either inspection or by interviewing the building owner. Such information include the composition of building envelope systems and operational schedule of appliances, lighting and AC systems.

The workflow of the software starts with selecting a weather file for the location intended for the research. The software then allows the creation of building geometry, defining of building type, activities and building characteristics. Despite the number of rooms in the villa, each floor was considered as one single zone for simplicity. Table 15 summarizes the characteristics and specifications of the investigated villa.

Table 15: Base Case Module Characteristics

Building Characteristic	Description
Location	Dhahran
Orientation	Main elevation facing East
Floor to Floor Height	3.5m
Floor Area	Total: 504 m^2 ; Ground Floor: 264 m^2; First Floor: 240 m^2
Window Wall Ratio	8%
Exterior Walls	13mm Plaster / 100mm Concrete Block (Medium) / 30mm Extruded Polystyrene / 100mm Concrete Block (Medium) / 13mm Plaster U-Value: 0.58 W/m^2k
Roof	30mm Terrazzo Tiles / 30mm Extruded Polystyrene / 200mm Reinforced Concrete / 13mm Plaster U-Value: 0.97 W/m^2k
Windows	Single glazed with aluminum frame
Lighting	Ground Floor: 20 W/m^2; First Floor: 12 W/m^2
AC	Split Units and One Central AC

All the characteristics and specifications were fed into DesignBuilder to complete the model. Figure 34 shows a 3D view of the house modelled in DesignBuilder. Before running the simulation it was necessary to input operational schedule for equipment, lighting and AC systems. The simulation was performed for an entire year in a monthly bases.

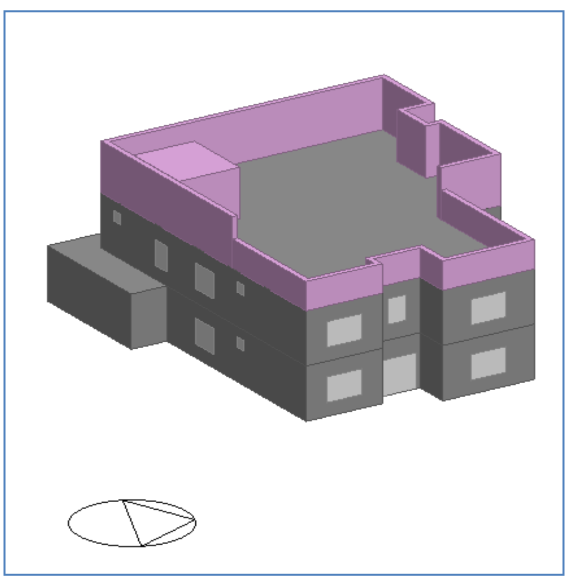


Figure 34: 3D View of the House Model

4.4.1.2. On-site Electricity Generation

After the completion of the base case, PV modules are installed on rooftop to simulate their impact on the building consumption. DesignBuilder allows for the creation of PV panels and their integration within the building model. As the software is not designed initially to integrate PV technology, it can simulate a limited number of modules. Hence, each PV string was modeled representing a single PV unit having a multiplication of one module area. This will allow the software to handle a large number of modules and also will simplify the work. The software also allows users to design for different PV systems including grid-tied or stand-alone systems through the generation tap. Although the current version (version4) offers few items within the database for PV panels, inverter and batteries, it allows for a user-defined components/systems. A grid connected system was considered with a base load operation scheme and direct current with inverter as the electrical buss type. The first scenario takes in consideration the actual condition of the villa in terms of availability of space for PV utilization (Utilization Factor). PV modules where integrated to the rooftop considering 0.16 utilization factor. The second and third scenarios account for utilization factors of 0.25 and 0.40 respectively. The simulation was performed for the three cases to observe the impact of each scenario as a reduction on the electricity consumption. Figure 35 shows 3D-view of the three different scenarios modelled in DesignBuilder.

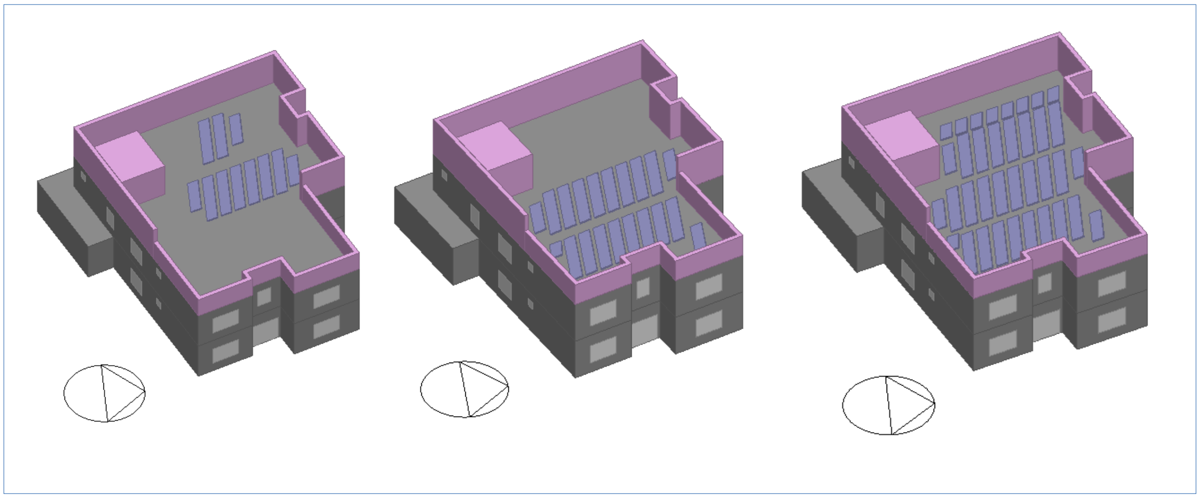


Figure 35: 3D-View of the Three Different Scenarios

4.4.1.2. Cooling Load Reduction

Beside the ability of PV panels to generate electricity and supply part of building demand, PV impose shadows on the structure supporting them, in this case the roof. PV panels in this case act as an additional roof material which in turn will impact heat gain through the roof. Dominguez et al. 2011) investigated the impact of tilted and flat PV panels on roof heat transfer under California climate. The authors used a Crank–Nicholson method to model the conduction heat flux through the roof. The research involved a thermal imagery for the rooftop to demonstrate ceiling temperature when exposed to solar radiations and when under the PV modules. The study resulted in great benefits from PV application as a 38% reduction in cooling load. (Yang and Peng, 2016) investigated the capability of Energy Plus simulation engine to model the impact of building integrated photovoltaics (BIPV) on rooftop temperature. The authors concluded that none of the Energy-plus simulation models can accurately quantify the impact of PV panels on the roof temperature.

4.5. Environmental Analysis

An important advantage of PV technology is reducing the greenhouse gases (GHGs) emissions that would be otherwise generated by burning fossil fuels. The greenhouse gases (GHGs) are calculated and estimated based on the available data in the literature (Brander et al., 2011). The values obtain from the literature are as follow:

- The conversion factor for Carbon Dioxide is 0.796 (tonCO2/MWh).
- The conversion factor for Methane is 0.02375 ($kgCH_4/MWh$).
- The conversion factor for Nitrous oxide is 0.00409 (kgN_2O/MWh).

The impact of greenhouse gases (GHGs) savings can also contribute to economic saving when considering the profit from the sale of CO_2 credits.

4.6. Economic Analysis

Implementation of rooftop PV requires a feasibility analysis in order for the owner to decide wither to invest or not to invest in this technology. As mentioned earlier in section (2.7) that there are several indicators to evaluate the profitability and the economic aspects of any type of technology. These include net present worth (NPV), annual worth (AW), simple payback period (SPP), discount payback period (DPB), internal rate of return (IRR) and profitability Index (PI) (Rodriguesa et al., 2016).

The economic evaluation in this study is applied for a case by case scenario as there are many factors that impact the feasibility of PV which vary from building to another. First, two alternatives will be evaluated, alternative one represents the base case which is the existing building before installing PV panels where only the electricity consumption cost is the expenditure.

The second alternative represents the same building but after installing PV where the cost of PV and savings from its production are considered. Figure 36 represents the cash flow diagram for the two alternatives.

