Brunel University London

Investigation into Using Stand-Alone Building Integrated Photovoltaic System (SABIPV) as a Fundamental Solution for Saudi Rural Areas and Studying the Expected Impacts

by

Abdulkarim Albaz

Thesis submitted to Brunel University London for the degree of Doctor of Philosophy

April, 2015

Abstract

A number of natural resources can be exploited for providing energy, such as the sun, wind, water flow, tides, waves and deep heat generated within the earth. Recently, renewable resources especially that extracted from solar have been significantly encouraged mainly for environmental worries, such as climate change mitigation and global warming, coupled with high oil cost and security and economic matters. The crucial need of energy in human development has also been another important drive pushing the rapid progresses in renewable technologies, which results in both large-scale strategic projects for covering wide urban and rural areas and simple systems suitable for individual buildings. Solar energy has become a widely desired option, especially in high solar radiation areas. The Middle East, especially Gulf region is an ideal geographical area for solar power where it has one of the highest solar irradiation rates across the world. The population in Gulf Cooperation Council (GCC) countries is significantly small compared to the geographical areas and populations are distributed mostly throughout huge areas forming small villages and rural communities on substantial distances from the main power networks. In Saudi Arabia, there is a crisis in supplying enough electricity to the large cities and domestic remote area in various parts in the country and a wide range of remote areas still suffer from a severe shortage of power supply.

In this project, the opportunity of using small-scale solar energy technologies, such as Stand-Alone Building-Integrated PV (SABIPV) systems has been investigated as an optimal solution for providing solar energy to a great deal of off-grid areas in Kingdom of Saudi Arabia and the expected short and long-term impacts of such solution have been studied. The study showed that the main reasons behind the crisis in supplying electricity to domestic remote and rural off-grid areas in Saudi Arabia are the weakness of the financial returns compared to the cost of providing the service, the difficulty of the natural topography of areas, high cost of maintenance works, and the regulations of providing electric services in Saudi Arabia. This is in addition to the expected environmental impacts, such as raising the pollution rates in the area and the safety influences of extending the high voltage lines over huge areas. On the other hand, the lack of the necessary infrastructure services, particularly electricity and the looking forward for better level of prosperity lead people who live in countryside and remote areas usually to immigrate to in-grid areas which has several short and long-term negative impacts on economic, social and security sides.

This study shows that SABIPV system is a cost-Impactive, powerful, and fundamental solution for all off-grid areas in Saudi Arabia including remote villages and rural communities and providing the same level of electricity services that can be achieved in urban on-grid areas. The system is expected to have positive impacts including reducing pollution and greenhouse gas emissions, the expansion of agricultural land and reduce desertification, reducing the influence of high-voltage electrical lines on living organisms, providing adequate electricity service at lower cost, offering more job opportunities for people in remote areas, increasing agricultural and handicraft products, developing the tourism sector in rural areas, reducing the rate of migration from rural areas to the cities, and reducing the slum areas in cities which helps to reduce the rate of crimes, ignorance, the low level of morality, and health and environmental problem.

Acknowledgements

In the name of ***Allah****, the most Gracious, the most Merciful*

Firstly, and most important, thanks to ***Allah*** *for making all this possible,* ***He*** *is truly magnificent.*

Secondly, this work would not have been possible without the support of a number of people; I would like to send my thanks to.

I wish to express my love and gratitude to ***my beloved family*** *for their understanding, endless love, continuous support, encouragement and great sacrifice throughout the years of my study.*

I would like to acknowledge the financial support of ***the Saudi Government.***

I wish to express my gratitude to ***my supervisors*** *who were abundantly helpful and offered invaluable assistance, support and guidance.*

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Abbreviations

BIPV	Building Integrated Photovoltaic
CSP	Concentrated Solar Power
ESC	Electric Saudi Company
GCC	Gulf Cooperation Council
KSA	Kingdom of Saudi Arabia
OPT	Optimal
PV	Photovoltaic
SABIPV	Stand Alone Building Integrated Photovoltaic
SAPV	Stand Alone Photovoltaic
SAR	Saudi Arabian Riyal

Chapter One: Introduction

1.1 Introduction

Several natural resources can be utilized for deriving energy, such as the Sun, wind, water flow, tides, waves and deep heat generated within the earth. This type of energy is known as renewable energy where its sources are replenished constantly on a human timescale and available over wide geographical areas (Johansson & Burnham, 1993). Renewable energy tends to be used for generating electricity and heating. In 2011, renewable energy covered approximately 17% of total energy consumption across the world depending mainly on conventional biomass and hydroelectricity. Other resources, such as solar, wind, geothermal, and bio-fuels present no more than the fifth of the whole contribution of renewable energy in the global energy supply (Nema et al., 2009; Sadorsky, 2009).

Recently, renewable resources, especially extracted from wind and solar have been considerably promoted mainly for environmental concerns, such as climate change mitigation and global warming, coupled with high oil cost and security and economic issues. The crucial need of energy in human development has also been another important motivation driving the rapid progresses in renewable technologies, which results in both large-scale strategic projects able to cover wide urban and rural areas and simple systems suitable for individual buildings. This might help to meet the requirements of the many poorer nations for better levels of prosperity. For more details: (Karekezi & Ranja 1997; Nema et al., 2009; Saffarini et al, 2012)


Fig 1.1: An example of CSP systems


Fig 1.2: An example of PV systems
https://www.google.com/imghp

Solar is regarded as one of the main promising renewable energy resources in which solar radiations including light and heat are converted into electricity, either directly using photovoltaic (PV) or indirectly via Concentrated Solar Power (CSP). In CSP systems, a large area of sunlight is focused into a small beam using lenses or mirrors with the help of sun path tracking systems. This is not the case with PV systems where sunlight is converted into electric current using the photovoltaic impact. Photovoltaic array are an important and suitable solution for generating electrical energy, especially for off-grid constructions and temporary structures where grid power, if available, might be inconvenient or highly expensive to be connected. However, using solar energy is increasing day by day even in grid-connected areas as the cost of solar electricity is limited in installation cost (Kreider & Kreith, 1975; Lewis, 2007; Mills, 2004; Radhi, 2011; Zakharchenko, 2004).

Based on the capturing and converting method, solar technologies can be divided into passive and active solar. Architectural design plays a considerable role in passive solar techniques, where buildings are designed with specific angle to the Sun and spaces for circulating air naturally. The design should also include choosing the suitable materials in terms of thermal mass and light dispersing properties. However, in active solar techniques, photovoltaic panels and solar thermal collectors are used to generate energy (Nema et al., 2009; Taleb & Sharples 2011; Taleb & Pitts, 2009; Tiwari & Sodha, 2006; Santamouris et al., 1994).

Reliance on independent inexhaustible resource, such as solar is expected to have global advantages in increasing energy security of countries, reducing pollution and global warming impact and reducing the expenditure of mitigating climate change. Such advantages, beside the expected huge long-term benefits, make renewable energy technologies, principally wind and solar from the fastest developing sectors. During the last decade, global renewable energy demand grew yearly at rates of 10 to 60% for many technologies. During 2009, growth in wind energy increased significantly compared with the previous period, where wind power demand was considerably more than any other renewable technology. However, grid-connected PV technology had the fastest annual average growth rate among all renewable technologies reaching about 60%. By the end of 2014 and the beginning of 2015, PV systems are expected to exceed those of wind in terms of installed capacity and energy generation (Lewis, 2006; UNEP, 2011; REN21, 2012).

The maintenance expenses for PV systems tend to be neglected and the only required cost is almost that of installation. This helps in the wide spread of the stand-alone photovoltaic power systems (SAPVS), which are independent of the utility grid. These systems can be used alone with solar panels and sometimes integrated with a diesel generator or a wind turbine. SAPVS is able to provide a household or commercial construction with clean and usable renewable energy suitable for electrical needs, such as lighting and operation appliances. There are two types of SAPVS, namely direct-coupled system without batteries and stand-alone system with batteries. SAPVS consists of solar PV panels, an inverter, single or dual axial sunlight trackers, and cables with or without battery.


Fig 1.3: Stand-alone PV system
https://www.google.com/imghp

In direct-coupled system, solar panels are connected directly to a direct current load without storing energy in battery. Therefore, this module is competent of powering common electrical device, such as fans, and water pumps only during the day. In the case of stand-alone photovoltaic power systems, battery banks are usually used to storage the electrical energy produced by the photovoltaic panels when the sunlight is available. The stored energy is used when the demand from the load is more than the solar panel capacity. Moreover, a storage battery helps to provide stable current and voltage by eradicating transients supply surge currents, which are suitable for loads including motors (Taleb & Pitts, 2009; Tiwari & Sodha, 2006; Wai et al., 2008).

Flat solar PV panels have to be mounted to open-sky area with direct sunlight to be able to convert solar energy into direct current electricity. This last, then, is converted via the inverter into alternating current electricity with the required voltage level (240/120V). Monitoring the individual components of SAPVS can help to improve the entire system performance. Monitoring the charge/discharge profiles of battery is regarded as one of the most important checks required for avoiding the system failure. The performance of the system can be affected by several load related problems. Choosing the unsuitable loads to be powered by SAPVS is one of the common problems. Moreover, the system's response is affected by low quality wiring and low efficiency and stand-by loads, which increase energy consumption and waste energy. Capacity load and rated inverter size should also be matched to avoid reducing the overall system efficiency (Huang, 2001; Kreider & Kreith, 1975; Rashid & Press, 2010; Simoes & Farret, 2004).


Fig 1.4: PV panels integrated with building https://www.google.com/imghp

Photovoltaic arrays can be integrated with buildings during the architectural and structural design or mounted on top of the existing roof and walls or on the ground areas surrounding the constructions. Roofs are often the most convenient and suitable place to fix the PV array. The PV array can be fixed above the roof and often parallel to surface with a space of several inches for cooling purpose. With flat roofs, a separate structure with a suitable tilt angle should be used as seen in Figure 1.5. At the meantime, supports of PV frames in new buildings are designed to be mounted after decking the roof and before installing the roofing materials. The roof structure must be checked whether it is able to deal with the additional weight of the PV system.

Roofs are often structurally designed above the limit of their weight-bearing capacity, which is enough for the PV array to be safely mounted and in some cases, additional supporting is required. Another common option for mounting the PV systems is shade structures, such as a terrace cover or deck shade trellis which can support different sizes of PV systems. See Figure 1.5. With tilted shade structure, wind loads should be considered and additional structural supporting might be essential. The average weight of


Fig 1.5: Fixing PV panels on flat roofs https://www.google.com/imghp


Fig 1.6: Using shade structures for mounting PV systems. https://www.google.com/imghp

the PV array is 4 lbs./ft^2, which is frequently within additional design dead loads of shade support structures (Hestnes, 1999; Taleb, & Pitts, 2009; Taleb & Sharples, 2011).

These days, the idea of Building-Integrated Photovoltaic (BIPV) is significantly used in new buildings, either domestic or industrial as a main or additional source of electrical power. In this system, solar panels are designed to have a passive cooling impact on buildings during the day and help to hold accumulated heat in at night. Such positive design helps to reduce the required energy for heating and cooling. This can be attributed to the open gaps between the panels and the roof, which allow air to be circulated.

When integrating PV with buildings, solar PV modules should be considered not only as technical components for providing electricity, but also as resourceful construction materials. Therefore, PV modules should meet the architectural and structural design requirements of buildings. As BIPV techniques are relatively modern, BIPV systems are normally used in urban areas and on-grid applications rather than off-grid micro generation. PV panels in BIPV systems can be installed during and after the actual building phase of construction (Chen et al., 2010; Henemann, 2008; Prasad & Snow, 2005).

Fig 1.7: An example of BIPV system, where PV panels are used in the architectural and structural design. https://www.google.com/imghp

Panels can be assembled into arrays on ground, roof or pole mounting system. In the case of solar parks, panels are often mounted on a large frame fixed on the ground. For buildings with oblique roofs, many different frames have been designed and for flat roofs, racks, bins and building integrated solutions are often used. Solar panel frames can be designed as stationary or moving. The moving racks can move in one-axis, two-axis or multi-axis depending on how the frame is fixed. For the multi-axis movements, the frame has to be mounted on top of pole. In addition to providing shadows, pole mounted panels are open to more cooling air on their underside and permits for better sunlight tracking, which improve the system performance. Also, pole mounting allows adjusting the panels seasonally in vertical direction (up and down), especially for systems not provided with sun tracker. Depending on the technology and efficiency of PV products, most moving PV systems produce in average 7.5 (+/- 2.5) Watts per square foot of array area. This means that nearly 300 square feet of open sky area are required for sitting a typical 2 kW PV system taking into account the required access space (Cheng et al., 2009; Braun & Rüther, 2010; Parida et al., 2011).

Fig 1.8: An example of PV system with two-axis rotating capability. https://www.google.com/imghp

Recently, solar energy has become a widely desired option, especially in land areas, which receive high solar radiation. Modern BIPV technologies are often preferred when designing new building as PV panels can be used for different purpose, such as providing electricity and shadow and as a construction material. The Middle East, especially Gulf region is an ideal geographical area for using solar power as a renewable energy resource, where it has one of the highest solar irradiation rates across the world. Also, domestic buildings in GCC countries are designed with big spaces and extended flat roofs for providing more shadows and allowing the air to be circulated. This is in addition to meeting the requirements of local traditions and customs. Roofs are often exposed fully for sunlight and not utilized throughout the day time due to the high temperature and direct sunlight, which increase the internal heat, especially at top floors. As a consequent, more energy is required for cooling. Such big roofs and the high solar irradiation rate allow for more PV panels to be mounted and for more sunlight to be collected and converted to electricity (Athienitis, 2007; Alnaser et al., 2008; Hestnes, 1999; Kamat, 2007; Marsh, 2008; Raouf, 2008; Taleb & Pitts 2009).

However, PV panels in almost all BIVP systems are designed to be stationary with specific angle. This in general reduces the overall efficiency of the system due to the limited period in which the PV panels are exposed to direct sunlight. Fixing more PV panels with different angles might help to increase the system capacity, but such solution is unpractical and costly. A suggested solution for this problem is to provide BIPV systems with single, dual or multi-axis sunlight tracking system, where the orientation and tilt angle above the horizon have a significant impact on the performance of PV panels. This can be attributed to the fact that the amount of solar energy received by the surface of PV panel is changed depending on both of these parameters (Abdallah & Badran, 2008; Chong & Wong, 2009; Mousazadeh et al., 2009).