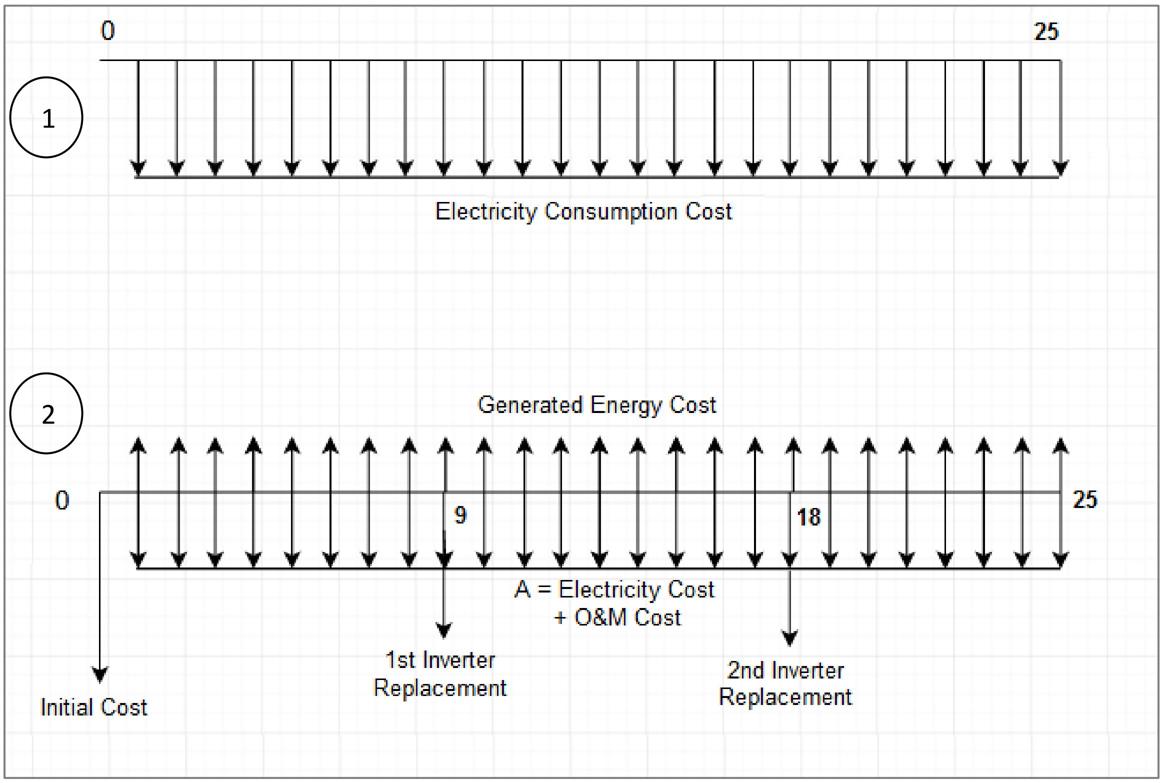


Figure 36: Cash Flow Diagram Representing the Two Alternatives Considered in the Economic Analysis

The NPV can be evaluated by comparing the present value of all outgoing (expenditures) and incoming (benefits) cash flows of the study period as indicated in equation (1). The sum of all cash flows at their present value is called NPV, in which if it is positive then investment is worth it.

$$\mathrm{NPV} = \sum_{y=1}^{Y} \frac{C_y}{(1+r)^y} - C_0 \qquad (1)$$

Where;

C_y is the yearly net cash flow ($),

C_0 is the initial investment ($),

Y is the system service life and

r is the interest rate.

SPP is the simplest form of economic indicators and it can be defined as the time required to repay up-front cost of the investment. This method is simple as it does not include the time value of money, so an interest rate value is not required. The parameters used for SPP calculation are shown in equation (2):

$$\text{SPP} = \frac{\text{Initial Cost of Investment (\$)}}{\text{Annual Energy Saving (\$/year)}} \qquad (2)$$

However, the payback period used in this study considers the LCOE of PV in which it includes life cycle costing (LCC), hence the time value of money is considered. The payback period (PBP) referred to in this study is expressed in equation (3):

$$PBP = \frac{LCOE_{PV} \times E_A \times n}{ET \times E_A} \qquad (3)$$

Where;

E_A = PV annual energy production,

n = PV system lifetime and

ET = Electricity tariff.

The following points are considered for the economic analysis:

- The system life expectancy for the PV panels is mostly between 25-30 years and 10 years for inverters.
- The initial cost has to take in consideration the following elements; system cost including PV panels, inverters, support and integration, and cost of work and were collected from local practitioners.
- The maintenance and operating (O&M) cost has to take in consideration replacements cost; mainly inverters are replaced every 10 years with a cost of 9% of the initial cost (Zweibel, 2010). Overall maintenance cost can be 1% of the initial cost (Adaramola, 2015).
- The Performance Ratio (PF) for mono-crystalline PV commonly falls between 75 and 85% due to system losses (Peng et al., 2013).
- Degradation which is the reduction in output over time should be considered in a linear manner. The manufacture guarantees a minimum power output of 93% and 85% over 12 and 25 years respectively. This can be seen as an average degradation number of 0.6%/year.
- Interest rate was considered to be 2% based on the average of the previous 10 years (Tradeeconomics, 2017).

The costs of PV system including panels and inverters were collected from local practitioners. Table 16 summarizes the economic and cost parameters used in the assessment.

Table 16: Economic and Cost Parameters

Parameters	**Description**
Initial cost of system (including PV, inverter, cabling and installation)	$1330/kWp
Maintenance cost	1% of the initial cost; inverters replacements in years 9 and 18 with 9% of initial cost.
Interest rate	2%
Lifetime	25 years

It was found from the literature that mostly Levelized Cost of Electricity (LCOE), in which its value is constant over the lifetime, is the most common used method for comparing electricity generation technologies, and hence it will be used in this study. LCOE can be calculated using equation (4):

$$LCOE = \frac{C_A + C_{(O\&M)a}}{E_A} \qquad (4)$$

Where;

C_A = Initial cost (annual)

$C_{(O\&M)a}$ = Annual operating and maintenance cost

E_A = PV annual energy production

The cash flow used to determine the LCOE of PV includes PV initial cost, O&M and the two replacements for the inverter. Including the salvage value is debatable as some scholars mentioned that the salvage value doesn't impact the overall cost of the PV system. Figure 37 depicts the cash flow diagram for the PV system.

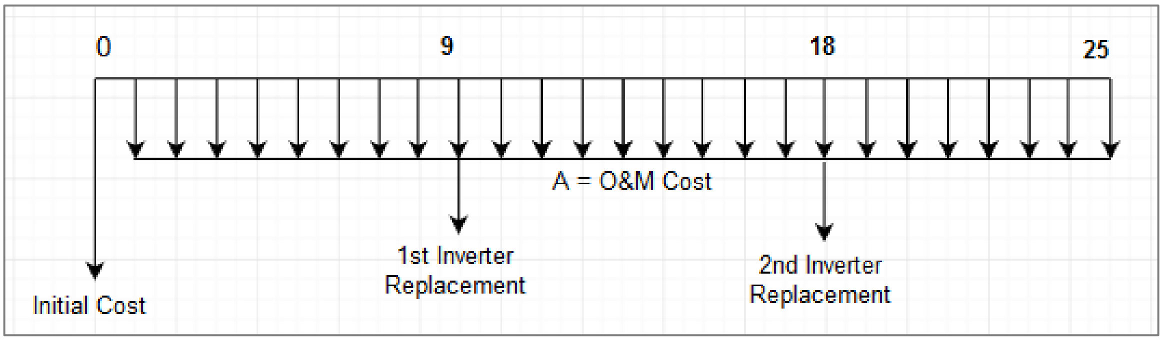


Figure 37: Cash Flow Diagram for the PV System

After determining the LCOE of PV system, the LCOE is compared to the electricity tariff (ET) to check the feasibility of the PV system. The electricity tariffs system in KSA uses a slabs of tariffs in which each range of consumption (kWh) per month has a different cost. The current tariffs system is shown in Figure 38.

<table>
<tr><th>Consumption categories (Kwh)</th><th>Residential (Halalah / kwh)</th><th>Commercial (Halalah / kwh)</th><th>Agricultural & Charities (Halalah / kwh)</th><th>Governmental (Halalah / kwh)</th><th>Industrial, private educational facilities, private medical facilities (Halalah / kwh)</th></tr>
<tr><td>1 – 2000</td><td>5</td><td rowspan="2">16</td><td rowspan="2">10</td><td rowspan="5">32</td><td rowspan="5">18</td></tr>
<tr><td>2001 – 4000</td><td>10</td></tr>
<tr><td>4001 – 6000</td><td>20</td><td rowspan="2">24</td><td rowspan="2">12</td></tr>
<tr><td>6001 – 8000</td><td rowspan="2">30</td></tr>
<tr><td>More than 8000</td><td>30</td><td>16</td></tr>
</table>

Figure 38: Current Consumption Tariffs for all Sectors

Villas consume more electricity in terms of kWh/month compared to apartments. Hence an average electricity tariff of 20 Halala/kWh and 10 Halala/kWh were considered for villas and apartments respectively.

Sensitivity analysis is conducted to better evaluate the impact of the different parameters considered in the analysis. These parameters include capital cost, O&M cost, interest rate, percentage of utilizable area and electricity prices. Every time one variable is changed based on an error range while other parameters are fixed to see the impact on NPV. The error range considered for the sensitivity analysis in this study is $\pm 50\%$.

In case the PV system is found infeasible, different scenarios will be considered to investigate the possibility of making it feasible (Table 7). The scenarios involve different direct and indirect incentives such as providing financial support relative to the PV initial cost and Feed-in-Tariff (FIT) incentives. The impact of the scenarios are investigated separately to find the breakeven point and then several combinations of scenarios are considered. Other scenarios such as increasing electricity tariffs (ET), considering the cost of electricity production and considering CO_2 credits are also investigated. The payback period (PBP) was then calculated using equation (4).