According to (Kacira et al., 2004), the amount of power generated with the help of two-axis solar tracking increased by a percentage of 34.6 compared to a fixed PV panel with 14° tilt angle on the same day in July in Turkey. Such improving in the system effectiveness works on reducing the required number of PV panels and as a result decreasing the overall cost and the requisite area. Also, moving the panels can theoretically reduce the thermal impact of the Sunlight, where PV panels during the day prevent the direct sunlight to reach the roof from one side and allow the air to circulate from the other side. However, sunlight tracking sensors are quite expensive and complex and moving number of panels continuously throughout the day needs more energy depending on the size and weight of panels and the flexibility of supports (Abdallah & Nijmeh 2004; Kacira et al., 2004).

To overcome this limitation, BIPV system has been provided with one axis three position sun tracking PV module. With this one axis tracking module, the PV position is adjusted only at three fixed positions with specific angles, namely morning, noon and afternoon. This helps to diminish the power required for orienting the panels and reduce the overall cost. According to (Huang & Sun, 2007), the optimal position in the morning and afternoon is with approximately 50° angle from the solar noon position and 25° is the critical angle for rotating the attitude of the PV panels from position to the other. Contrasting the rotating time, these angles are independent of the latitude. With this simple sunlight tracker, the performance of the system in terms of generating power has increased with nearly 24.5% compared to a fixed PV module (Chang, 2009; Huang & Sun, 2007; Li et al., 2011).

The population in GCC countries is relatively small compared to the geographical areas and inhabitants are distributed generally across huge areas forming small villages and rural communities on significant distances from power supply stations. Saudi Arabia is a clear example, where there is a crisis in supplying enough electricity to large cities and domestic remote area in various parts, especially small villages located on the western's side, middle part, and the north of the country. This problem becomes significant during the summer time due to the high demands for electricity required for air conditioning. Connecting the isolated and remote off-grid areas to the main electricity grid is often challenge and extremely costly and requires frequent repairing. This is in addition to increasing the pollution rates in the area, where more oil and gas will be used. On the other side, the lack of the necessary infrastructure, particularly electricity and the looking forward for better level of prosperity lead people who live in countryside and remote areas usually to immigrate to in-grid areas. This has several short and long-term negative impacts, such as the proliferation of slum neighborhoods, increasing congestions and the steady rise in real estate prices, which have harmful impacts on economic, social and security sides (Alawaji, 2001; Alnaser & Alnaser 2011; Bachellerie, 2012; Hepbasli & Alsuhaibani, 2011).

During the last decade, almost all researches and studies in GCC countries generally and in Saudi Arabia particularly have concentrated on large-scale solar energy projects. Such projects tend to be designed for urban areas to avoid the expected gaps between the growing demand for electricity and supply. This can be seen in chapter two which presents in some parts the most important advances and projects in Gulf region. However, the possibility of using Small-scale solar energy technologies, such as SABIPV systems in GCC countries, especially in Saudi Arabia as a fundamental solution for supplying a wide range of remote and distant and rural with electricity still needs more and more studying and investigating. In this project, using SABIPV technologies with sunlight tracking systems will be investigated as an optimal solution for providing solar energy to a great deal of off-grid areas in Kingdom of Saudi Arabia and the expected long-term impacts of such solution will be studied, such as encouraging the reverse migration from big cities to rural areas and mitigating the pollution impact.

1.2 Aim

This project aims to investigate the possibility of Stand-Alone Building Integrated PV system to be used as an optimal solution for providing a wide range of remote villages and rural communities in Saudi Arabia with solar energy. This study will also address the expected short and long-term advantages and impacts of such solution on some important sides, such as those of economy, environment and social.

1.3 Objectives

1- Investigating the reasons behind the crisis in supplying electricity to domestic remote and rural off-grid areas in Saudi Arabia and highlighting the limitations of the current in use solutions and the alternative suggested solutions.

2- Choosing one of the remote villages in Saudi Arabia as a study case and collecting, presenting, and analyzing the most important factors that affect and help to design SABIPV systems.

3- Designing SABIPV system for one of the houses in the chosen village using the collected data in objective two.

4- Investigating whether the designed system is cost-effective and can provide the village with the required level of electricity services

5- Studying the expected short and long-term impact of such system on some important sides, such as economy, environment, and social

1.4 Methodologies

In order to fulfill the objectives mentioned above, the next methodologies will be followed:

1- **Objectives One and Two**: to inspect the size of crisis in supplying electricity to domestic remote and rural off-grid areas in Saudi Arabia and looking into the main reasons and the suggested solutions, official existing statistics and studies carried out by the Saudi Electric Companies and NASA website are planned to be adopted in this project. Direct interviews will also be adopted for collecting some specific data which might not be available in the accessible documentations.

2- **Objective Three:** Designing the SABIPV system for the chosen house will include studying: the average solar radiation received in the area, declination angle, hour angle, solar altitude, solar azimuth, the Sun path at that latitude, projection impact, relationship between the solar radiation and the solar angle of incidence, calculate installed power to fulfill load, calculate number of modules, calculating the distances between panels to avoid the self-shading impact and define system elements, such as battery, charge regulator and inverter.

3- **Objective Four**: Comparing the expected energy generated by the designed system with that required in the chosen area and comparing the cost of this solution with the expected cost of linking the area to the main grid.

4- **Objective Five:** investigating whether the crisis in supplying electricity is one of the main players behind the countryside-to-city migration and the impact of providing electricity to remote rural areas on the reverse migration. Also, the environmental impact of using solar energy for the whole remote areas in Saudi Arabia will be investigated by calculating the expected pollution rate results from supplying the same areas with fuel based conventional electricity.

1.5 Contributions to Knowledge

Although using solar energy in the GCC countries goes back to the beginning of the seventies of the last century, the efforts for using this great energy resource in commercially viable projects have been scattered and almost unnoticed and the main researches and investments, particularly in Saudi Arabia have concentrated on large-scale projects. Such strategic projects were still driven by the governments of these states to avoid the expected gaps in urban areas between the growing demand for electricity and supply. Meanwhile, wide range of remote areas still suffers from a severe shortage of power supply due to: the prohibitive cost of connecting such distant areas to the main electric grids, the financial returns futile and the difficulty and high cost of maintenance works. In addition to these reasonable reasons, increasing the dependency on oil and gas increase the pollution rates in the area. Instead, the lack of the necessary infrastructure, particularly electricity and the looking forward for better level of prosperity encourage the phenomenon of countryside-to-city immigrate. In addition to increasing congestions and the steady rise in real estate prices, this type of immigration usually leads to the proliferation of slums. These impacts have harmful impacts on economic, social and security sides.

The possibility of using Small-scale solar energy technologies, such as SABIPV in GCC countries, especially in Saudi Arabia as a fundamental solution for supplying a wide range of remote, distant and rural areas with electricity and overcoming the problems mentioned above still needs more and more studying and investigating. The contribution of this project to knowledge is to provide a clear prospect and reliable investigation into the potential of using SABIPV technologies as an optimal solution for providing a great deal of remote villages and rural communities in Saudi Arabia with solar energy. The study will also present the expected long-term impacts of solar energy on some important issues, especially those of countryside-to-city migration and pollution.

1.6 Thesis Structure

This thesis consists of eight chapters which have been organized as followed:

Chapter One: includes a brief introduction presenting the main features of the project. This is followed by: the aim, objectives and methodologies which have been organized for each objective to have a specific point in the methodologies.

Chapter Two: includes a literature review presenting the history and the most important advances in the general area of renewable energy, solar energy technologies, SABIPV systems and sunlight tracking sensors, especially in GCC countries and in Saudi Arabia.

Chapter Three: shows the mathematical and theoretical concept behind the methods and ideas used in this project. This will include generating solar energy via PV panels, one axis, dual axis, multi-axis one axis-three positions sunlight tracking devices, solar radiation, declination angle, hour angle, solar altitude, solar azimuth, the Sun path related to latitude, projection impact, solar angle of incidence, system sizing, self-shading panel impact, energy storing battery, charge regulator and inverter.

Chapter Four: this chapter covers the research and collected data methods used in this project.

Chapter Five: this chapter covers the first and second objectives highlighting the size of crisis in supplying electricity to domestic isolated and countryside off-grid areas in Saudi Arabia and explaining the main causes and the possible solutions. The alternative solutions suggested for providing electricity services to these rural communities will be discussed showing the advantages and limitations.

Chapter Six: this chapter covers objective three and four identifying the study area in terms of geographical location, population and the average loads required throughout the year from the official sources or field study. The chapter will also comprise designing SABIPV system. Important related points will be discussed in details throughout this chapter, such as the average solar irradiation of the chosen area, declination and hour angle, solar altitude and azimuth, the Sun path at the latitude of the study area, the impact of sunlight projection, the impact of solar angle of incidence on solar radiation, calculate number of PV panels, studying the impact of self-shading panels on the system performance, and define system elements, such as battery, charge controller and inverter. Then, the predictable energy generated by the suggested system and that required in the study area will be compared taking into account the overall cost of the system.

Chapter Seven: This chapter covers the last objective for investigating the expected impact of using solar energy in remote areas on some important issues related to economy, environment, and social.

Chapter Eight: This chapter presents the conclusions of the whole project, recommendations and future works.

Chapter Two: Literature and Critical Review

2.1 Introduction

Before starting using oil in the middle of the 20th century, almost all energy sources used by human bean were renewable, taking in general the form of conventional biomass and fuel fires. The historical records show that the most important sources of conventional renewable power have been human effort, animal, water flow, wind, firewood, and a traditional biomass (Johansson & Burnham, 1993).

Wind is regarded as the second renewable resource used, where it is employed for driving ships over water as traced back 7000 years ago from the old Egyptian ruins. In addition to that, wind has been used for powering some machines, such as those of grounding grain and pumping water thousands years ago. With the electric power development, wind power is still used for supplying buildings with lighting, especially those remote from the main electrical grid. During the previous century, small wind energy systems appropriate with farms or houses have been developed hand in hand with strategic-scale wind generators, which can be connected to electricity grids for remote use of power paths. At present, generators powered by wind function in huge size range starting from tiny system for charging batteries and up to wind stations, which supply electricity to countrywide electrical networks (Johansson & Burnham, 1993; Nelson, 2013; Wind turbine, 2014).

Fig 2.1: Wind energy turbine (Wind turbine, 2014)

2.2 Solar Energy

As for history of solar energy, the most significant advances in this area will be mentioned briefly in this chapter and the reader is referred to (Johansson & Burnham, 1993; Meinel, 2008; Sieferle, 2001; Smith, 2005; Timeline of solar cells, 2014) for more details.

At the beginning of the seventeenths of the 18th century, using solar energy started to be encouraged driving by serious concerns of coal running out. This supporting of solar energy continued for nearly 30 years and then stopped due to the First World War. Throughout the seventeenths of the last century, environmentalists encouraged progressing renewable energy for avoiding the expected impact of using oil and for security issues related to oil-dependence. The world’s first solar collector was created in 1767 by Swiss scientist, Horace de Saussure and this design was used by John Herschel for cooking food after nearly 60 years. In 1816, Robert Stirling built heat engine using concentrated thermal energy of the Sun for producing power. After 23 years, in 1839, the photovoltaic impact was discovered by Edmond Becquerel while testing the impact of light on an electrolytic cell and he built the first photovoltaic cell across the world.

During the period between 1860 and 1880, August Mouchet and Abel Pifre designed solar-powered steam engines and built up the first solar based engines, which became the base of recent parabolic dish collectors. Adams and Day found out in 1876 that selenium is affected when exposed to light giving electricity and solar cells made by selenium failed to change adequate sunlight to power electrical devices. On the other hand, they demonstrated that change light into electricity via solid materials is possible without heat or moving parts.

2.3 Photovoltaic Cell

In 1883, Charles Fritts built up the first solid state photovoltaic cell via covering the semiconductor selenium with an extremely skinny golden coating to form the junctions which provided nearly 1% efficient. In the mid of last century at Bell Laboratories, Dary Chapin, Calvin Souther Fuller and Gerald Pearson built up the first functional photovoltaic cell using diffused silicon which provided 6% efficiency. During the followed decade, Hoffman improved the efficiency of solar cells from to reach 14%.

Due to the significant increase in the efficiency made by Hoffman Electronics, solar cells were used in the Vanguard I satellite which was launched in 1958. This helped to extend the task time. After one year, the U.S.A launched Explorer 6 with winged large solar arrays, which consisted of 9600 solar cells similar to those improved by Hoffman (Explorer 6, 2014).

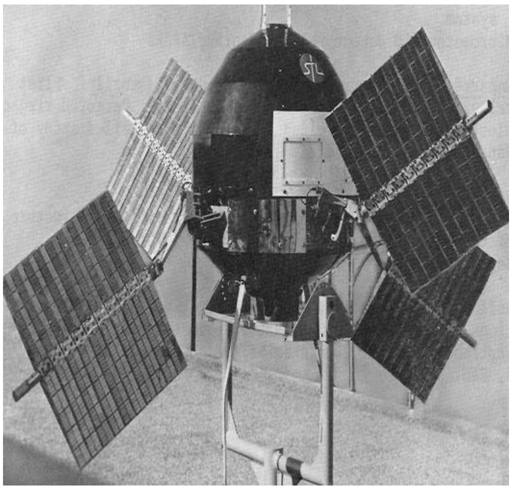


Fig 2.2: Explorer 6 with solar arrays (Explorer 6, 2014).

Over the next two decades, progress in this area was relatively slow and concentrated on space applications as their power-to-weight ratio was better than other power generated technology. During this improving, increasing the efficiency the solar system was the only concern in space applications due to the huge budget of such projects and this led to slow progress in terms of providing lower-cost solutions.

2.4 PV and Building Integrated PV Systems

Throughout the seventeenths of the 19th century, the U.S. Department of Energy (DOE) including collaborations with industry started supporting projects to develop distributed photovoltaic systems and integrate photovoltaic panels with building materials.

During the next decade, PV shingle prototypes have been developed in several companies, such as General Electric and Sanyo, but technical challenges and high costs were the main reasons behind slowing the commercialization of such models. With increasing the efficiency and reliability of PV technologies during the followed years, PV devices started to be integrated with building materials, especially when initiating Building Opportunities program for PV in the U.S.A and similar programs in Europe and Japan, which helped to commercialize innovative Building Integrated PV systems.

During the 1980s, BIPV was considered as a niche product compared to frame-based PV modules. This can be attributed to the fact that BIPV has been used commonly for showcasing solar applications in sustainable building designs. According to Arthur D. Little 1995, homes with BIPV was built as a first time in U.S.A in 1980 and then systems started to be integrated and used on commercial structures. In 2010, huge BIPV systems have been installed on the Hongqiao Railway Station in China, which can provide 6.5-MW.

BIPV systems are simply common PV system design integrated with installation methods. These days, BIPV designs are substantially customized for specific buildings and architectural designs and BIPV products are lower-costs, better performance and more flexible to be integrated with many common building materials. For more details, the reader is referred to (Benemann et al., 2001; Hestnes, 1999; James et al., 2011; Taleb & Pitts, 2009; Taleb & Sharples, 2011).