Table 17: Economic Scenarios Considered in the LCOE Analysis

Scenarios	Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
Description	Current ET	Sc0 + CO_2 tax	Increasing ET by 50%	LCOE of PV	Sc3 + CO_2 profit	Sc3 + FIT 13 Hal/kWh	Sc3 + 35% of PV initial cost	sc3 + sc4 + sc5	sc3 + sc4 + 20% of PV initial cost

CHAPTER 5

RESULTS AND DISCUSSION

5.1. Introduction

This chapters display the main results obtained in this study and discusses them in details. It also illustrate the results in a tabular and graphical formats to draw conclusions easily. The sections in this chapter are arranged in a similar sequence to the chapters, i.e. starting with rooftop area assessment, energy analysis and finally environmental and economic analysis.

5.2. Rooftop Area Assessment

This section discusses the results of the rooftop area assessment at unit scale and at the city scale.

5.2.1. Assessment at Unit Scale

For the gross roof area, there was no typical roof among all sample buildings, as each roof was unique in mostly in terms of how it is actually being utilized. However, for the inspected apartment building samples, the gross roof area ranged from 209 m^2 to 708 m^2 with an average of 331 m^2. For villas, it ranged from 185 m^2 to 423 m^2 with an average of 298 m^2. The difference between the average roof size for both apartment buildings and villas is 33 m^2.

The structural coefficients for apartment buildings ranged from 0 to 1 with 0 meaning that PV modules cannot be installed due to structural restrictions, and 1 meaning that there are no structural restrictions at all. The average coefficient was found to be 0.85. For villas, structural coefficients ranged from 0.71 to 1 with an average of 0.91.

The services coefficients for apartment buildings ranged from 0 to 1 with 0 meaning that PV modules cannot be installed due to the full utilization of roof space by service restrictions and due to the poor arrangement, and 1 meaning that there are no service restrictions at all. There is no building that has no service restrictions, the value of “1” means that structural restrictions is preventing the installing of PV with C_{str} of 0. So from now on the value of 1 for any coefficient will be ignored for the same case. Excluding these extreme cases, because they are not common, the range is from 0.13 to 0.85. The average coefficient was found to be 0.57. For villas, services coefficients ranged from 0.37 to 0.78 with an average of 0.59.

The accessibility coefficient for apartment buildings ranged from 0.37 to 0.84 with an average value of 0.67, while it ranged from 0.29 to 0.67 with an average of 0.47 for villas. The shading coefficient for apartment buildings ranged from 0.6 to 1 with an average value of 0.9, while it ranged from 0.76 to 1 with an average of 0.91 for villas. These values are considered optimistic but actually it doesn’t mean we have less shadows over the total roof area because the shading coefficient is considering within the available space for PV installation only. The minimum C_{oth} for apartment buildings is 0.32, the maximum is 1 and the average is 0.75. The minimum C_{oth} for villas is 0.65, the maximum is 1 and the average is 0.93. The coefficient C_{oth} is higher for apartment buildings compared to villas. This is because usually villas have courtyard or gardens where they can be exposed to fresh air as mentioned in section (*3.2.5.5*).

The utilization factor ranged from 0 to 0.4 for apartment buildings, with an average value of 0.16. Translating utilization factor (UF) into utilizable area (UA) gives us a minimum area of 0 m^2, a maximum area of 284 m^2, and an average area of 58.81 m^2. In the villas case, the UF ranged from 0.16 to 0.29 with an average value of 0.20. Looking into the results in terms of the utilizable area (UA), a minimum area of 31.3 m^2, a maximum area of 107.2 m^2, and an average area of 61.5 m^2 was found for the villa rooftops (Figure 39). We can conclude that based on the collected samples, and as an average, 16% of apartment rooftops and 20% of villas rooftops can be utilized for PV applications. The reason behind the variation in the minimum, maximum and average value is due to the variation of the samples as the samples were chosen from different parts of the city (refer to section 3.2.1.).

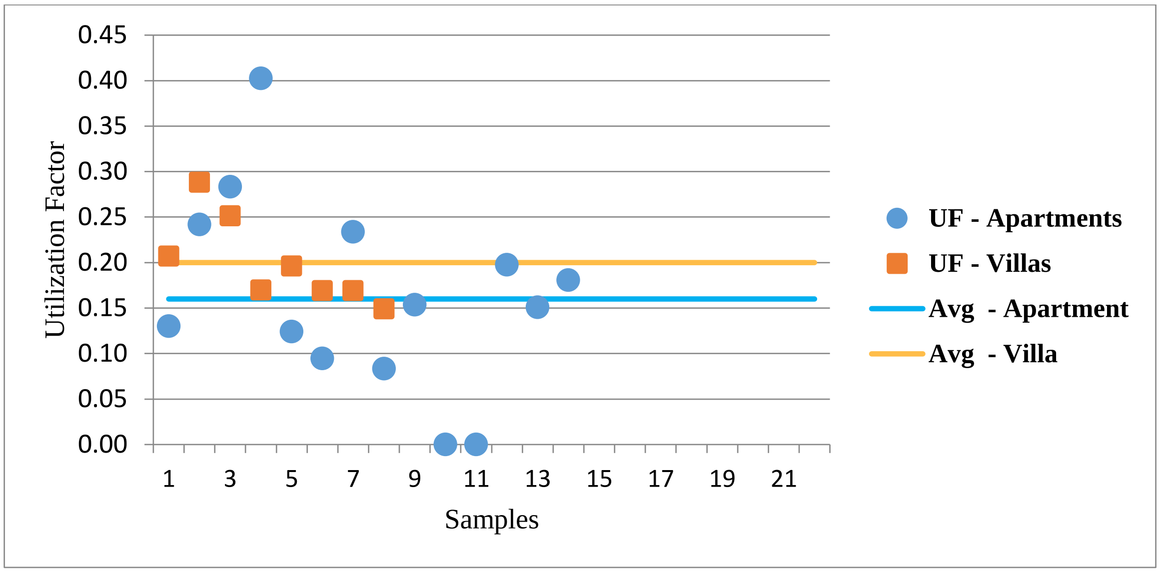


Figure 39: Summary of the Utilization Factors for All Samples

5.2.2. Assessment at City Scale

ArcMap® was used to analyze the data based on different scenarios. As mentioned in section (3.2.6), the analysis was first done considering villas and apartment buildings as one sample and to represent residential sector. The analysis showed that the total roof area (RA) equals to 14,206 km^2 which in turn provides a total of 3,214 km^2 PV area (PVA). Separating the analysis into two categories, i.e. apartment buildings and villas, this show a total roof area

(RA) of 8,539 and 5,666 km^2 and a total PV area (PVA) of 1,943 and 1,194 km^2 respectively. Table 18 summarizes the findings of this section.

Table 18: Summary of Area Calculation at City Scale

Type	# of total Parcels	# of Parcels with 19 m^2 or Less PVA Area	# of Parcels with more than 19 m^2 PVA area	Total Roof Area (m^2)	Total PVA Area (m^2)
Total	32,947	2,208	30,739	14,206,485	3,214,600
Villa	19,104	10	19,094	8,539,872	1,943,689
Apartment	13,843	3,651	10,192	5,666,613	1,194,395

5.3. Energy Analysis

This section discusses the results of the energy production from the installed rooftop PV at a unit and city scale. It also discusses the results of the energy savings at a unit scale.

5.3.1. Energy Production

Electricity production of all building samples was simulated using PV*SOL™ software as illustrated with a sample calculation in section (4.2). Orientation and inclination optimization was conducted and two options are considered in this study. The first option is to tilt the panels 24° due south and the second is to consider flat PV panels. The minimum, maximum and average values of different energy parameters considering all 42 PV sub-areas are summarized in Table 19. The minimum, maximum and average values of different energy parameters considering the 22 samples are summarized in Table 20.

Table 19: Energy Parameters for 42 PV Sub-Areas

	Minimum	**Average**	**Maximum**
Capacity (kWp)	1	4	13.7
Specific Annual Yield (kWh/kWp)	1008	1391	1589
Performance Ratio	56.2	70.13	77.3
Yield Reduction due to Shading (%)	3.1	13.4	31.8
PV Generator Energy (Ac grid) (kWh) – Tilted (24°)	957	5682.73	19796
Energy/Geometry (kWh/m^2) – Tilted (24°)	62.7	114	161
Energy/Module area (kWh/m^2) – Tilted (24°)	152	209.5	237.8

Table 20: Energy Parameters for 22 Sample Buildings

	Min	**Average**	**Max**
Total Generated Energy (AC Grid) (kWh) – Tilted (24°)	5,781	1,4364	62,664
Total Generated Energy/Module Area (kWh/m^2) – Tilted (24°)	170.50	214.1	236.5
Total Generated Energy (AC Grid) (kWh) – Flat	8200	19279	80547
Total Generated Energy/Module Area (kWh/m^2) - Flat	157.5	204.4	229.8

The energy generation at the city scale was computed by multiplying the average electricity production per unit area (kWh/m^2) by the total available PV area (PVA) which was calculated using GIS. The analysis showed that the total energy produced for tilted panels equals to 675,066 MWh and 393,985 MWh for flat panels. Separating the analysis into two categories, i.e. apartment buildings and villas, this show a total energy produced of 413,811

MWh and 247,000 MWh for tilted panels and a total energy produced of 393,985 MWh and 246,642 MWh for flat panels respectively. Table 21 summarizes the findings of the total electricity produced by PV panels, considering the existing roof conditions, at the city scale. Table 22 summarizes the findings of total electricity produced by PV panels, considering arrangement of service components, at the city scale.

Table 21: Total Electricity Produced by PV Panels at the City Scale

Type	Total PVA Area (m^2)	Total Energy Produced – Titled 24° (kWh)	Total Energy Produced - Flat (kWh)
Total	3,214,600	675,066,000	655,778,400
Villa	1,943,689	413,811,388	393,985,760
Apartment	1,194,395	247,000,886	246,642,568

Table 22: Total Potential Electricity Produced by PV Panels at the City Scale

Type	Total PVA Area (m^2)	Total Energy potential (24°) (kWh)	Total Energy potential (Flat) (kWh)
Total	4,320,521	907,309,410	881,386,284
Villa	1,959,613	417,201,608	397,213,555
Apartment	1,723,045	356,325,706	355,808,793

5.3.2. Energy Savings from PV Implementation

The base case simulation showed a total load of 63,756 kWh segregated as 62.5% cooling, 24% lighting and 13% appliances. The results of the three scenarios mentioned in section (4.4) are discussed thoroughly in this section. Considering a typical villa, the total on-site generation when tilted PV panels are installed within the utilizable area (UA) can substitute 10% of the total consumption. It is important to mention that Saudi Arabia residential consumption is much high compared to similar units in other countries. Hence, energy conservation measures should be adopted in order to reduce the high demand and eventually PV technology will have more value. Increasing the utilizable area from 0.16 to 0.25 increases the percentage of saving from 10% to 19%. Further increment in the utilizable are up to 40% of the roof, increases the percentage of savings to 29%. Considering the latter case, if the tilted PV panels are replaced with flat panels within the same utilization factor (UF), i.e. 0.4, the savings can reach to 36%. Transferring these results in term of kWh/m^2 gives values of 13, 23.7, 36.6 and 45 kWh/m^2 for all the scenarios in that order (refer to Figure 40).

Considering the shading impact of PV panels on the roof heat gain for a typical villa result in 8.5% reduction in roof heat gain when installing PV in the utilizable area (UF= 0.16). As the utilizable area increases to 0.25 and 0.24, the reduction almost double reaching 16 and 24.5%. Converting this into cooling load saving results in 1%, 2% and 3% reduction when considering the utilizable area in the same order. For the case where the PV panels are flat and covers full roof, the heat gain reduction reached 27.4% allowing a reduction of 3.2% in the cooling load (refer to Figure 41).

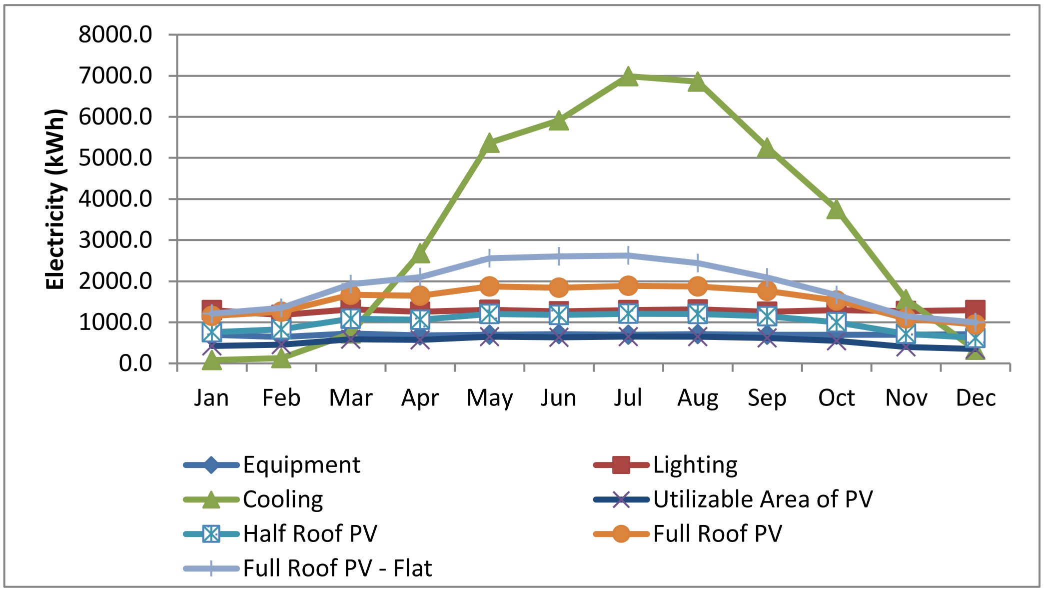


Figure 40: Comparison of Fuel Breakdown and PV Generation

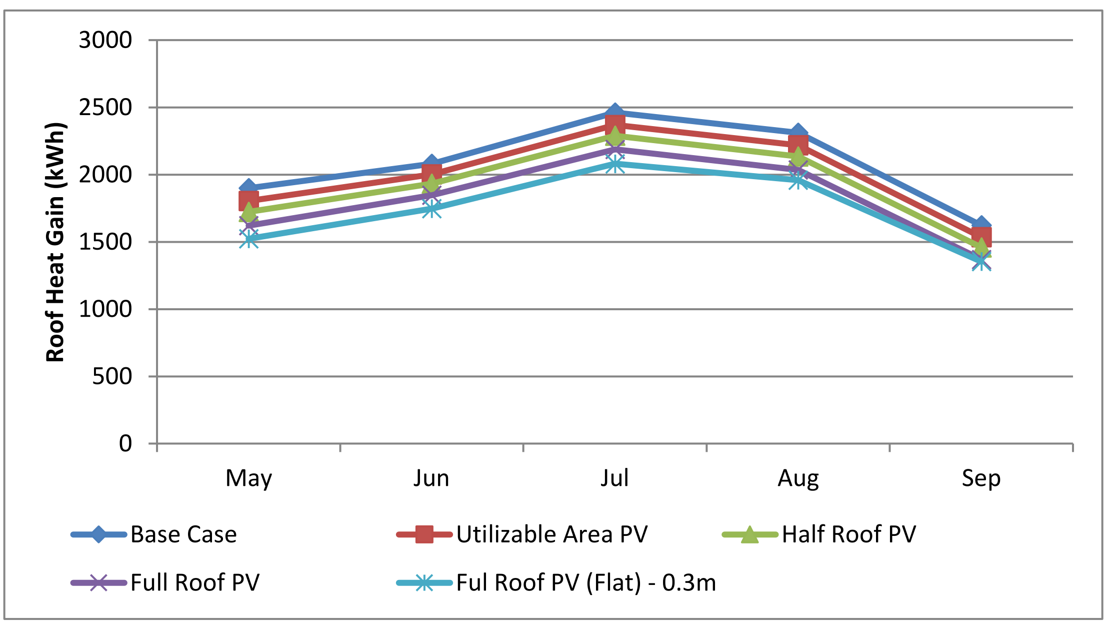


Figure 41: Heat gain through Roof for Different Scenarios

5.4. Environmental and Economic Analysis

The GHGs emissions reductions were calculated and presented in Table 23.

Table 23: GHGs Emissions Reductions

Type	Total Energy Produced – Titled 24° (MWh)	Reductions in CO_2 emissions (tons)	Reductions in CH_4 emissions (kg)	Reductions in N_2O emissions (kg)
Total	675,066	537,353	16,033	2,761
Villa	413,811	329,394	9,828	1,693
Apartment	247,001	196,613	5,866	1,010

The economic evaluation of the PV systems is considered in a case by case scenario. The assessment cannot be generalized due to the different conditions of each building in terms of energy use and roof utilization. The villa and apartment investigated in section 4 was considered also for the economic analysis. The a2nalysis considered two methods, first by considering two alternative systems including the base case and the building with PV panels. The second method considered LCOE for the PV system compared to the electricity tariffs (ETs). Table 24 shows a summary of the analysis using the first method and using the net present worth (NPV) indicator. The table indicates that the utilization of rooftop PV in the investigated villa is not feasible as the NPV of alternative two is more than that of alternative one (260,158 > 248,950). Table 25 shows a similar analysis but for the investigated apartment, in which the same conclusion can be drawn.