In general, the worldwide deployment of BIPV systems cannot be compared with that of stand-alone PV systems. According to (EuPD Research, 2009; James et al., 2011, Mints and Donnelly, 2011; Pike Research, 2010), the whole global installed capacity of BIPV systems was 250–300 MW by the end of 2009, which is nearly 1% of that of stand-alone frame mounted PV systems. This can be attributed to some architectural design concerns and the relatively high-cost of BIPV compared to frame-mounted PV systems.

2.5 Sunlight Tracking System

The history of solar tracker as an element of BIPV and stand-alone PV systems will be also introduced briefly in this chapter and for more details, the reader is referred to (Abdallah & Badran, 2008), (Abdallah & Nijmeh, 2004), (Chang, 2009), (Cheng et al., 2009), (Chong et al., 2009), (Huang & Sun 2007), (Kalogirou,1996), (Li et al., 2011), (Mousazadeh et al., 2009) and (Rothet al., 2005).

Solar tracking can be returned back to the sixteenths of the 20th century when Steve Baer built his first passive tracker in 1968 and this product was manufactured commercially after a few years. Then, non-motorized pole-top tracker, which shifts PV panels in the direction of the Sun has been manufactured using refrigerant and aluminum channel reflectors. During the 1980s, closed loop optically controlled solar trackers were produced and they are still in use today. In 1983, on the Carrizo Plains in California, the first large-scale sunlight trackers were built. For the duration of the early 1990s, designs of sunlight tracker required the standardization, reliability and, the cost structure to be put into large scale operation.

At the same period, in the U.S.A, one of the main US-based systems integrator at the time, which is Power Light Corporation, with the help of a small engineering firm, called Shingleton Design manufactured the Single-Axis Max Tracker. This innovative single-axis tracker is provided with one economic motor to rotate PV modules.


Fig 2.3: An example of single-axis sunlight tracker (T0 design)

This design Power is generally regarded as the foundation and basic of all large-scale single-axis tracker products. The latest revision of this tracker was designed by Sun Power and introduced in 2006. This design, named T0 and shown in Figure 2.3 is solar powered and considered as one of the most widely used single-axis PV tracker system across the world. This design was improved recently giving a tilted single-axis tracker system with a 20° tilt angle.

As the performance of the solar PV system improves significantly with solar trackers and because installed solar capacity amplified yearly between 2003 and 2008, several global companies, such as German FIT started the global solar business and the PV tracker manufacturing. Currently, there are more than 100 manufacturers provide trackers to the global market both passive or active according to motive method and single or dual based on the number of axes.

Active trackers are more accurate than passive trackers, where the first use motors as shown in Figure 2.4 to rotate PV panels from horizon to horizon, whereas the second utilize the heating and cooling of “refrigerant-like liquid” elements and reflective mirrors to slope the tracking panels in the direction of the Sun. Figure 2.5 shows an example of passive tracker with hydraulic dampers (dark blue elements). “The tracker head in Spring/Summer tilt position with panels on frame rotated to morning position against stop”. (Solar tracker, 2014).


Fig 2.4: Slowing drive for active multi-axis sunlight trackers


Fig 2.5: An example of passive sunlight tracker (Solar tracker, 2014)

However, in the case of flat-plate PV arrays, accuracy is less important than it is for concentrating solar technologies as flat panels generate energy via global horizontal irradiance which is “the sum of both direct normal irradiance and diffuse horizontal irradiance”. The other explanation between tracker types is the number of rotating axes. Simply, single-axis trackers track the Sun via one rotation axis, whereas dual-axis trackers track the Sun moving around two axes.


Fig 2.6: An example of passive sunlight tracker (Solar tracker, 2014)

PV trackers provided with a single rotation axis are globally the most usable sunlight trackers. In the U.S.A, Sun Power Company has used single-axis trackers when building up several huge PV systems, such as solar generation system at the DeSoto Energy Center, Nellis Air Force Base in Nevada and the lately commissioned Greater Sandhill Solar Farm in Mosca, Colorado. The types of single-axis tracker are classified based on the relationship of the rotation axis relative to the ground to three main categories, which are horizontal, vertical and tilted.

Tracking the azimuth and elevation of the Sun towards east-to-west direction keeps on a more steady and accurate angle of incidence between the PV panel and the Sun. This can provide better performance compared to fixed-tilt or single-axis sunlight trackers, which is suitable for several applications of flat PV panels. In the case when the PV technology depends completely on direct normal irradiance as the fuel source, fixed-tilt or single-axis sunlight trackers cannot be used and dual-axis tracking is necessary.

An example of low concentration PV technology suitable for single-axis tracking is that developed by Solaria. A clear example of concentrated PV designs, which require accurate dual axis sunlight tracking to keep constant power output is the technology established by Amonix (Abdallah & Nijmeh, 2004; Roth et al., 2005).

Fig 2.7: Dual axis sunlight tracker (Solar tracker, 2014)


Fig 2.8: One axis three positions sunlight tracker, Huang & Sun, 2007.

A new sunlight tracking design for PV module, called one-axis three-position tracker was proposed and discussed recently in (Huang & Sun, 2007; Huang et al., 2011). The mechanism of this tracker is to rotate the PV position only at three specific angles: morning, noon and afternoon. This one-axis three-position sun tracking PV system is a low cost simple structured module. Tests show that the most advantageous stopping angle in the morning and afternoon is approximately (+\-) 50 from the vertical solar noon position and the best possible changing angle from position to the other is +\- 25. These angles are independent of the latitude.

Experiments proved that the performance of the system increased by nearly 24.5% as compared to a fixed-angle PV module and when using low concentration (2X) reflectors with one-axis three-position tracking PV, the total improving in power generation is about 56%. In terms of price, evaluation shows that the cost reduced by 25% in average as compared to the flat plate PV modules available in markets (Huang et al., 2011).

2.6 GCC Countries and Solar Energy

Moving to highlight the current situation of solar energy in Gulf Cooperative Council (GCC) countries, the energy needs are increasing more and more, particularly in the GCC area, where since 2005, huge expansion projects are carried out to avoid the risks of the main dependency on hydrocarbons based economy. Hydrocarbons during the last decades supported the economy of the majority of these countries by feeding the increasing needs of industrialization and civilization when combined with growth across the GCC countries. There are many reasons can motivate the GCC countries to take a significant role in the development of solar energy sector, such as the appropriate geographic and climatic features, where the region has the largest potentials across the world for generating solar energy. Also, this clean energy will help to reduce impact of the climate change as well as greenhouse gases, where many of these countries are regarded as among those emitting the highest amount of greenhouse gases in the world relative to the number of population (Abi-Aad, 2009; Solar energy in GCC construction, 2012).

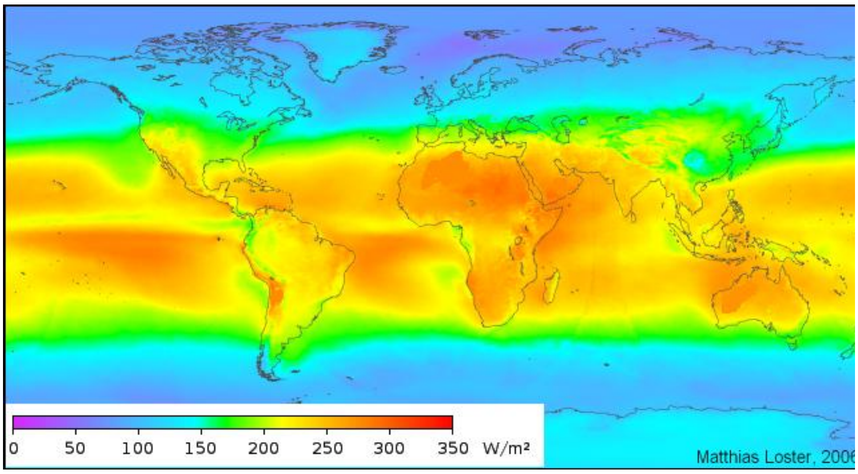


Fig 2.9: Worldwide solar radiation (Solar energy, 2014)

Moreover, solar energy can help to reduce the rapid rise of pollution levels in the area, which has currently the second highest rate of air pollution in the world. Using solar energy can also reduce the cost of oil and gas used in the local electricity supply and the saved cost can be used in more profitable fields, such as those of education and medicine. This is in addition to providing more jobs, as the oil and gas sector, which produces 47% of the total domestic product in the GCC provides just 1% of the jobs in the area. This can help in booming the local economy (Alnaser & Alnaser 2009; Bachellerie, 2012).

For countries, such as Saudi Arabia, UAE, and Qatar, solar energy are given a high priority on the current and near future plan, where investment in solar energy sector is expected to fill in the gaps between energy demand and supply. On the other hand, Kuwait does not have so clear policy on including nuclear energy into their energy mix, especially after Japan nuclear disaster. The development of renewable energy and its strategic framework is still at a nascent step in the majority of GCC countries, regional alliances are expected to be an aim in near future and plans to improve this sector are probable to be under focusing throughout the next two decades for optimize solar energy as an important energy source for the GCC countries (Doukas et al., 2006; Solar energy in GCC construction, 2012).

The two main sources of generating solar power, namely: Concentrated Solar Power (CSP) and Photovoltaic Solar Power (PVSP) have a great potential in the GCC area and can be commercially used. The GCC construction industry is regarded as one of the most growing investment sectors accompanied by the worldwide economic slowdown. Furthermore, maturity of this construction industry has helped to establish standard international construction industry with revolutionary technologies across sustainable construction ways. The extensive growth and diversification plans with the wide supporting of the governments helps in keeping the industry successful (Alnaser et al, 2009).

However, the industry faced unstable periods after a fast and enthusiastic successfulness between 2007 and 2009. The sudden increase ended quickly affected by the international economic slowdown, which led this sector to move slowly by the end of 2009. When this sector started growing up again, solar energy, which is the most important renewable energy resource in the region returned back to be under focusing due to the huge expected benefits and to meet the high standards of sustainable construction of the construction industry in the GCC countries (Bachellerie, 2012; Solar energy in GCC construction, 2012).

Green building policy indicates a number of requirements to enhance the design and overall performance of existing as well as new constructions while reducing their environmental impact and cost and each requirement is given a weight or individual rate, which helps the construction achieve the required green building certifications from area to another. An example of such policies is LEED or USABC ratings which extensively support using solar energy in the GCC construction industry.

Bahrain as one of the GCC continues is regarded as the least energy efficient in terms of GCC building construction. Furthermore, huge savings for Building-Integrated Photovoltaic (BIPV) in construction designs and high insulation rates have been recorded in this country. Also, PV panels installed on roofs or structure of buildings are expected to allow for nearly 30% of electricity to be generated from BIPV alone. However, away from the Trade Centre in Bahrain, which does not exactly follow the global standards of renewable energy, compliance standards has been one of the few constructions that adopted solar energy as an important resource for supplying electricity (Farhat et al., 2013).

Kuwait is another example of Gulf States, which has the largest solar irradiation levels in the area. This provides great capability for adopting PV and CSP solar technologies. After meeting the electricity requirements of individual residential homes, using BIPV systems in Kuwait is expected to provide nearly 25 MWh per year of electricity. Using solar energy in Kuwait returned back to 1984 when the Kuwait English School was the first building in the Middle East provided with BIPV panels for generating electricity (Alotaibi, 2011) and (Farhat et al., 2013).

Although excited solar projects applied in Kuwait, such as solar cooling for the Ministry of Kuwait Building and providing agricultural green houses with PV systems, interest in solar energy in Kuwait construction has been insignificant due to practical and economic capability issues. In the mid of 2000s, Kuwait's First Gold LEED rated building the Sabah Al Ahmed Financial Center adopted considerable solar energy usage in its building design.

Currently, projects designed with BIPV systems are significantly encouraged by Kuwait’s government. Examples of such solar energy based buildings are those of the Ministry of Electricity and Water and a new airport terminal provided with solar panels and BIPV technology (Solar energy in GCC construction, 2012).

Oman, in the south of Gulf region, has also a high capability for utilizing solar energy across buildings. One of the main oil companies in this country, PDO, helps to improve the solar technologies as it plans to use steam generated by solar technologies, such as CSP for enhancing oil recovery. Also, Oman’s government has supported individual solar pilot projects to reduce the main dependence on gas (Al-Badi et al., 2009; Bachellerie, 2012),

Qatar, the small peninsula in Arabian Gulf, is similar to the other countries in the area in terms of high irradiation levels and great potential to utilize both CSP and PV solar technologies. Generally, the cost of solar energy in GCC area is higher than traditional technologies, such as gas turbines where these countries are classified from the main global supplier of oil and gas.

Fig 2.10: Qatar World Club 2022 stadium with PV panelshttps://www.google.com/imghp

However, this has not deterred Qatar from adopting solar energy as an alternative energy resource and using a green construction designs and modern technologies in wide range of projects. An example of these projects is using pioneering technologies, such as the artificial cloud with solar panels to convert solar radiation into energy for cooling stadiums additionally with protecting players from the direct harsh sun rays (Doukas, 2006; Solar energy in GCC construction, 2012).

Furthermore, it also has a committed Qatar Solar Technology manufacturing facility to commercially manufacture solar technologies for PV panels and solar systems, which will help to decrease the cost of adopting solar energy. Plans to create solar power in Qatar have been included in the international strategy but projects are still at the nascent step. The World Cup 2022, which is planned to take place in Qatar, has provided a great opportunity to commercially evaluate using solar technologies for air conditioning and cooling of stadiums and other similar huge structures (Doukas, 2006).

The United Arab Emirates (UAE) has one of the highest CO^2 emission rate in the area. UAE as the other countries needs to verify its energy resources instead of the main dependency on hydrocarbon. UAE’s government chose the solar energy as the optimal solution for these issues as well as for reducing its carbon impact. Solar energy is huge in UAE, where it is located along the region’s solar belt with large irradiation rates. This helps to establish a number of huge solar power based projects across the country (Bachellerie, 2012).

One of these projects is the first carbon neutral city, MASDAR, in which a number of high-tech renewable energy technologies have been used depending mainly on solar power. Solar cooling is another area supported significantly by the UAE's government with technical supporting from international institutions to develop solar based cooling technologies. In addition to that, a number of solar based projects have been designed on different scales and carried out or planned in the big cities of the UAE, namely Abu Dhabi, Dubai, Ras al Khaimah and Fujairah. In 2012, 68% of the GCC's installed solar capacity was in these cities at 115 MW (Farhat 2013).

Fig 2.11: Examples of the solar energy projects (PV & CSP) in MASDAR City (UAE)
https://www.google.com/imghp

Moreover, BIPV technologies are considered as a promising sector is the UAE, especially with its huge and growing construction boom and the rapid expansion in the construction field. However, with the exception of MASDAR city in Abu Dhabi and the pacific control systems headquarters in Dubai, using BIPV technologies are still limited and the general efforts to exploit solar energy are still under the expected level (Chen, 2010; Hamdan, 2011; Patlitzianas 2006; Solar energy in GCC construction, 2012).

Solar energy has been adopted for lighting and air conditioning in the pacific control systems headquarters, which is a USGBC LEED certified platinum rated green building. In the case of MASDAR city, all buildings are planned to have stand-alone PV solar panels, which are expected to cover more than 30% and 75% of the required electricity percent and water heating, respectively. The rest is planned to be provided by a solar PV station of 10 MW capacity connected to the grid of UAE’s capital (Bachellerie, 2012; Solar energy in GCC construction, 2012).

2.7 Solar Energy in Saudi Arabia

Saudi Arabia, the largest country in the Gulf region has huge potentials for exploiting solar energy with both CSP and PV technologies. This is in addition to the country’s long coasts, which are ideal for CSP solar energy to be used for producing power and water desalination plants. Saudi Arabia can be divided into four main physiographic areas with relatively cloudless for the most part of the year.

The first area is the western mountains with an average height of 1.5 km above the sea level. The second region is the central hills with very hot and dry summers and dry and cold winters. The desert is the third, which covers vast areas across the country with temperatures of nearly 50s ^{o}C in summers. The coastal areas (2230 km) is the last, which are located on the Red Sea and the Arabian Gulf and have hot summer with high humidity and warm winters (Bachellerie, 2012; Hepbasli & Alsuhaibani, 2011).

Saudi Arabia as the other Gulf countries is rich in renewable resources as it is rich with hydrocarbons. In addition to the significant wind resources, geothermal and biomass from urban waste, Saudi Arabia benefits from strong regular sunshine and has vast empty areas suitable for developing huge solar power plants. Saudi Arabia has seen express economic growth and has become one of the major energy consumers in the Middle East, where electricity consumption is increasing annually by nearly 4%. This means that generating capacity should be amplified twice every 10 years. Electricity generated from renewable resources, especially solar energy means that more oil and gas will be exported as domestic consumption in terms of hydrocarbons will be reduced.

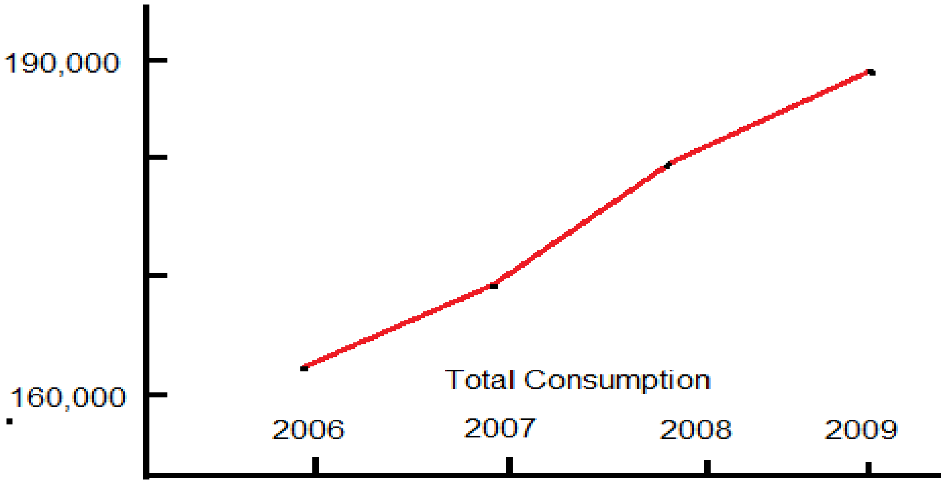


Fig 2.12: Total consumption electricity in Saudi Arabia (Bachellerie, 2012)

In 2005, the Saudi population reached about 23 million and electricity consumption of nearly 7 kWh per capital. This last increased annually by 6.2% during the period from 2005 to 2008 meanwhile population grew yearly by 2.2% during the same period. In accordance with the Ministry of Water and Electricity in Saudi Arabia, the residential sector consumed around 53% of the entirety electricity generated in 2007 and 80% of this value is consumed for residential air conditioning due to the harsh climate conditions and design of buildings which is usually far from being energy-efficient (Solar energy in GCC construction, 2012; Taleb & Sharples, 2006).

The rest of the whole electricity produced in 2007 was distributed between industrial sector, government and the commercial sectors as 18%, 11.7% and 11.4%, respectively. On the other hand, during the period of 2004 to 2007, the commercial sector was found as the most rapidly growing area in terms of consuming electricity with annually increasing of 12 %. This is followed by households, government, and industry with yearly growing of 7.5%, 6%, and 2.4% in this order (Bachellerie, 2012).

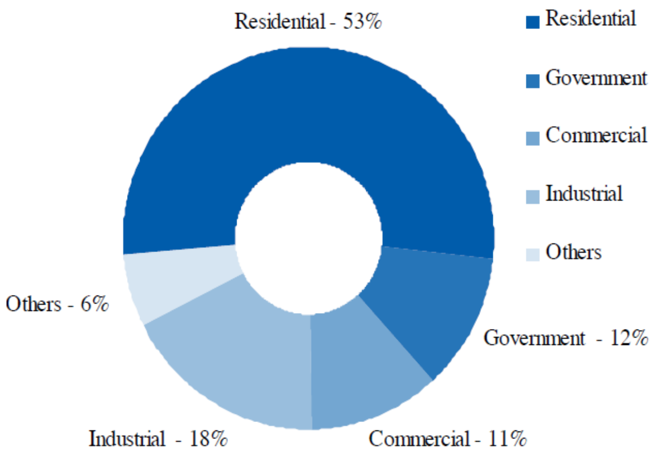


Fig 2.13: Electricity consumption in Saudi Arabia in 2007(Bachellerie, 2012)

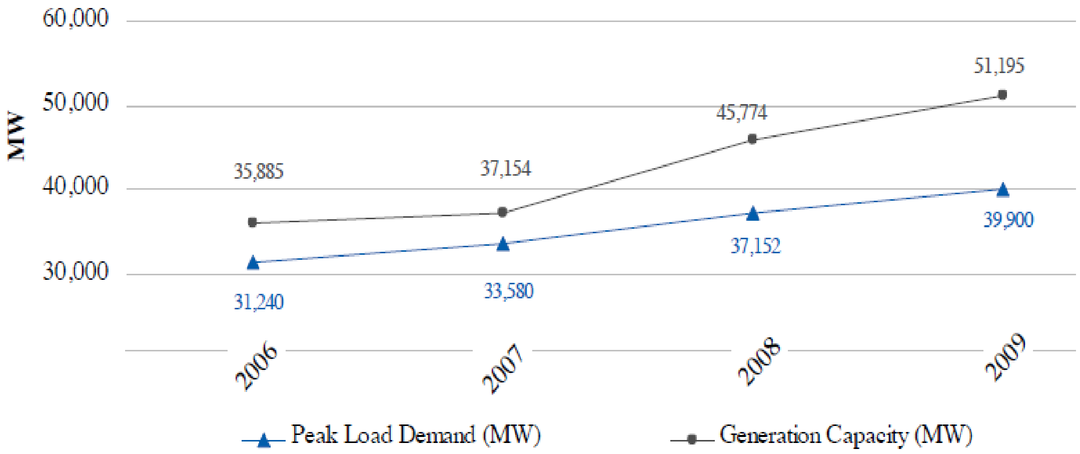


Fig 2.14: Electricity consumption and peak load in Saudi Arabia (Bachellerie, 2012)

In general, the whole electricity consumption increased significantly during the last few years reaching about 193.5 GWh/year in 2009. In Saudi Arabia, electricity capacity and peak load have raised hand in hand over the last years with a reserve margin of 15% in average. However, decommissioning of 5 GW is expected by the end of 2015 if the peak load continues with the current growing rate.

Based on that, huge investments have been adopted by Saudi Arabia's governments throughout the last a few decades in solar technologies. This includes research and development programmers for developing the local solar energy sector and meeting the country's growing demand for power and water in recent years. Such huge demand is extremely difficult to be met via hydrocarbon fuels without reducing exportable surplus.

Solar energy is also expected to help Gulf countries in general and Saudi Arabia specifically for reducing CO_2 emissions, where the six GCC countries, namely Saudi Arabia, UAE, Qatar, Kuwait, Oman and Bahrain are in the top 14 per capita emitters of carbon dioxide across the world. This can also be supported by the fact that generating electricity via solar energy, especially in areas with high solar irradiation, such as GCC region becomes more commercial with time, where the efficiency of solar energy systems tend to be significant (Solar energy in GCC construction, 2012; Taleb & Sharples, 2006).

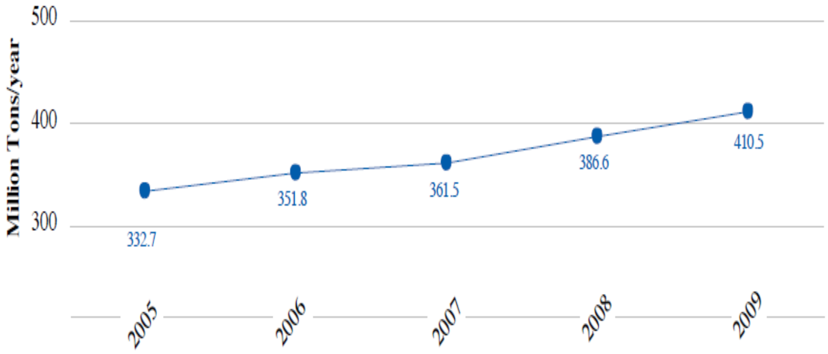


Fig 2.15: CO^2 emissions in Saudi Arabia (Bachellerie, 2012).

Also, the cost of the system itself drops dramatically due to improving technology and growing competition. Furthermore, solar power generation is naturally matched with demand patterns throughout the year where in summers air conditioning dominates the electricity demand curve, particularly in GCC countries (Alnaser & Alnaser, 2011, Doukas et al, 2006).

Producing commercially viable and low-cost solar power technology has been a common aim between the country’s governments and a number of private institutions, which led the solar energy research projects in Saudi Arabia. Power generation via PV technologies is considered as one of active and hot research areas in this country. These researches have two main objectives, namely allowing the expansion in this industrial sector to be large commercialization in near future and meeting climatic and geographical conditions.

Several factors, such as the availability of financial resources, low cost energy, and considerable demand potential help Saudi Arabia to be an attractive market for both CSP and upstream PV manufacturing activities. One of the most promising activities is to industrialize silicon ingots and wafers to meet the requirements of the region’s solar technology markets (Bachellerie, 2012; Solar energy in GCC construction, 2012; Taleb & Sharples, 2006).

For the industrial solar sector in Saudi Arabia and generally in GCC countries, 2013 was an optimistic year, where several big projects were opened or became operational, such as Shams 1 plant in Abu Dhabi and Dubai's first solar power plant. Also, Kuwait and Oman made a decision to build up their first solar power plants.

Currently, several local and natural companies, such as Mutajadedah Energy Co, Chemical Development Co Incorporated, and KCC Corp are working in poly-silicon technology project along the Gulf coast in Saudi Arabia, which is planned to provide 3350 metric tons of solar grade poly-silicon annually by the end of 2014. The annual capacity of the project is planned to be increased to 12000 metric tons by 2017. Also, Manufacturing of ingots and wafers is another near future aim of this project. Saudi's solar goals appear to be the most competitive in the region, where the government plans for solar energy to form one-third of the whole electricity demand by 2032. Additionally, new studies in Saudi Arabia found the cost of solar generated electricity had become as cheap as that generated via oil and gas (Bachellerie, 2012).

2.8 Chapter Conclusion

Although GCC countries have been undertaking solar energy projects for more than 3 decades and despite the wide planes for considering solar energy as an important energy resource in these states generally and in Saudi Arabia particularly, the efforts for using this great energy resource in commercially viable projects have been scattered and almost unnoticed. Also, more reliable and independent investigations and studies into the potentials of using solar energy technologies both PV and CSP to cover the expected decommissioning in electricity supplying are required.

This project aims to investigate whether the Stand-Alone Building-Integrated PV system can be used as an optimal solution for providing a wide range of remote villages and rural communities in Saudi Arabia with solar energy. This study will also address the expected long-term advantages of such solution on some economic, environmental and social sides, such as encouraging the reverse migration from big cities to rural areas, and mitigating the pollution impact.

This is planned to include studying the reasons behind and the best possible solutions for the crisis in supplying electricity to off-grid areas in Saudi Arabia and choosing a remote village as a study case to determine the average of electricity demand throughout the year. Based on the village required demand, SABIPV system will be designed taking into consideration all the technical and geographical issues.

Then, the cost of the designed system will be compared with that of the suggested alternative solutions to investigate whether the solar system is a cost-effective solution.

Finally, limited surveys will be carried out to investigate: whether the crisis in supplying electricity is one of the main players behind the countryside-to-city migration and the impact of providing electricity to remote and rural areas on the reverse migration and prices of properties. Also, the environmental impact of using solar energy for the whole remote areas in Saudi Arabia will be assessed by calculating the expected pollution rate resulted from supplying the same areas with hydrocarbons based electricity.

Chapter Three: Fundamental Theory

3.1 Introduction

After providing the reader with literature review about using SABIPV systems in GCC countries, especially in Saudi Arabia, the mathematical and theoretical concept behind the methods and ideas used in this project will be briefly described in this chapter. This will include photovoltaic impact, generating solar energy via PV panels, sunlight tracking devices, self-shading panel impact, solar radiation, and system sizing. The reader will be referred to the main sources for more details.

3.2 Fundamental Theory

3.2.1 Photovoltaic Impact

The reader is referred for more information about this section to: (Albrecht, 1975; Jager-Waldau, 2004; Tauc, 1962, Tang & Moubah et. al., 2012, Wang, et. al., 2007). The photovoltaic impact can be defined as the creation of voltage or electric current in a material when exposure to light. The photovoltaic and photoelectric impacts are directly related, despite the fact that they are different processes. When the surface of material faces light, such as the sunlight, the electrons existing in the valence band absorb the light energy. This energy leads the electrons to be excited and jump to the conduction band and by the end of the procedure, the electrons become free. These exceedingly active and non-thermal electrons diffuse reaching sometimes a point where they are accelerated into a different material by a built-in Galvani potential. This helps to create an electromotive force and as a consequence, a part of the received light energy is converted into electric energy. The photovoltaic impact can also result from absorbing two photons simultaneously which is called two-photon photovoltaic impact.

However, in the photoelectric impact, electrons are ejected from the surface of material into vacuum, when receiving light. These ejected electrons are finally captured on another electrode which helps to generate some electric energy. The main difference between photovoltaic impact and the photoelectric impact is that the excited electrons in the first pass directly from one material to another, avoiding the difficulty of passing through the vacuum in between as in the case of the second impact.