Table 24: Economic Analysis of Villa Rooftop PV in Saudi Riyals for Systems < 20 kWp

Villa - 15% of Roof - Tilted PV panels		NPW	AW
Total Villa consumption (kWh)	63,756.6	-248,950.4	-12,751.3
Electricity tariff (Riyals/kWh)	0.2		
Total electricity bill (Riyals)	12,751.3		
Interest Rate	0.02		
Villa Electricity consumption after adding PV (Riyals/year)	57,594.6	-224,889.6	-11,518.9
PV Capacity (kWp)	5.3		
PV Production (kWh)	6,162		
Capital Cost (Riyals/kWp)	4,990	NPW	AW
PV Initial Cost	-26,447	-26,447.0	-1,354.1
PV O&M = 1% of initial cost	-264.47	-5,163.4	-264.47
Replacement of inverter at year 9 = 9% of initial cost	-2,380.2	-1,991.8	-102.0
Replacement of inverter at year 18 = 9% of initial cost	-2,380.2	-1,666.6	-85.3
Total Costs		-35,268.79	-1,805.87
Total PW (Cost and benefits)		-260,158.4	-13,324.8

Table 25: Economic Analysis of Apartment Rooftop PV in Saudi Riyals for Systems < 20 kWp

Apartment - 13% of Roof - Tilted PV panels		Base Case	
		NPW	AW
Total Villa consumption (kWh)	188,740	-368,486.5	-18,874.0
Electricity tariff (Riyals/kWh)	0.1		
Total electricity bill (Riyals/year)	18,874		
Interest Rate	0.02		
Villa Electricity consumption after adding PV (Riyals/year)	182,661	-356,618.2	-18,266.1
PV Capacity (kWp)	5.1		
PV Production (kWh)	6,079		
Capital Cost (Riyals/kWp)	4,990	NPV	AW
PV Initial Cost	-25,449	-25,449.0	-1303.0
PV O&M = 1% of initial cost	-254.5	-4,968.5	-254.5
Replacement of inverter at year 9 = 9% of initial cost	-2,290.4	-1,916.6	-98.1
Replacement of inverter at year 18 = 9% of initial cost	-2,290.4	-1,603.7	-82.1
Total Costs		-33,937.90	-1,737.7
Total PW (Cost and benefits)		-390,556.1	-20,003.8

Sensitivity analysis is conducted for five variables as shown in Figure 42. It can be concluded from Figure 42 that electricity price is the most critical factor in the feasibility of PV for the villa case, followed by interest rate.

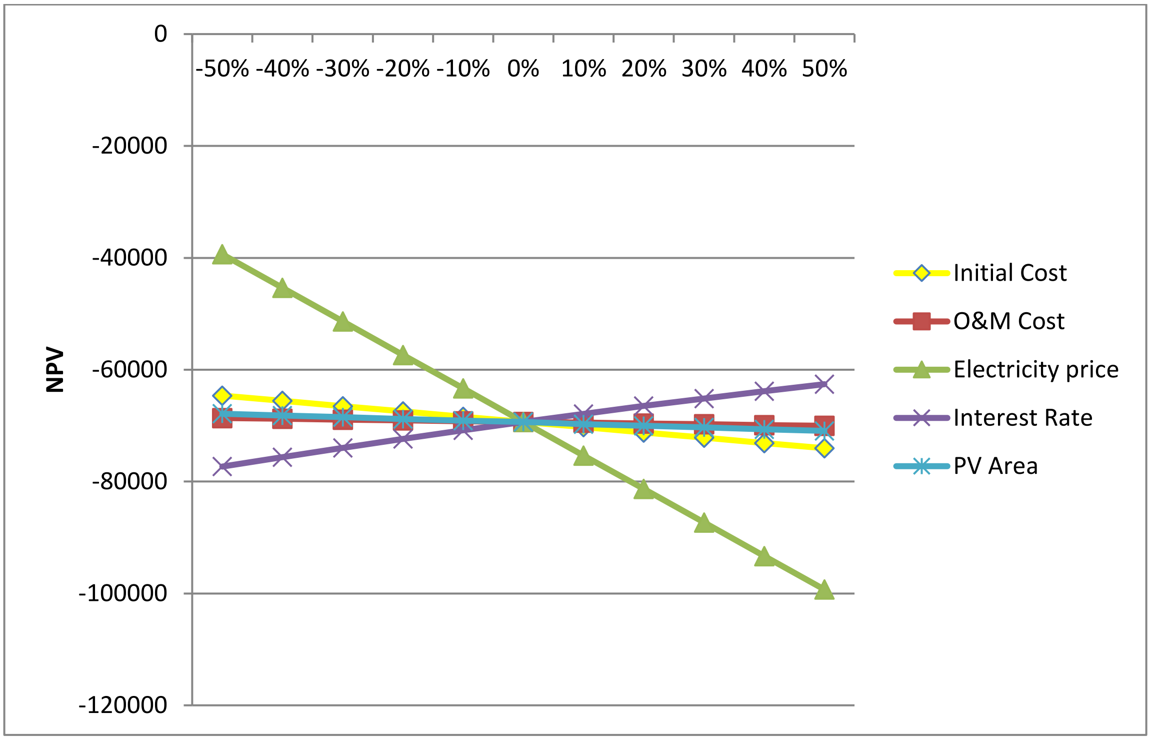


Figure 42: Sensitivity Analysis for PV installed in the Investigated Villa

The unit cost from the first method (i.e. alternative method) was found to be 21 Halala/kWh for the investigated villa which is slightly more than the electricity tariff being 20 Halala/kWh. Whereas the unit cost for the apartment was found to be 12 Halala/kWh which is more than the apartment electricity tariff being 10 Halala/kWh.

Working with the second method (i.e. LCOE), the LCOE was found to be almost same for the investigated villa and apartment with a value of 29 Halala/kWh (0.078$/kWh). Since the PV system was found to be infeasible, different scenarios (Table 17) are considered based on the policies and incentives implemented in other countries. Some of the scenarios were investigated in more details to analyze their impact on the feasibility such as available service area, electricity tariffs (ETs) and direct financial incentives. Figures 43 and 44 depict the results from the LCOE analysis and show the payback period (PBP).

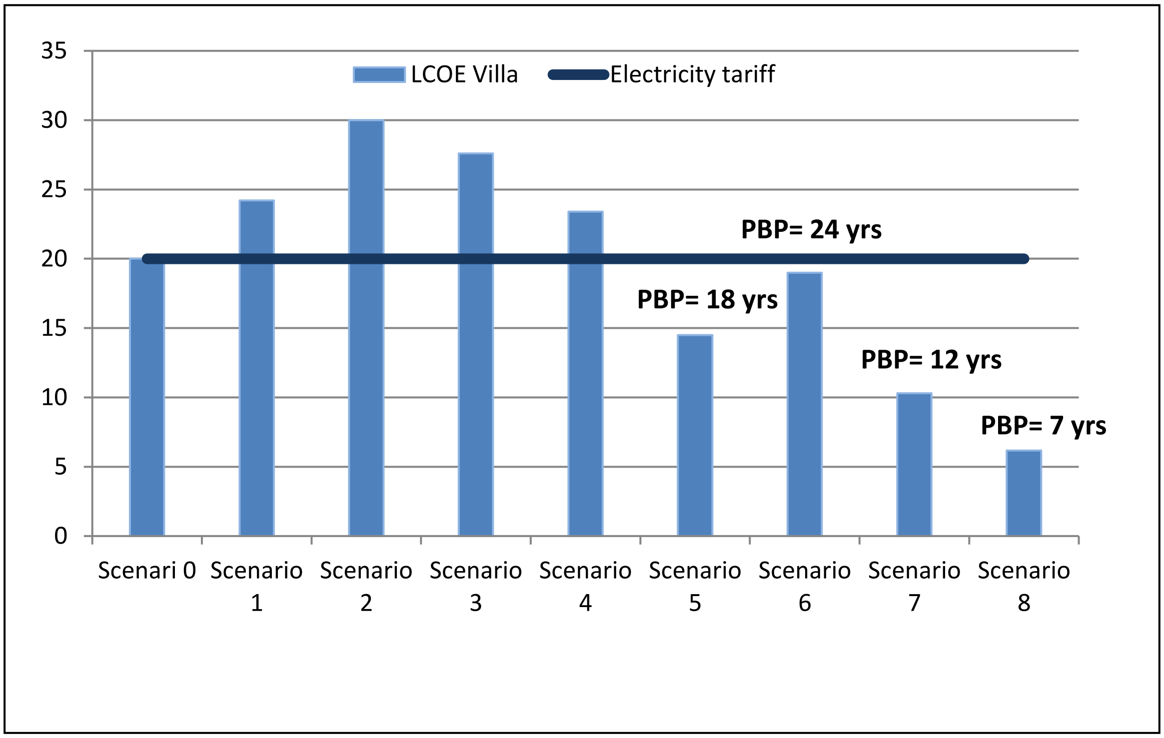


Figure 43: LCOE Analysis for the Investigated Villa Considering Different Scenarios

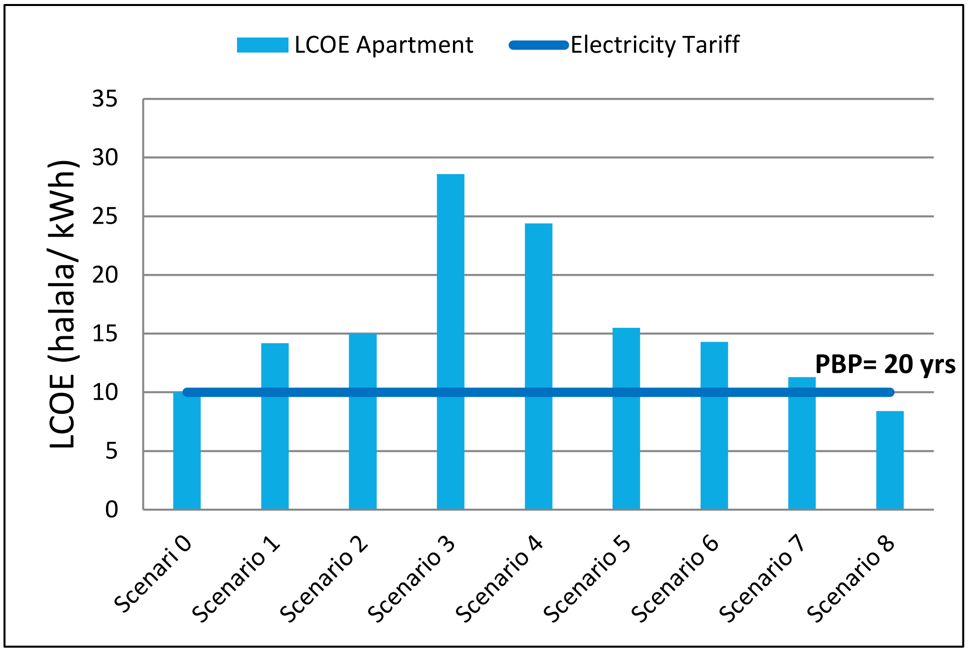


Figure 44: LCOE Analysis for the Investigated Apartment

The impact of direct financial incentive in terms of a percentage of initial cost on the LCOE of PV was investigated. Figure 45 depicts the results of the analysis and shows that with around 35% of the initial cost covered by the government, parity can be achieved.

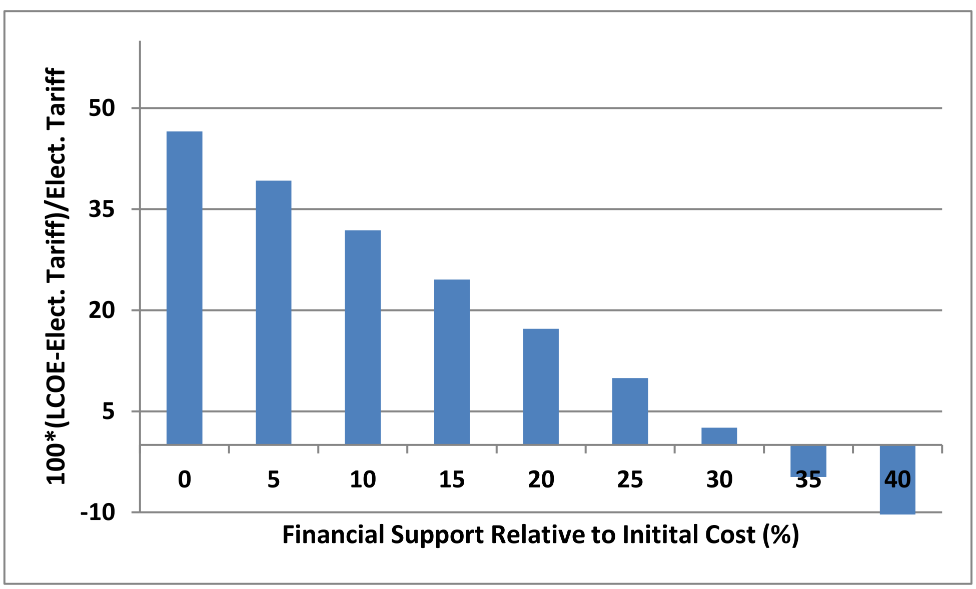


Figure 45: The Difference between LCOE and Electricity Tariff as a Function of Financial Support

It is interesting to investigate the impact of the availability of area on the economy of PV. Figure 46 depicts the LCOE for the PV system when the percentage of utilizable area is increased compared to the electricity tariffs. It shows that the breakeven point occurs at 85% utilizable area. However, this figure changed to 30% when CO_2 credit reduction, as a type of incentive, was considered.

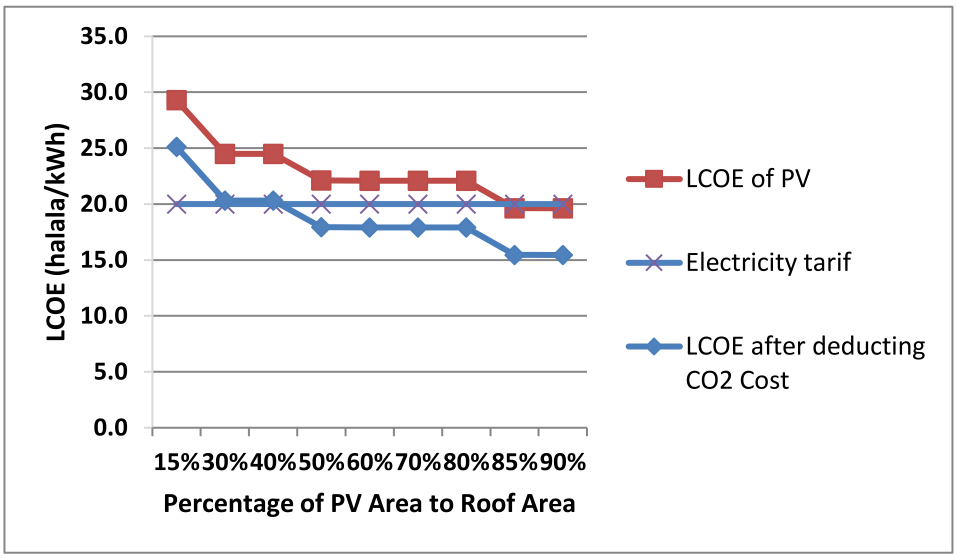


Figure 46: LCOE of PV Vs. Percentage of Utilizable Area

Analyzing the impact of the interest rate was also carried out as shown in Figure 47. Two scenarios were considered on which the first one considered the actual utilization factor (15%) and the second considered 40% utilization factor. The analysis that considered the CO_2 credit reduction incentive showed a breakeven point at 15% interest rate for the 40% utilization factor scenario. Furthermore, increasing the utilizable area will make PV more feasible because of the concept of economy of scale.

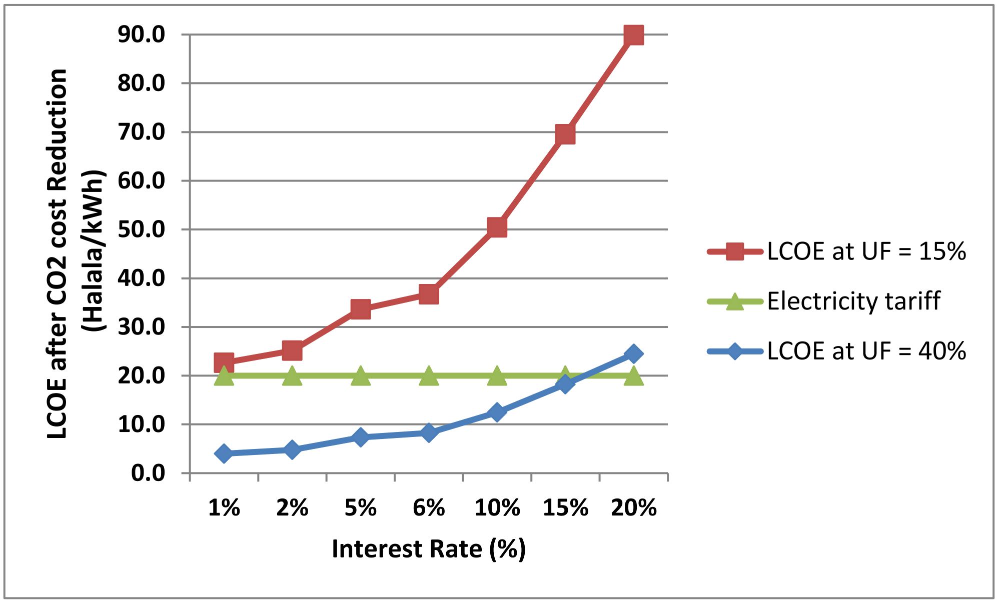


Figure 47: LCOE of PV Vs. Interest Rate

This economic analysis showed the importance of incentives in its different forms. Saudi Arabia has to benefit from the policies undergoing in other advanced countries. The subsidized costs of electricity is the major factor behind the infeasibility of the PV system. The fact that Saudi Arabia has started a subsidy reform program in which it will increase electricity tariffs gradually (Arabian Business, 2017), will help promoting PV market.