In addition to generating electric energy via the direct excitation of free electrons, a photovoltaic impact can also occur simply because of the heating resulting from absorbing the light. The heating increases the temperature of material, which is accompanied by temperature gradients. These thermal gradients in turn tend to create a voltage through what is known as the Seebeck impact. However, the photovoltaic impact even with direct excitation or thermal impacts depends on many material parameters.

In most photovoltaic applications, the received radiation is the sunlight, and receiver is solar cells. When these last receiving the sunlight, an electric current is generated as highly active electrons and the remaining holes are swept in various directions by the built-in electric field of the depletion region. The built-in field exerts a force on free electrons, efficiently tilting the electron states and forcing the active free electrons into an external electrical load where their excess energy can be degenerated. The external load can be a simple resistor or it can be any of a numerous of electrical or electronic devices

In photovoltaic impact, two dissimilar materials in close contact create an electrical voltage when facing light or other radiant energy. When materials, in which electrons are usually not free to move from atom to atom within the crystal, such as silicon or germanium facing light, energy that needed to free some electrons from their bound condition is provided. Free electrons go across the junction between two dissimilar crystals more easily in one way than in the other. This gives one side of the junction a negative charge and consequently a negative voltage with respect to the other side. This is normally done by using a *p-n* junction rather than a pure semiconductor. A *p-n* junction happens at the juncture between positive type (*p*) and negative type (*n*) semiconductors. These conversed regions are created by adding different impurities to offer extra *n*-type electrons or additional *p*-type holes. The sunlight helps to free electrons and holes on opposite sides of the junction to create a voltage across the junction providing direct current.

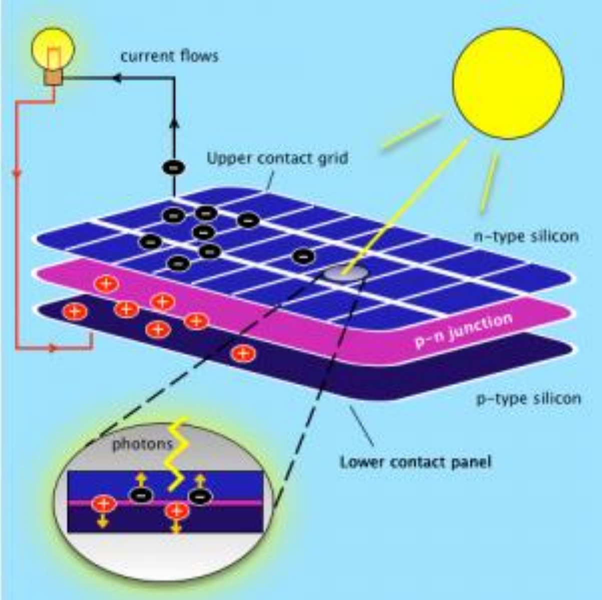


Fig 3.1: Photovoltaic Impact

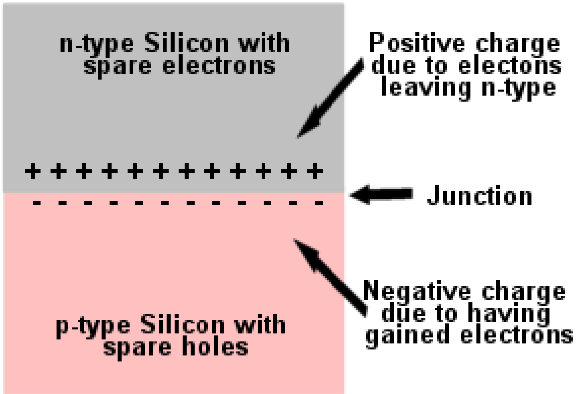


Fig 3.1: n-type and p-type silicon,
https://www.google.com/imghp

This is similar to one electrode of a battery which has a negative voltage with respect to the other. Providing voltage and current are continued via the photovoltaic impact as long as the materials are receiving light. The generated current can be used to determine the intensity of the received light or as a resource of power in an electrical circuit, as in the case of PV systems.

Radiation at higher frequencies, such as X and gamma rays can also cause photoelectric impacts. The higher-energy photons of these rays can even free electrons near the atomic nucleus, as they are strongly bound. When such an internal electron is ejected, a higher-energy external electron speedily drops down to fill in the vacancy. The additional energy results in the release of additional electrons from the atom, which is called the auger impact.

Devices that are based on the photoelectric and photovoltaic impact should have a number of required features, such as providing a current that is directly relative to light intensity and a very fast response time. Photoelectric and photovoltaic cells are regarded as a type of the basic device that can detect radiation, measure the intensity of light, and convert light into electrical energy. Currently, these devices are used in several areas, such as solar cells, controlling industrial process, monitoring pollution rates, detecting light in the fibre optics of telecommunications networks.

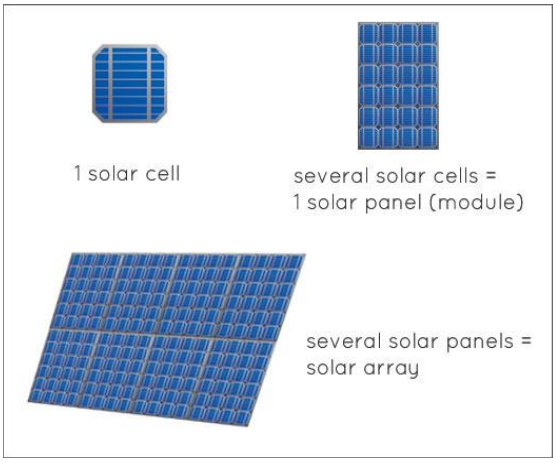


Fig 3.2: Solar cell, panel and array,
https://www.google.com/imghp

Photovoltaic devices normally include a semiconductor *p-n* junction and in the case of solar cells, crystalline silicon is usually used which has the ability to convert about 15% to 18% of the received light into electric energy. One photovoltaic cell is able to provide a very small amount of electricity. Therefore, several cells tend to be connected together and mounted in a frame making a solar panel. Such module can produce a bigger and useful amount of electricity which is regularly used to generate electric energy in particular environments, such as space satellites and remote telephone installations. Multi panels can be connected together to create a solar array and stand-alone PV systems often include several arrays. The electricity generated by PV solar cells is direct current (DC) which has to be converted to alternating current (AC) through an inverter before it can be used to run electrical devices.

3.2.2 Generating Solar Energy via PV System

For more details about this section, the reader is referred to: (Koutroulis et. Al., 2006, Kolhe et. Al., 2002; Salas et. al., 2006, Wai et. Al., 2008 and Zhou et. al., 2010). As mentioned in the previous section, solar panels convert sunlight energy directly into useful electrical energy. To generate as much electricity as possible, PV panels should be subjected to the direct sunlight as much time as possible as seen in Figure 3.3. The semiconductor is protected from hailstones, sand, wind, and wildlife via a sheet of glass as seen in Figure 3.3 and the semiconductor is also covered in an antireflective material, which helps to absorb a great amount of the sunlight instead of reflecting it ineffectually away.

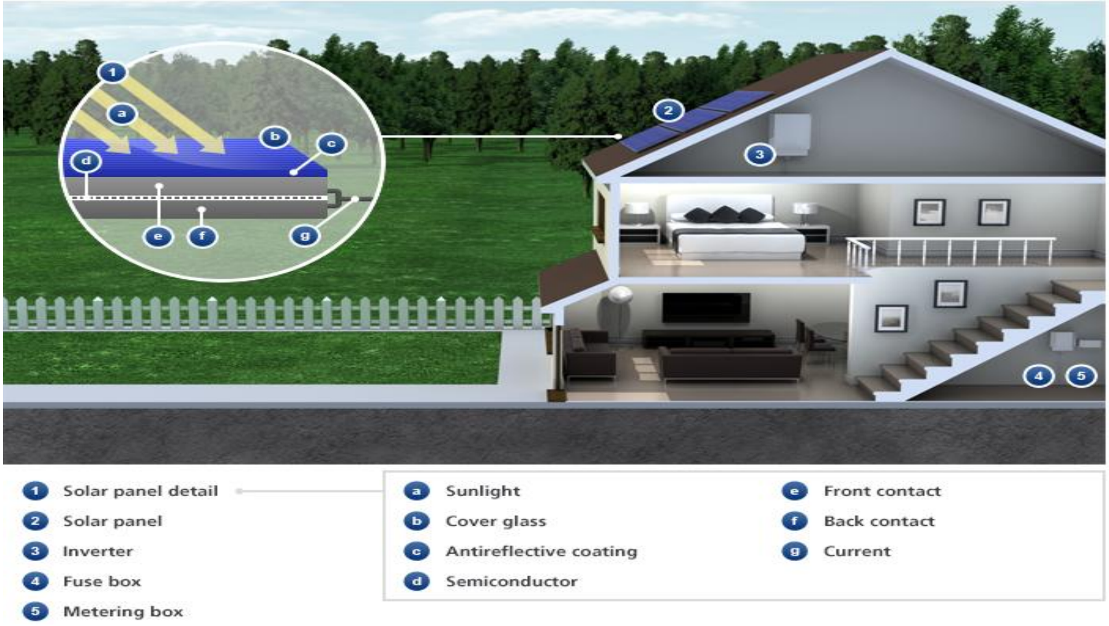


Fig 3.3: Generating solar energy via PV systems, https://www.google.com/imghp

When receiving the sunlight by PV panel, the absorbing energy helps to free electrons from some of the atoms of the semiconductor, which is charged on positively and negatively the two sides. This pushes all the active electrons to travel in the same direction, generating an electric current. This last is captured by the contacts shown in Figure 3.3 and push current in an electrical circuit. The electricity generated by PV panels is direct current which has to be changed into alternating current using an inverter. The inverted current passes throughout a fuse box to the connected devices. A dedicated metering box can also be used to measure the electricity rate generated by the panels.

PV system consists normally of PV panels, cables, mounting or fixing frame, an inverter, charge controller, battery storage, back-up generators and other minor components in the case of stand-alone off-grid systems. In the case of grid-connected systems, special electricity meters for rating the capacity of PV panels are often required. Charge controller is power-conditioning equipment used to regulate battery voltage. Battery is used to store direct current electrical energy which is used when the required power is more than that generated or at night as the efficiency of the PV system reaches zero. The inverter is an electrical device which is able to change direct current to alternating current to run loads working on alternating current.

In general, peak electrical output of PV panel under standard test conditions is used to rate the modules. This means that a panel with a 0.2 kWp rating (0.2) can provide output of 0.2 kW under standard test conditions. Currently, PV panels with peak electrical output of 0.005 to 0.2 kWp are available. A typical PV system for normal house is around 1 to 3 kWp which require a number of smaller modules to be connected forming solar array and an area of around eight square meters for a standard 1-kilowatt system in high latitudes. In a sunny climate, a 2 kW PV system can provide up to 300 kWh of electricity monthly and such system need about 240 square feet of solar panels. A correct orientation of solar panel should be taken into account to help the PV cells to receive direct sunlight for longer period throughout the day.

The amount of electricity can be generated by a PV system depends mainly on the intensity of the received sunlight. Thus, less electricity can be generated on cloudy days and in the morning and evening. At night no electricity can be generated and the maximum amount of electricity tends to be obtained in the middle of the day. PV panels work well in both rural and urban conditions. The ideal position to fix PV panel is in open sky places that receive a great amount of sunshine throughout the year.

Panels are usually mounted on roofs and sometimes placed on facades, conservatory roofs, sunlight shades, garages or specially-built frames on the ground. The typical crystalline silicon cell can convert about 22% of the received light to electricity and this reduces to reach 15% and 18% in the case of commercial rooftop panels. The efficient of PV cells increases depending on the quality of the material used and the application required. For example, satellites are provided with very high quality PV cells, which can convert up to 50% of the received light to electricity. PV systems can produce power in all types of weather. On partly cloudy days, they produce as much as 80% of their potential energy. Even on extremely cloudy days, they can still produce about 25% of their maximum output (Wang, et. al., 2007).

A solar regulator is another important part of stand-alone PV system, which controls the flow of current from the solar panel to the battery. This means that when charging the battery completely, the charge controller stops flow the generated electricity to the battery which might be damaged due to overcharging. Solar regulators tend to be rated by the quantity of current they can receive from the PV modules. Direct current with low voltage output range can be saved in batteries store. As almost all modern devices are operated on alternating current and work on 240 volts, an inverter is required to convert direct current stored in the battery source to household alternating current electricity. The main role of inverter is to increases the12/24/48 Volt battery power to 110/240 alternating current power which is able run domestic device, such as TVs, lights and computers.

Deep cycle batteries are often used with solar PV systems. This type of batteries is designed to be charged and discharged over long time period. They are different from those providing a large amount of current for a short period of time, such as car batteries. To guarantee long battery life, solar controller is configured to stop flow the generated electricity to the deep cycle batteries when they are full. At the same time, the batteries should not be discharged further than 50% of their capacity as this level significantly decreases the life expectancy of the battery. This type of batteries is rated in Ampere hours. For example, the battery illustrated in Figure 3.4 has a rate of 220 Ampere hours which represents the amount of current in Ampere that the battery can supply over a period specified in hours.

Fig 3.4: Deep cycle batteries used with PV system,
https://www.google.com/imghp

Temperature is an important factor should be considered when rating or sizing a solar panel as it affects the performance of a solar system increasing the output by approximately 25% above the nominal rated current. For this reason, solar regulators tend to be oversized with 25% to deal with the increased short circuit current.

3.2.3 Sunlight Tracker Devises

As mentioned in the previous chapter, sunlight trackers direct solar panels toward the sun throughout the day and follow the sun's path to maximize energy capture. In PV systems, trackers help to reduce the angle of incidence between the received light and the line perpendicular to the surface of panel. This increases the amount of received light energy and as a consequence increases the generated electricity. All concentrated solar systems, such as concentrated solar PV and concentrated solar thermal, must have trackers as no energy can be generated unless directed correctly toward the sun. For more details about this section, the reader is referred to (Abdallah & Badran, 2008; Abdallah & Nijmeh, 2004; Chang, 2009; Cheng et al., 2009; Chong et al., 2009; Huang & Sun 2007; Kalogirou,1996; Li et al., 2011; Mousazadeh et al., 2009; Rothet al., 2005)

There are also several methods of driving solar trackers. Passive trackers move from a compressed gas fluid driven to one side or the other. Motors and gear trains direct active solar trackers by means of a controller that responds to the sun's direction. Single-axis solar trackers have the ability to rotate on one axis moving back and forth in a single direction. This single axis can be horizontal, vertical, tilted, and polar aligned.