CHAPTER 6

CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

6.1. Conclusions

Energy has become one of the top concerns in developed as well as developing countries. KSA has set future plans to meet the increasing energy demand targeting a diverse and sustainable sources of fuel for energy use rather than depending only on fossil fuels as per vision 2030. An integral part of the vision is to generate 9.5 GW of electricity from renewable energy resources. It was noticed that Saudi Arabia is mainly investing on large scale PV projects as those already existing in the country. Although the utility scale projects are constituting the larger share of the solar market in most part of the world, small scale applications are growing rapidly and incentives are offered for end users. Saudi Arabia's climate is harsh and in sequence impacts PV output negatively.

This research aimed to evaluate the feasibility of the utilization of PV technology on residential rooftops for electricity production given Saudi Arabia's climatic and economic conditions. Four stages were considered, rooftop area assessment was conducted at unit scale and city scale to quantify the available area for PV utilization. The second stage considered orientation and inclination optimization for PV system design at both unit and city scales. After that, savings from PV implementation was analyzed in terms of production and cooling load reduction. Finally environmental and economic analysis were conducted to evaluate the feasibility of PV applications in the residential sector.

Based on the collected samples, and as an average, 16% of apartment rooftops and 20% of villas' rooftops can be utilized for PV applications. At a city scale, the analysis showed that the total roof area (RA) equals to 14.2 km^2 which in turn provides a total of 3.2 km^2 PV area (PVA). It also showed that the total energy potential for tilted panels considering the existing roof conditions equals to 675 GWh, while this can increase by 34% if we consider proper rearrangement of service components.

Considering a typical villa, the total on-site generation when tilted PV panels are installed within the utilizable area (UA) can substitute 10% of the total consumption. Increasing the utilizable area from 0.16 to 0.25 increases the percentage of saving from 10% to 19%. Further increment in the utilizable are up to 40% of the roof, increases the percentage of savings to 29%. Reductions in cooling load are not very significant, as installing PV panels in 40% of the roof area with a tilt of 24° can provide 3% savings.

Considering the current conditions, and from economic point of view, it is easier for end users to depend on the grid-supplied electricity. However, considering financial incentives helped in reducing the gap between LCOE and Electricity tariff especially for villas. LCOE of PV can be reduced to reach 6.17 halalas/kWh by considering CO_2 profit incentive and a direct financial support in terms of 20% of the initial cost. This scenario provides a payback period of 7 years.

6.2. Recommendations

The investigate samples show that roof utilization in the residential sector is not well organized. Service components are installed somehow randomly without considering to leave a vacant area for other purposes. However, based on the analysis of the study, the following recommendations are important for policy makers and for regulators:

- Rooftop PV applications should be considered as part of the renewable energy strategies in the kingdom, as the focus currently is on large-scale utility projects.
- They key to promote rooftop PV applications is through Policy intervention which creates a demand for PV that in turn allows the PV market subsequently to develop.
- Direct measures such as financial incentives (relative to initial cost) or indirect incentives such as Feed-in-Tariff (FIT) should be adopted by policy makers as it will help in encouraging investments on PV.
- It is important before utilizing PV technology to consider energy conservation measures. Here we are talking about practical and easy measures such as replacing existing light bulbs with more efficient bulbs rather than major retrofitting majors.
- Roofs have high parapet walls especially for villas, the height can be reduced as the roof is not usually utilized as a sitting Area. The case with apartments is understandable.
- Structural restrictions such as columns and rebars should not be left on roofs. As it was noticed some buildings have uncompleted structural elements and still kept even after 25 years.
- It was highlighted that services restrictions have the greatest impact on the implementation of PV technology. Hence, the following points are alternative options to reduce their impact.
- Dish antennas should be limited to the number of occupants, i.e. one dish antenna per occupant.

- Dish antennas can be arranged in a way that they are placed near by parapet walls, under shaded areas, and close to each other in series.
- A better option and in order to utilize the roof area more efficiently, dish antennas can be connected to one central dish hence the number of dish antennas will be reduced and more area will be available.

6.3. Future Work

This study focused on existing residential buildings, it is also worth it to investigate the potential based on a new design and regulations considering orientation, geometry and other factors. This study was limited to mono-crystalline silicon PV, other type and new technologies such as bi-facial PV are worth the investigation. In addition, other mounting conditions such as BIPV on rooftop or even on walls or as part of windows is another area of study. Large commercial facilities and their parking areas can be investigated in term of PV potential, tracking systems can also be investigated.

REFERENCES

Abderrezek, M. & Fathi, M. 2017, "Experimental study of the dust effect on photovoltaic panels' energy yield", Solar Energy, vol. 142, pp. 308-320.

Ahrens, C.D. 2009, Meteorology today: an introduction to weather, climate, and the environment, West Pub. Co, St. Paul, Minn.

Aksakal, A. & Rehman, S. 1999, "Global solar radiation in Northeastern Saudi Arabia", Renewable Energy, vol. 17, no. 4, pp. 461-472.

Alajlan, S. A. and M. S. Smiai, 'Performance and Development of PV - Plant for Water Pumping and Desalination for Remote Area in Saudi Arabia' (1996) 8 Renewable Energy 441.

AlYahya, S. & Irfan, M.A. 2016, "Analysis from the new solar radiation Atlas for Saudi Arabia", Solar Energy, vol. 130, pp. 116-127.

American Society for Testing and Materials (ASTM), 2008, "E 1036M Standard Test Methods for Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays using Reference Cells".

Asif, M. 2016, "Growth and sustainability trends in the buildings sector in the GCC region with particular reference to the KSA and UAE", Renewable and Sustainable Energy Reviews, vol. 55, pp. 1267-1273.

Bahaidarah, H., Rehman, S., Subhan, A., Gandhidasan, P. & Baig, H. 2015, "Performance Evaluation of a PV Module under Climatic Conditions of Dhahran, Saudi Arabia", Energy Exploration & Exploitation, vol. 33, no. 6, pp. 909-929.

Bansal, N.K. & Goel, S. 2000, "Integration of photovoltaic technology in cafeteria building, at Indian Institute of Technology, New Delhi", Renewable Energy, vol. 19, no. 1, pp. 65-70.

Benghanem, M. & Mellit, A. 2014;2013;, "A simplified calibrated model for estimating daily global solar radiation in Madinah, Saudi Arabia", Theoretical and Applied Climatology, vol. 115, no. 1, pp. 197-205.

Bergamasco, L. & Asinari, P. 2011, "Scalable methodology for the photovoltaic solar energy potential assessment based on available roof surface area: Application to Piedmont Region (Italy)", Solar Energy, vol. 85, no. 5, pp. 1041-1055.

Ciulla, G., Lo Brano, V. & Moreci, E. 2013, "Forecasting the Cell Temperature of PV Modules with an Adaptive System", International Journal of Photoenergy, vol. 2013, pp. 1-10.

Cristaldi, L., Faifer, M., Rossi, M., Toscani, S., Catelani, M., Ciani, L. & Lazzaroni, M. 2014, "Simplified method for evaluating the effects of dust and aging on photovoltaic panels", Measurement, vol. 54, pp. 207-214.

D. R. Myers, K. Emery, and C. Gueymard, 2002, "Revising and validating spectral irradiance reference standards for photovoltaic performance", in Proceedings of the ASES/ASME solar conference, Reno, Nevada.

Dash, P.K. & Gupta, N.C. 2015, "Effect of Temperature on Power Output from Different Commercially available Photovoltaic Modules", International Journal of Engineering Research and Applications, vol. 5, no. 1, pp. 148-151.

Davis, M.W., Fanney, A.H. & Dougherty, B.P. 2001, "Prediction of Building Integrated Photovoltaic Cell Temperatures", Journal of Solar Energy Engineering, vol. 123, no. 3, pp. 200.

Del Cueto JA. 2000, "Model for the thermal characteristics of flat-plate photovoltaic modules deployed at fixed tilt", In Proceedings of the 28th IEEE photovoltaic specialists conference, Anchorage, AL, p. 1441–5.

Denholm, P. and Margolis, R., 2008, "Supply curves for rooftop solar PV-generated electricity for the United States", Natl. Renew, Energy Lab. 1–23.

Dubey, S., Sarvaiya, J.N. & Seshadri, B. 2013, "Temperature Dependent Photovoltaic (PV) Efficiency and Its Effect on PV Production in the World – A Review", Energy Procedia, vol. 33, pp. 311-321.

Elhadidy, M.A. & Abdel-Nabi, D.Y. 1991, "Diffuse fraction of daily global radiation at Dhahran, Saudi Arabia", Solar Energy, vol. 46, no. 2, pp. 89-95.

El-Sebaii, A.A., Al-Hazmi, F.S., Al-Ghamdi, A.A. & Yaghmour, S.J. 2010, "Global, direct and diffuse solar radiation on horizontal and tilted surfaces in Jeddah, Saudi Arabia", Applied Energy, vol. 87, no. 2, pp. 568-576.