The other type of solar trackers is the dual-axis trackers which continually face the sun as they have the capability to move in two different directions. Dual-axis tracking is normally used to adjust a mirror and reflect sunlight along a fixed axis towards a fixed receiver. Dual-axis trackers help to get maximum solar energy generation as they can follow the sun vertically and horizontally.

Selecting a solar tracker depends on several factors, such as system size, weather, efficiency required, and latitude. Strategic-scale and large projects typically use horizontal single-axis solar trackers, whereas dual-axis trackers are mostly used with smaller residential applications. For high latitudes, vertical-axis trackers are the most suitable as a consequence of their fixed or adjustable angles.

Compared with fixed panels, using solar trackers can increase electricity generation by around 30% to 40% depending on type of solar tracker, regions and the solar radiation rate. A single axis tracker increases annual output by nearly 30% and a dual axis tracker adds up to 6%. This means that the conversion efficiency is improved when the panels are continually adjusted to the optimal angle as the sun moves across the sky. The advantage of using trackers with small-scale solar project tends to be quite in significant. However, with utility-scale solar projects, difference is often considerable.

On the other side, solar trackers have some limitations, such as increasing the overall cost of the system by adding more equipment. Also, solar trackers include moving parts and gears which often require regular maintenance, repair, and replacement of broken parts. This is in addition to reducing the efficiency of the system significantly when breaking the solar tracker system down as the solar panels will stay at an extreme angle until fixing the system again. Dealing with wind is regarded as another disadvantage of solar tracker where panels might be damaged in a storm than the fixed panels.

Sunlight can be divided into two components, namely: the direct beam which carries nearly 90% of the solar energy, and the diffuse sunlight which carries the rest. As the majority of the energy is in the direct sunlight, increasing the efficiency of PV system requires the sunlight to be visible to the panels as long as possible. The energy achieved from the direct beam drops off with the cosine of the incident angle of incoming light. Also, the reflectance is almost constant for incidence angles up to nearly 50° and after that, reflective rate degrades significantly. The relationship between direct power lost (%)

and incident angle (*i*) is given as in equation 3.1 and Figure 3.5 illustrates how the incident angle increase the direct lost power.

Lost = 1 - cos (*i*)..3.1

Fig 3.5: Sunlight incident angle Vs. Direct lost power

In non-concentrating PV systems, high accuracy tracking is not required where trackers with accuracy level of a few degrees can provide more than 99.6% of the direct beam energy and the whole energy of the diffuse light. From the perspective of any fixed on the Earth, the visible portion of the sun path is 180 degrees during an average of 12 hours period. However, due to local horizon impacts, this portion is reduced to nearly 150 degrees. A typical fixed solar panel can just see a motion of about 75 degrees and thus, according to equation 3.1 and Figure 3.4, approximately 75% of the energy in the morning and evening will be lost. Rotating the panels to the east and west directions via a single-axis tracker can help to overcome this problem. The normal to the cell is at a 90 degree angle to the cell's exposed surface and the sunlight hits the panel at an angle. The angle of the sunlight to the normal is named as angle of incidence (*i*). The mathematical relationship between the sunlight intensity (λ), the angle of incidence (*i*), and power generation (P) can be calculated as:

$$P = \lambda \cos(i) \quad \text{......3.2}$$

$$P = R^2 (\text{sun}) * P (\text{sun}) / D^2 \quad \text{......3.3}$$

where: P (sun) is the power density at the sun's surface as determined by Stefan-Boltzmann's blackbody equation. R (sun) is the radius of the sun in meters as shown in the Figure below. D is the distance from the sun. Stefan-Boltmann's equation includes the total radiated energy R(T) emitted by a black-body is proportional to T^4 with constant of proportionality(∂), Stefan's constant (k), Planck's constant (h), and speed of light (c).

$$R(T) = \partial T^4 \quad \text{......3.4}$$

$$\partial = (2 \pi^5 k^4) / (15 \times c^2 \times h^3) \quad \text{......3.5}$$

As cells cannot convert the whole absorbed sunlight into electrical energy, equation 3.2 should be multiplied by a scale factor E which represents the efficiency of the PV cells.

$$P = E \times \lambda \cos(i) \quad \text{......3.6}$$

$$E = (\text{Work output} / \text{Work input}) \times 100\% \quad \text{......3.7}$$

From equation 3.3, the highest power generated can be obtained when the angle of incidence is zero (cos (0) = 1) and no power can be achieved when the sunlight is at a 90 degree angle to the normal (cos (90) = 0). This means that with fixed solar panels, significant power is lost during the day as the PV cells and the sun's rays are not perpendicular to each other. The role of tracking system is to keep the angle of incidence within a certain range to increase the power generated.

In addition to moving the sun in East-West direction, the sun moves in North-South direction during a year by nearly 47 degrees (+/- 23.4^o in each direction). This can reduce the system efficiency by nearly 8.3%. A tracker that is able to deal with both daily and seasonal motions is known as a dual-axis tracker. Reducing the system efficiency due to moving the sun in north-south direction is complicated by changes in the length of the day, increasing collection in the summer in northern or southern latitudes. As the length of the day in the summer is significant, especially at higher latitudes, the panels are often tilted closer to the average summer angles for reducing the whole annual losses. Active solar trackers use motors and gear trains to move the tracker as commanded by a controller depending on the solar direction. Light sensing trackers commonly have a number of photo-sensors, such as photodiodes. These sensors are fixed on different places on the PV panels and work on sensing light. When receiving the same level of light, they output a null. Mechanically, they should be fixed on the same level with 90 degrees apart.

This causes the sharpest part of their cosine transfer functions to maintain equilibrium at the steepest part, which transform into maximum sensitivity. However, when there is not enough difference in brightness level from one direction to another as in the case of cloudy weather, the panels should not be rotated which helps to save the energy consumed by the motors. Active solar trackers use an optical sensing system to track the sun. These sensors are usually fixed on the base of controller or around the module itself and to feed the control circuitry with digital information about the amount of sunlight. As the system is running in a closed loop state, the amount of brightness is used to monitor the sun’s position across the day. Using this information, the controller tries to balance the sunlight received by opposing sensors for each axis. The controller circuitry modifies the tracker sensitivity automatically. The light sensitivity increases with increasing direct sunlight and decreases with scattering or diffusing light as in the case of cloudy weather reducing unnecessary searching and rotating.

Fig 3.6: Passive tracker, https://www.google.com/imghp

As for passive trackers, the most common type of these devices use a low boiling point compressed gas fluid. The pressure of this is increased due to solar heat which leads the gas fluid to move from one side or the other. This movement causes the tracker to move in response to an imbalance. Although such type of sun tracker is unsuitable for certain types of concentrating photovoltaic collectors due to the low precision of rotations, it works fine with typical PV systems. Figure 3.6 shows an example of passive solar tracking system.

Reflectors tend to be used to reflect early morning sunlight to the panel. This is to provide the system with the necessary power for tilting the panels toward the sun, which can take nearly an hour. This period can be greatly reduced using a self-releasing tie-down which positions the panel slightly past the zenith. Therefore, the gas fluid does not have to overcome gravity and the same can be said for the evening.

Passive trackers consist usually of two pipe tanks fixed at the sides of the PV panels. When the PV panel is not aligned with the Sun, the distribution of the fluid's temperature across the tanks will not be consistent resulting in pressure difference. This will push the fluid throughout a connecting pipe to the pipe tank with the lowest temperature.

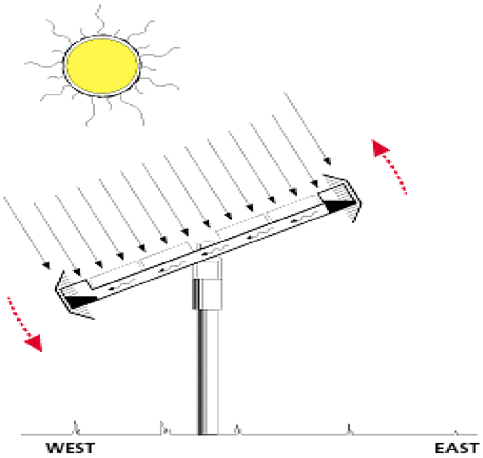


Fig 3.7: Design concept of passive solar tracker, https://www.google.com/imghp

Moving the liquid from side to another creates unbalance on the two sides of the panel. This allows gravity to turn the PV solar panels to face the Sun. Figure 3.7 illustrates the design concept of passive solar tracker.

Passive solar tracking systems have several advantages over active systems, such as the low-cost, no need for regular maintenance, and no need for electricity and motor. Although the accuracy provided by passive solar tracking systems is limited to a few degrees, they are widely used with PV systems where no need for precise rotations comparing to concentrated solar power systems.

On the other hand, passive solar tracking systems tend to be inactive, particularly in the morning and evening where the temperature is limited. Also, PV arrays provided with passive tracker should be flexible to be rotated under the weight impact which reduces the resistance of the panels to the wind impact.

3.2.4 Solar PV Self-Shading

As multi PV panels are connected together to form solar PV array, any shading on a single module can affect the performance of the whole solar PV system. Some shading in the early morning and evening may not reduce the overall power generated. However, in mid-day when the sunshine intensifies, shading can affect the performance of a solar PV array significantly and preferably should be avoided.

Fig 3.8: Shading occurring via trees, https://www.google.com/imghp

Shading can occur from obstructions, such as neighbouring constructions and faraway tall buildings. Also, the increased growth of trees, shrubs and other vegetation should be taken into consideration when fixing the PV panels where they may shade the system after short period. See Figure 3.8 illustrating shading due to trees.

The architecture design of the building itself might provide another sources of shading. This can be noted clearly in the houses with multi-level roofs. Also, some terraces tend to be designed with different level (set back or forward) from the other parts of the house to give visual interest and this can shade a part of the roof where PV panels are usually installed. See Figure 3.9. Such problems can often be seen in old architecture designs as solar power systems have not been taken into account.

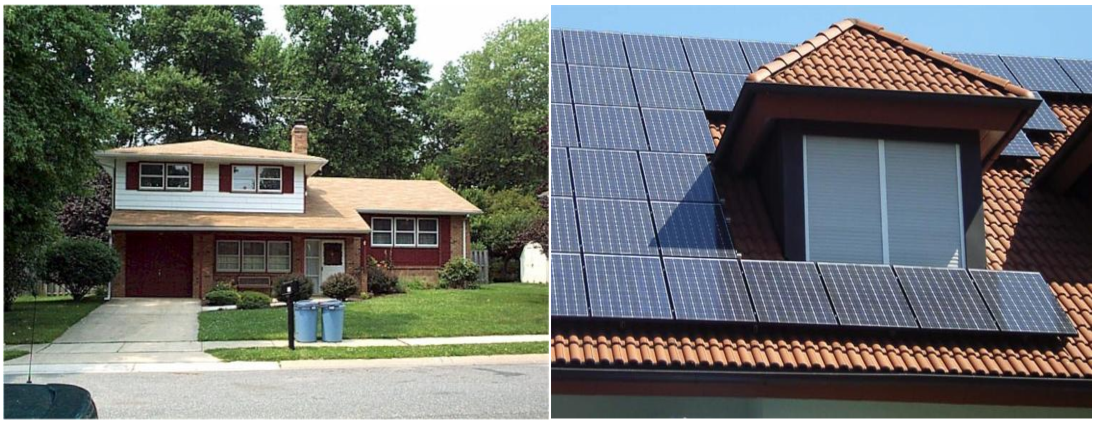


Fig 3.9: Shading due to architecture design, https://www.google.com/imghp

The other important sources of shading are snow, bird droppings and other types of soiling and muddying. Snow is an important factor, especially in mountainous areas. In industrial and desert areas, soot and dust can also have a significant impact on the system performance. Such temporary shading can be reduced considerable using the solar PV array self-cleans. Some systems are provided with cleaning system including tiny water pumps and electrical wipers. However, this can increase the cost of the system. To avoid such extra cost, the panels are often tilted with angle of a few degrees which is sufficient to reach this aim.

Fig 3.10: PV panels and self-shading impact

The other important source of shading is the self-shading of the solar PV modules itself. When fixing a number of panels in the system frame, self-shading impact can be caused by the row of panels at the front, especially in early morning and evening. Space requirements and shading losses can be reduced throughout optimal design with calculated tilt angles and distances between the module rows. See Figure 3.10. Also, the place of each PV panel should be studied to avoid the impact of micro-shading which is caused by panel clamps and projecting screws.

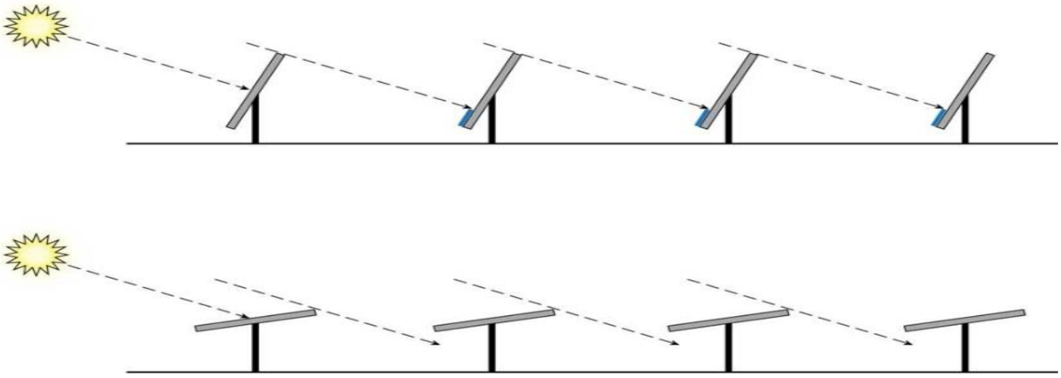


Fig 3.11: Self-shading Impact Vs. PV tilting angle

Figure 3.11 illustrates the relationship between the PV panel tilting and the self-shading impact with the same sunlight incident angle. It is clear from the Figure that when the sun’s elevation angle is low in the sky as in the early morning and evening, self-shading has the potential to decrease the system efficiency. By rotating the array aperture away from the sun, the impact of the self-shading can be reduced increasing the system functionality. However, the minimum slop angle that allows avoiding the self-shading impact should be used as tilting the panels too much increases the sunlight incident angle and affects the whole system performance.

Designing the system with an optimal distance between modules plays a substantial role for avoiding the self-shading impact and increasing the system functionality. When the rows of tilted panels are fixed close to each other, each row will shade a part of the next, causing further losses. On the other hand, increasing the distance between rows significantly can cancel out the self-shading impact but at the expense of space and number of models.

The ideal tilt angle of the panels depends on the latitude and geographical location, which will affect peak sun hours. This should be taken in consideration when designing the system.

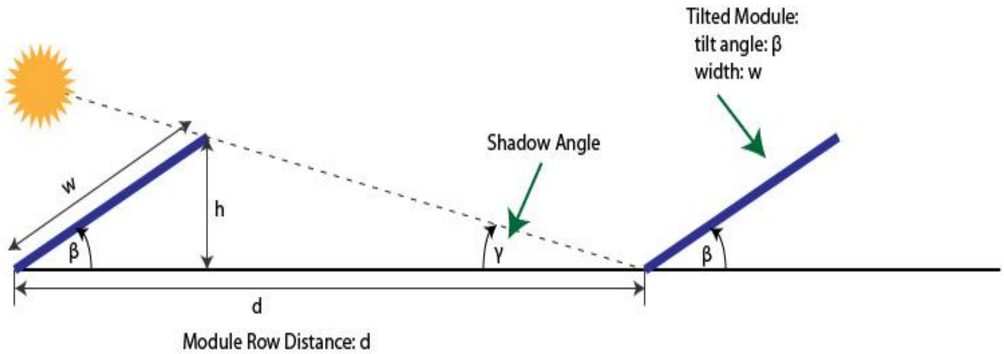


Fig 3.12: Avoiding the self-shading via an optimal design

From Figure 3.12, the mathematical relationship between panel width, tilt angle, shadow angle and the distance between the rows can be extracted from Sine low as following:

$$d / \sin(180 - (\beta + \gamma)) = W / \sin(\gamma) \qquad \textbf{3.8}$$

In the case of fixed panels, β angle is constant which typically takes the same angle of slop roofs, say 30^o. As mentioned before, from the perspective of any fixed on the Earth, the visible portion of the sun path is 180 degrees during an average of 12 hours period. However, due to local horizon impacts, this portion is reduced to nearly 150 degrees. This means that the first 15^o in east and the last 15^o in west direction will not be considered. To avoid the whole impact of self-shading, d distance should be calculated with the minimum γ angle, which is 15^o. By simple calculations, it can be extracted that d should be nearly three times the value of W.

In the case of rotated panels and designing the models to follow the sun making an incident angle of nearly zero, equation 3.4 can be rewritten as following:

$$d / \sin (90) = W / \sin (\gamma) \qquad \textbf{3.9}$$

This means that with the minimum sunlight elevation angle of 15^o and to avoid the whole self-shading impact, the system should be designed with distance between rows (d) approximately 4 times the width of panel (W). This can reduce the number of PV rows in specific area or more space is required to cover the required energy.

However, as the efficiency of the system is often low in early morning and evening due to weak solar irradiation even with avoiding the whole impact of self-shading, minimum sunlight elevation angle of 30^o can be used which reduce the distance between rows to be about double W value and as a result, more PV rows can be mounted in smaller area and more energy can be generated.

In general, it is necessary to carry out a shading analysis of the site, which comprises monitoring the view of the solar module from sunrise to sunset and recording the horizon. This should be done for distance objects, such as mountains and high buildings as well as objects in the neighbourhood. Also, as the impact of shadow is different based on the changing of sun path throughout the year and the latitude and longitude of the location, this should be taken into consideration when designing the system. Currently, simulation software is often used to estimate the impact of the close and distance objects on the system across the year.

3.2.5 Sizing of Stand-Alone PV System

Designing a perfect stand-alone PV system includes sizing each element in the system, namely: solar array, controller, inverter and battery. In this section, a brief description of designing these elements will be discussed as more details will be given in chapter five.

The first step of designing the system is to determine the average yearly solar isolation for the location in which the system will be installed. The coordinates of the site can be determined based on GPS. Code stand-alone GPS technique with accuracy of a few metres can be used as solar irradiation tends to be the same for vast areas. Figure 3.13 shows the world solar irradiation map.

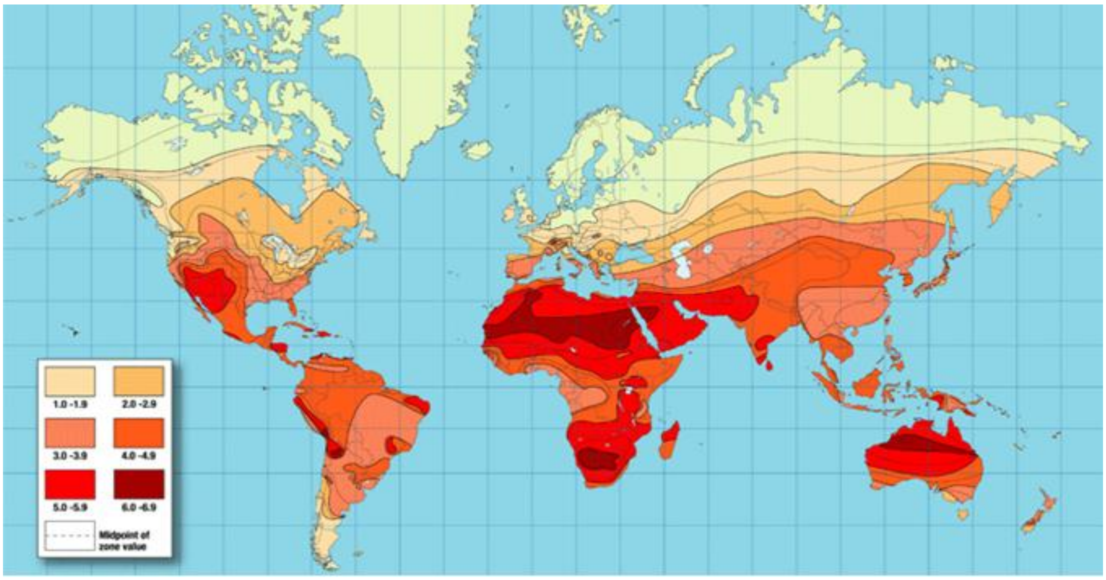


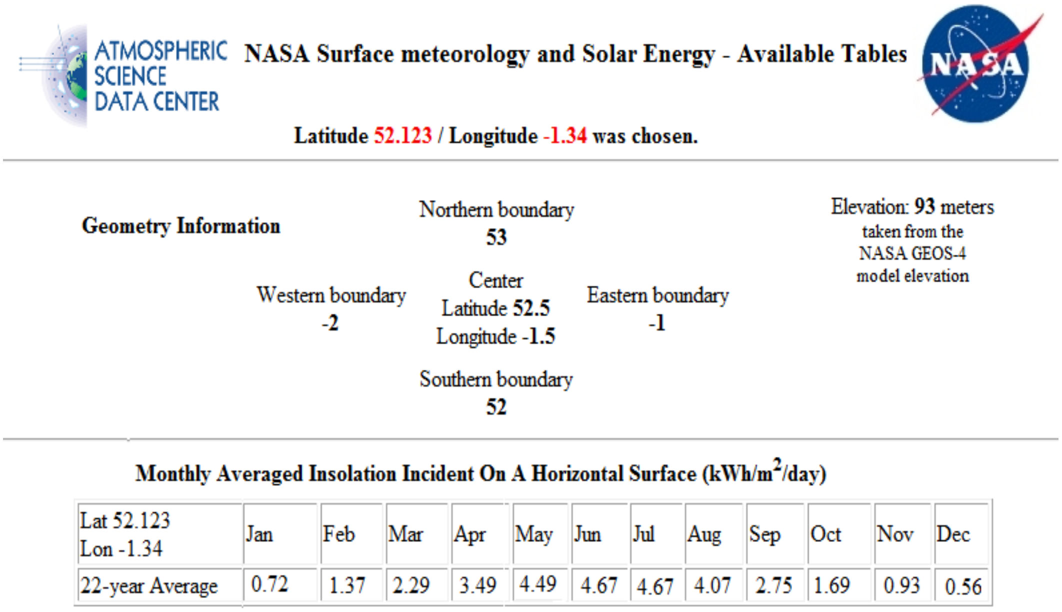
Fig 3.13: World solar irradiation map (Abdallah & Badran, 2008)

Solar radiation consists of three main components, namely direct, diffuse, and albedo radiation. The first is named beam radiation as it is made up of beams of light, which are not scattered and not reflected. This component reaches the surface in a straight line directly from the sun. The second component is the scattered light, which reaches the surface not directly from the sun but from the whole sky. The last radiation is that caused by the light reflected onto the surface from other surfaces.

Two quantities are often used to measure solar radiation, namely irradiance and irradiation. The first is defined as the density of the power which is received by a surface (W / m^2). The second provides more details and defined as the density of the energy that received by a surface over some period of time such as an hour or a day (Wh / m^2 per hour/day).

Solar irradiation can be estimated by NASA Surface Meteorology and Solar Resource website as only the GPS coordinates of the site are required. The user can get for any site estimated values of the monthly minimum, average and maximum solar irradiation (in kWh / m^2 / day) at ground level with different tilt angles. From the website, the user can choose the suitable tilt angle of the panels and show the distribution of solar irradiation across the year. This is in addition to providing the minimum, average and maximum daytime temperatures at the location of the system and the actual solar irradiation measurements. Figure 3.14 gives an example of using NASA Surface Meteorology and Solar Resource website to get the average solar irradiation.

In the case of using fixed PV system, PV arrays are installed with an incline to the horizontal for maximal solar collection. The amount of irradiation obtained from tilted panels is different from that achieved with a horizontal surface. The estimated irradiation data on sloped planes can be obtained directly from the website mentioned above.



ATMOSPHERIC SCIENCE DATA CENTER

NASA Surface meteorology and Solar Energy - Available Tables

Latitude 52.123 / Longitude -1.34 was chosen.

Geometry Information

Northern boundary
53

Western boundary
-2

Center
Latitude 52.5
Longitude -1.5

Eastern boundary
-1

Southern boundary
52

Elevation: **93** meters
taken from the
NASA GEOS-4
model elevation

Monthly Averaged Insolation Incident On A Horizontal Surface ($kWh/m^2/day$)

Lat 52.123 Lon -1.34	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
22-year Average	0.72	1.37	2.29	3.49	4.49	4.67	4.67	4.07	2.75	1.69	0.93	0.56

Fig 3.14: NASA Surface Meteorology and Solar Resource (websitehttps://eosweb.larc.nasa.gov/sse/)

Alternatively, the amount of irradiation attended with sloped modules can be accurately estimated from the irradiation of horizontal plane and the optimal angle as following:

$$Irr\ (\beta_{opt}) = Irr\ (h) / (1- 4.46 * 10^{-4} \times \beta_{opt} - 1.19 \times 10^{-4} * \beta^{2}_{opt}) \ldots\ldots\ldots\ldots\ldots\ldots 3.10$$

where: β_{opt} is the optimal tilt angle (deg)

$Irr\ (\beta_{opt})$ is the solar irradiation on a surface at the optimal tilt angle (Wh / m^2/ day)

$Irr\ (h)$ is the solar irradiation on the horizontal plane (Wh / m^2/ day)

$$Irr(h) = R2\ (sun) \times Irr\ (sun) / D^2 \ldots\ldots\ldots\ldots\ldots\ldots 3.11$$

The amount of β_{opt} is mainly related to the latitude of the system's location. At higher latitudes, the β_{opt} is higher as the system is designed to depend on summertime radiation collection over that of wintertime. β_{opt} can be determined from equation 3.7 using the site latitude (φ) and Figure 3.15 shows how the optimal tilt angle of PV panels increases with higher latitudes.

$$\beta_{opt} = 3.7 + 0.69\ (\varphi) \ldots\ldots\ldots\ldots\ldots\ldots 3.12$$

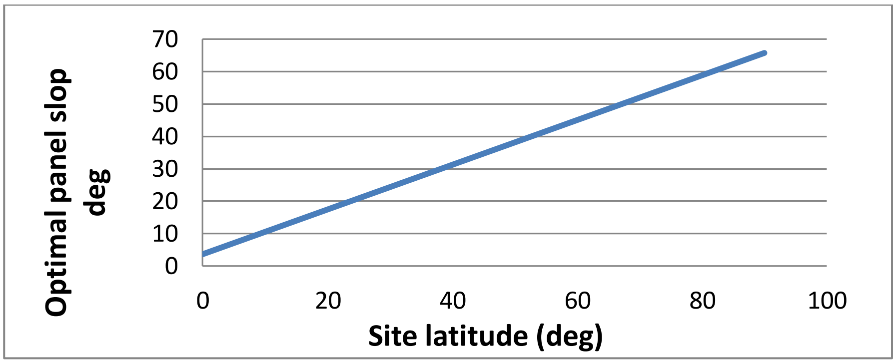


Fig 3.15: Optimal panel slop Vs. Site latitude

After determining the average monthly amount of irradiation for both horizontal and tilted plane and calculating the optimal sloping angle of the panels in the site, the second step is to find out the daily total power and energy consumption of all loads that need to be powered by the solar system in Watt-hours (Wh). For remote industrial purposes, the loads are typically for control systems and instrumentation equipment. For commercial purposes as in the case of telecommunication stations, the loads are generally the telecoms hardware with small area lighting for repairs. For housing purposes, the loads are typically domestic lighting, computers, radios, TV, garden devices, etc.

The power rating in Watts of each and every used electrical device and the number of using hours of each piece of equipment should be known. The Watt-hours needed for all appliances are added together to determine the total daily energy consumption in Watt-hours. An example of finding out the daily total power is shown in the following table:

Table 3.1: Example of determining total daily energy consumption

Electrical device	**No. of devices**	**Watt**	**No of hours/day**	**W/hours/day**
Fluorescent lamp	5	25	6	750
Fan	2	50	4	400
Refrigerator	1	85	24 (12 off & 12 on)	1020
TV	2	200	8	3200
Total daily energy consumption				5370

The determined amount of the daily total energy consumption should be multiplied by a design factor which depends on the efficiency of the system and expected rate of losing the energy. Generally, the calculated daily energy consumption is often increased by 30% to 50% to get the total Watt-hours/day which should be provided by the panels. The number of Watts that should be generated per each sun hour can be determined by the following equation:

W (Sh) = Whd / $Irr\ (\beta_{opt})$..3.13

where: W(Sh) is Watts that should be generated per each Sun hour (Wh)

Whd is Watt-hours/day which should be provided by the panels (Wh / day)

$Irr\ (\beta_{opt})$ is the solar irradiation on a surface at the optimal tilt angle (Wh / m^2 / day)

The number of panels needed for the system to cover the required energy consumption can be calculated as following:

Number of panels = W(Sh) / Watts-hours generated by the chosen panel............3.14

Equation 3.12 gives the minimum number of PV modules required. Increasing the number of PV panels will help the system for better performance and longer battery life. On the other hand, using less number of PV panels that required reduces the efficiency of the system significantly, especially in cloudy periods which might affect the battery in terms of life period and effectiveness.