El-Sharkawy, A. 2005, Economic Feasibility Studies, Cairo: Cairo University.

Gadsden, S., Rylatt, M. & Lomas, K. 2003, "Putting solar energy on the urban map: a new GIS-based approach for dwellings", Solar Energy, vol. 74, no. 5, pp. 397-407.

Gagnon, P., Margolis, R., Melius, J., Phillips, C. & Elmore, R. 2016, " Rooftop solar photovoltaic technical potential in the United States: a detailed assessment", National Renewable Energy Laboratory.

Hofierka, J. & Kaňuk, J. 2009, "Assessment of photovoltaic potential in urban areas using open-source solar radiation tools", Renewable Energy, vol. 34, no. 10, pp. 2206-2214.

Hong, T., Koo, C., Park, J. & Park, H. 2014, "A GIS (geographic information system)-based optimization model for estimating the electricity generation of the rooftop PV (photovoltaic) system", ENERGY, vol. 65, pp. 190-199.

Hong, T., Lee, M., Koo, C., Kim, J. & Jeong, K. 2016, "Estimation of the Available Rooftop Area for Installing the Rooftop Solar Photovoltaic (PV) System by Analyzing the Building Shadow Using Hillshade Analysis", Energy Procedia, vol. 88, pp. 408-413.

International Energy Agency (IEA), Key world energy statistics, 2015.

Izquierdo, S., Rodrigues, M. & Fueyo, N. 2008, "A method for estimating the geographical distribution of the available roof surface area for large-scale photovoltaic energy-potential evaluations", Solar Energy, vol. 82, no. 10, pp. 929-939.

Joint Research Centre (JRC) 2001-2012, European Commission. Photovoltaic Geographical Information System (PVGIS), European Communities. Retrieved from <http://re.jrc.ec.europa.eu/pvgis/> (accessed on 07/12/2016).

Kaldellis, J.K., Kapsali, M. & Kavadias, K.A. 2014, "Temperature and wind speed impact on the efficiency of PV installations. Experience obtained from outdoor measurements in Greece", Renewable Energy, vol. 66, pp. 612.

Kang, M.H. & Rohatgi, A. 2016, "Quantitative analysis of the levelized cost of electricity of commercial scale photovoltaics systems in the US", Solar Energy Materials and Solar Cells, vol. 154, pp. 71-77.

Kannan, R., Leong, K.C., Osman, R., Ho, H.K. & Tso, C.P. 2006, "Life cycle assessment study of solar PV systems: An example of a 2.7 kWp distributed solar PV system in Singapore", Solar Energy, vol. 80, no. 5, pp. 555

Latinopoulos, D. & Kechagia, K. 2015, "A GIS-based multi-criteria evaluation for wind farm site selection. A regional scale application in Greece", Renewable Energy, vol. 78, pp. 550-560.

Makrides, G., Zinsser, B., Phinikarides, A., Schubert, M. & Georghiou, G.E. 2012, "Temperature and thermal annealing effects on different photovoltaic technologies", Renewable Energy, vol. 43, pp. 407-417.

Mani, M. & Pillai, R. 2010, "Impact of dust on solar photovoltaic (PV) performance: Research status, challenges and recommendations", Renewable and Sustainable Energy Reviews, vol. 14, no. 9, pp. 3124-3131.

Mejia, F., Kleissl, J. & Bosch, J.L. 2014, "The Effect of Dust on Solar Photovoltaic Systems", Energy Procedia, vol. 49, pp. 2370-2376.

Melius, J., Margolis, R. and Ong, S., 2013, "Estimating rooftop suitability for PV: a review of methods, patents, and validation techniques", National Renewable Energy Laboratory (NREL), Golden, CO.

Mills, D. 2004, "Assessing solar hot water system performance with GIS", Solar Energy, vol. 76, no. 1, pp. 153-157.

Mundada, A.S., Shah, K.K. & Pearce, J.M. 2016, "Levelized cost of electricity for solar photovoltaic, battery and cogen hybrid systems", Renewable and Sustainable Energy Reviews, vol. 57, pp. 692-703.

National Aeronautics and Space Administration (NASA), Climate and radiation, Solar radiation.

Ordenes, M., Marinoski, D.L., Braun, P. & Rüther, R. 2007, "The impact of building-integrated photovoltaics on the energy demand of multi-family dwellings in Brazil", Energy & Buildings, vol. 39, no. 6, pp. 629-642.

Ordones, J., Jadraque, E., Alegre, J. & Martínez, G. 2010, "Analysis of the photovoltaic solar energy capacity of residential rooftops in Andalusia (Spain)", Renewable and Sustainable Energy Reviews, vol. 14, no. 7, pp. 2122-2130.

Ouyang, X. & Lin, B. 2014, "Levelized cost of electricity (LCOE) of renewable energies and required subsidies in China", Energy Policy, vol. 70, pp. 64-73.

Paudyal, B.R. & Shakya, S.R. 2016, "Dust accumulation effects on efficiency of solar PV modules for off grid purpose: A case study of Kathmandu", Solar Energy, vol. 135, pp. 103-110.

Quinonez-Varela, G., Cruden, A., Graham, C., Punton, B., Blair, L. & Thomson, J. 2007, "A GIS/PSS planning tool for the initial grid connection assessment of renewable generation", Renewable Energy, vol. 32, no. 5, pp. 727-737.

Radhi, H. 2010, "Energy analysis of façade-integrated photovoltaic systems applied to UAE commercial buildings", Solar Energy, vol. 84, no. 12, pp. 2009-2021.

Ramachandra, T.V. & Shruthi, B.V. 2007, "Spatial mapping of renewable energy potential", Renewable and Sustainable Energy Reviews, vol. 11, no. 7, pp. 1460-1480.

Renewable Energy Policy Network for 21th Century (REN21), 2016, Renewables 2016: Global status report.

Sadineni, S.B., Atallah, F. & Boehm, R.F. 2012, "Impact of roof integrated PV orientation on the residential electricity peak demand", Applied Energy, vol. 92, pp. 204-210.

Saudi Electricity Company (SEC), Electrical data, 2000-2014.

Schott T. 1985, "Operation temperatures of PV modules", In Proceedings of the sixth E.C. photovoltaic solar energy conference, London, UK, p. 392–6.

Shaahid, S.M. & El-Amin, I. 2009, "Techno-economic evaluation of off-grid hybrid photovoltaic–diesel–battery power systems for rural electrification in Saudi Arabia—A way forward for sustainable development", Renewable and Sustainable Energy Reviews, vol. 13, no. 3, pp. 625-633.

Shaahid, S.M. & Elhadidy, M.A. 1994, "Wind and solar energy at Dhahran, Saudi Arabia", Renewable Energy, vol. 4, no. 4, pp. 441-445.

Shi, W., Wang, S. & Yang, Q. 2010, "Climate change and global warming", Reviews in Environmental Science and Bio/Technology, vol. 9, no. 2, pp. 99-102.

Singh, R. & Banerjee, R. 2013, "Estimation of roof-top photovoltaic potential using satellite imagery and GIS", pp. 2343.

Skoplaki, E. & Palyvos, J.A. 2009, "Operating temperature of photovoltaic modules: A survey of pertinent correlations", Renewable Energy, vol. 34, no. 1, pp. 23-29.

Skoplaki, E., Boudouvis, A.G. & Palyvos, J.A. 2008, "A simple correlation for the operating temperature of photovoltaic modules of arbitrary mounting", Solar Energy Materials and Solar Cells, vol. 92, no. 11, pp. 1393-1402.

Solargis 2013, Direct Normal Irradiation-Saudi Arabia, Bratislava, Slovakia, available at: <http://solargis.com/products/maps-and-gis-data/free/download/saudi-arabia> (accessed on 07/24/2017).

Touati, F., Massoud, A., Hamad, J.A. and Saeed, S.A., 2013, "Effects of environmental and climatic conditions on PV efficiency in Qatar", Renewable Energy and Power Quality Journal, 11.

United Nations Environment Programme (UNEP), 2012, Sustainable buildings and climate initiative, "Why buildings?". Retrieved from <http://www.unep.org> (accessed on 07/12/2016).

Wróżyński, R., Sojka, M. & Pyszny, K. 2016, "The application of GIS and 3D graphic software to visual impact assessment of wind turbines", Renewable Energy, vol. 96, pp. 625-635.

Zambelli, P., Lora, C., Spinelli, R., Tattoni, C., Vitti, A., Zatelli, P. & Ciolli, M. 2012, "A GIS decision support system for regional forest management to assess biomass availability for renewable energy production", Environmental Modelling and Software, vol. 38, pp. 203-213.

Zell, E., Gasim, S., Wilcox, S., Katamoura, S., Stoffel, T., Shibli, H., Engel-Cox, J. & Subie, M.A. 2015, "Assessment of solar radiation resources in Saudi Arabia", Solar Energy, vol. 119, pp. 422-438.

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