Choosing the appropriate solar regulator or charge controller is the next step in designing the stand-alone PV system. As mentioned before, the role of this device is to regulate the direct current from solar modules to avoid overcharging batteries. A charge controller includes a low voltage disconnect feature, which senses the battery voltage and if the battery voltage reaches a pre-determined cut-off voltage level or overcharging, the supply will be switched off. Solar regulator helps also to prevent the battery from feeding back into the solar panel when the modules stop working due to darkness.

Solar regulators are rated by the amount of current they can receive form the solar panels. Also, the solar regulator should be capable of handling the total short circuit current of a solar panel. As mentioned above, the capacity of solar regulator should be increased by 25% to allow for growth and because of the fact that the output of solar modules might exceed.

Choosing the suitable inverters for the system is based mainly on the maximum anticipated alternating current load to be supplied. The design capacity should cover the combined maximum load for all alternating current electrical devices running at the same time. Converting direct current to alternating current results in a loss of efficiency for the inverter reducing the energy with nearly 20% depending on the quality and efficiency of the inverter used (Wang, et. al., 2007). The design capacity of the inverter can be determined from the following equation:

$$(DC_{inv}) = Load_{(max)} \ / \ Inv_{(eff)} \quad \ldots\ldots\ldots 3.15$$

where: $DC_{(inv)}$ is the design capacity of the inverter.

$Load_{(max)}$ is the combined maximum load for all alternating current electrical devices running at the same time.

$Inv_{(eff)}$ is the efficiency of inverter.

$$Inv(eff) = (Work\ output \ / \ Work\ input) \times 100\% \quad \ldots\ldots\ldots 3.16$$

The design capacity of the inverter ought to include the electrical devices that are expected to be used even as a temporary, such as garden equipment, motor, compressor and water pumps. In such case, inverter size should be minimum 3 times the capacity of these devices and must be added to the inverter capability to deal with surge current during starting. In the case of grid connected PV systems, the input rating of the inverter should be the same of PV panel's rating to allow for safe and capable performance. Pure sine wave inverters are often recommended to be used with the PV systems where possible.

Sizing the batteries of solar PV system is regarded as one of the most important step of designing the system. The type of batteries that is recommended for solar PV system is deep cycle battery, which is specifically designed to be discharged to low energy level and rapid recharged. These batteries can be cycle charged and discharged continually for years.

The size of battery should be large enough to store sufficient energy to operate the electrical domestic devices at night and cloudy days. Most batteries live longer with shallow cycled discharging of only about 20% of their capacity. A moderate design can save the deep cycling for occasional use. This means that the battery bank should be approximately five times the daily load to provide power continuously for five days without any solar power generating or battery recharging.

To determine the total battery Ampere hours required is to determine the total Watt-hours required by all loads which discussed in Table 3.1. This value is divided by the direct current system voltage giving the amount of Ampere hours required to run all loads for a given period. The number of needed batteries can be calculated from the following equation.

No. of batteries (Amp) = Whd x D_{aut} / (B_{loss} x D_{cha} x B_{vol})......................................3.17

where:

Whd is the total Watt-hours per day required by all loads.

D_{aut} is the number of autonomy days that needed the system to operate without generating power by PV panels.

B_{vol} is the nominal battery voltage.

B_{loss} is battery loss based on the assumption that the battery will never be discharged less than a specific rate, say 20%. Therefore, B_{loss} will equal to the remains of the battery's capacity (80%).

D_{cha} is a constant for the battery depth of discharge (typically = 0.6).

When providing solar PV system with solar trackers to track the position of the sun across the day and rotate the panels accordingly, collecting solar irradiation by the modules increases significantly by nearly 20% to 30% for 1-axis trackers and an extra amount of 6% to 10% can be obtained with 2-axis trackers compared to a fixed panels at an optimal tilt angle.

For more details about designing stand-alone PV systems, the reader is referred to Fragaki et. al., 2013, Balouktsis et. al., 2006 and Salas et. al., 2006.

3.3 Chapter Conclusion

In this chapter, the mathematical and theoretical concept behind the methods, sensors and techniques used in this project have been briefly described. The chapter started with highlighting the photovoltaic impact which has been followed by discussing generating solar energy via PV panels. In addition to that, the design concepts of sunlight tracking devices for both active and passive types, self-shading impact and solar radiation have been explained. Finally, PV system sizing including PV panels, batteries, inverter, and charging controller has been discussed giving examples when necessary. In the following chapter, the methodologies used for collecting the data used in this thesis will be discussed. Then, the reasons behind the crises of providing a significant number of remote and distance villages in Saudi Arabia with electricity will be illustrated. This will include the cost of linking these areas to the main grids, the difficulty of maintenances, and comparing the cost with the financial returns. One of these villages will be used as a case study for investigating the possibility of using SABIPV systems as a main solution for providing electricity to such remote village.

Chapter Four: The Research Approaches and Data Collection Methods

4.1 Introduction

This chapter is the first of four chapters that aim to document and analyse the use, design and impact of the SABIPV system solution in the Kingdom of Saudi Arabia. As illustrated in chapter one section 1.3 and 1.4, this study uses the information gathered through case study strategy using different data collection methods. These methods include local and central government archival records, documents, limited surveys, and semi-structured interviews. The collected information together with the literature review is essential to meet three of the main objectives of this study. The first objective is to address the causes and current solutions offered to deal with the electric power crisis, specifically in the remote areas in Saudi Arabia. The second objective is to provide adaptive and customised design of SABIPV system for a selected village in Saudi Arabia. The third objective is to assess the economic, social and environment impact of adopting such system in the Kingdom of Saudi Arabia (KSA).

Initially, this research undertook a general literature review to cover two main themes or sections. The first section intended to provide the reader with an overview for the use of solar energy, focusing mainly on PV and Building Integrated PV Systems. The section has also introduced Sunlight Tracking System as an element of BIPV and stand-alone PV systems. The second section intended to examine the solar energy as an important energy resource in the GCC countries generally and in Saudi Arabia particularly. The section has also addressed the potential of using the stand-alone PV systems in GCC countries, especially in Saudi Arabia. Considering the aim of designing an adaptive and customised SABIPV system for a selected village in Saudi Arabia, a description provided for the mathematical and theoretical concepts behind the methods and ideas used in developing the system. This has included photovoltaic impact, generating solar energy via PV panels, sunlight tracking devices, self-shading panel impact, solar radiation, and system sizing.

To this end, the research of this thesis is based on secondary data. The rest of the research study combined both primary and secondary data, and this chapter provides thorough description for the empirical part of the research approach.

4.2 Research Subject

Renewable energy in general and solar energy in particular as a sustainable solution for electric power crisis in the kingdom of Saudi Arabia is an overarching concept, and have the potential to use the technology innovations for optimising the three main target dimensions, economic, social, and environmental. Therefore, the adoption of such system solution needs to consider the implications at and across many disciplines, and has to address many different functional areas of the proposed solution and its wider environment.

This research study is about developing SABIPV system solution and assessing the economic, social and environment impact of adopting such system solution in the Kingdom of Saudi Arabia. Therefore, on one hand, the research study can be considered as engineering research that addresses sustainability innovations and technology aspects. On the other hand, the study in reality is interdisciplinary research that goes beyond the engineering discipline and addresses the economic, social, and environmental dimensions in adopting such solution. According to the National Research Council (2005), the interdisciplinary research is a type of research that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or area of research practice.

Considering that this study is about analysing the use, design, as well as examining the multi-dimensional impact of the SABIPV system solution in the Kingdom of Saudi Arabia, the use of interdisciplinary research is vital to address these dimensions and explore them across various boundaries of disciplines as single discipline seems incapable of providing the sufficient information for this task.

4.3 Research Approach

In order to achieve the main aim of this thesis in examining the use of solar energy solution in the Saudi Arabia, providing a design of the SABIPV system solution, and assessing the economic social and environmental impact of such system in the Kingdom, it is important to choose an appropriate research approach. Galliers (1992) stated that the research approach is about the way of going about one's research, embodying a particular style and employing different research methods with which to collect and analyse data.

The process of selecting an appropriate research approach is determined by many factors, the most important ones are:

1. The type of research subject, the maturity of the research subject and the extent of existing knowledge on the area to be researched (Denzin and Lincoln, 1998; Saunders et al., 2007)
2. The research study questions and the research aim and objectives (Saunders et al., 2007; Yin 2003).
3. The time and resources available for the research (Saunders et al., 2007).

There is a widely used distinction in the literature (e.g. Lee 1999; Maxwell, 1998; Silverman 2000; Strauss and Corbin 1998) between two types of research approaches, quantitative and qualitative. Quantitative research was the dominant approach since its emerging centuries ago (Williams, 2007); the approach is driven by the need to quantify data to produce meaning and generate new knowledge. Quantitative approach to research is associated with key features, among the important of these features are the use of linear research design models (Maxwell, 1998), they are structured and theory precedes (Corbetta, 2003), and they produce hard, objective and standardized data (Robson 2003; Silverman 2000).

Qualitative research has been described as an unfolding interactive approach that occurs in a natural setting and enables the researcher to develop a level of detail from high involvement in the actual experiences (Creswell, 1994). Qualitative approach to research is associated with key features, among the important of these features are the use of open, interactive, and non-linear research design models. In such approach, the researcher may need to reconsider or modify any design decision during the study in response to new developments (Corbetta, 2003; Maxwell, 1998), and the methods developed within this approach produce soft, rich, flexible, and subjective data (Robson, 2003; Silverman 2000).

In view of the main aim of this research study, an integrated qualitative and quantitative research approach has been selected. The choice of adopting such approach is made for two main reasons:

1. Considering the limited amount of empirical and theoretical evidence on use and multi-dimensional impact of the solar energy solution in the KSA, hence the value of an integrated qualitative and quantitative research approach lies in its ability not

only to generate and validate the research assumptions but also to ground these assumptions in data.

2. It seems necessary to combine both research approaches to incorporate quantitative and qualitative methods. Such incorporation is essential to meet the research objectives and produce the required data for the validation process.

4.4 Single and multiple Case Studies

Yin (2003) has classified strategies of case study into two major types, namely: single-case and multiple-case and each one include holistic and embedded designs. In multiple-case study, holistic designs strategy is about studying and comparing cases in their totality based on a single unit of analysis for each case study. Alternatively, embedded designs in the same multiple-case study is about studying various units, processes or projects within distinguishable embedded cases based on a multiple unit of examination for every single case study.

Single case studies are usually employed when founding out one unique case study that is descriptive and comprehensive to cover all the aspect of a research problem. Single case studies can also be used in the case of investigative or experimental studies. On the other hand, the multiple-case studies are the most common used method when containing more than single case in various context providing many benefits over the single case studies. Multiple case study strategy with carefully chosen cases allows for investigating similarities and variances within and between cases. Also, the evidence and conclusions obtained from multiple-case study are often more reliable and convincing than those achieved from single case. However, multiple-case studies tend to be costly and time consuming (Christie, 2000; Smith, 1988; Yin, 2003).

In this research, when discussing the reasons behind electric power crisis in distance communities in Saudi Arabia, the whole country will be used as a holistic design case study covering all the expected reasons beyond this problem. Then, these reasons will be discussed again within a selected case study which forms a small village in the country which giving a descriptive and comprehensive view on the size of the problem in remote communities in Saudi Arabia. One of the residential buildings in this small village will then be used as an embedded design case study for designing SABIPV system which also is adequate for giving a clear indication on the ability of the system to cover the required power consumption and be a fundamental solution for the problem of providing electricity to rural areas in the Kingdom. In chapter seven, the whole country will be used again as a study case for discussing the expected influence of using this system on the economic, environmental social sides in the country.

4.5 Research Methods

Using case study strategy allows for facilitating a variety of data sources with different research methods. This can ensure that the research questions are investigated throughout a different methods allowing data triangulation and revealing the multiple facets of the research problem (Baxter and Jack, 2008). In general, in case study strategy, six types of research methods can be used to collect the data and each method have advantages and limitations and related to an array of data or evidence. The methods are: documentation, interviews, direct observation, participant observation, and physical artefacts. In the following sections, methods that have been selected to collect qualitative data for this research study which are documentation and interviews will be defined and discussed briefly.

4.7.1 Documentation

A document can be defined as an artefact that is commonly in the form of written text (Scott 1990). According to Yin (2003), different types of documents can be considered in data collection process, such as:

1. Letters, memoranda, e-mail correspondence and other personal documents.
2. Agendas, announcements, minutes of meetings and other organizational reports.
3. Administrative documents, proposals, progress reports, and other internal records.
4. Formal report of the same case study.
5. Journal and conference papers and articles.
6. News clippings and other media articles.
7. Archival records.

Yin (2003) has reported also that documentary data is probable to be related to every case study strategy. For increasing the dependability of documents and the quality of data, Grix (2001) has recommended to consider three factors with the selected documents used in qualitative research which are:

1. The origins of the documents which should be investigated for the selected documents along with checking and classifying the reliability of documents according to their authorship.
2. The point of the documents, where every document are written with an aim based on specific hypothesis and presented in a particular way or style, the selection of a specific document for a certain use must support the proposed purpose and assumptions.
3. The original audience of the documents where the importance, dependability, and accuracy of the information are determined to particular extend by the documents

original audience. Hence, it is essential to consider them in identifying, selecting, and using documents.

In this research study, documentation method has been used to gather the required initial data for literature and critical review from journal and conference papers. Then, different achieve records have been used for providing an important data that may not available in the published papers. Examples about the archives used in this thesis are:

1- Archives of Electricity Saudi Company, Jeddah
2- Archives of Electricity Saudi Company, Jazan
3- Archives of Electricity Saudi Company, Asear
4- Maintenance records, Maintenance Department, Saudi Electric Company, Riyadh
5- Saudi Ordnance Survey (SOS), Photogrammetry Department, Riyadh

A brief description for each document will be provided in the appendixes. .

4.7.2 Interviews

According to Myers (2009), an interview is regarded as one of the most used research method for collecting primary data for almost all types of quantitative and qualitative study. They are usually divided into three levels, namely: structured, semi-structured and unstructured interviews (Fontana and Frey, 2005).

The structured interviews which are also known as “standardized interviews” are precise type of interviews where all participants are asked the same questions with the same words and in the same order (Corbetta, 2003). This type of interviews provides some rigidity for the collected data as the questions of this type of interviews tend to be very specific, closed ended, and fixed choice which leaving the interviewees with fixed range of answers. Structured interviews are usually criticised due to using a questionnaire format with closed questions without providing adequate information for all participants to answer the interview question. The questions are structured to keep up high impact of the interviewer which may have an impact on the respondent’s replies and not reflecting the exact meaning (Bryman, 2001). For the previous reasons and because structured interviews are commonly used for quantitative rather than qualitative data, they have been not considered in this research study.

The second type is the unstructured interviews that are also known as informal interview or non-standardized interview. This level of interview is specific type of interviews in which neither the questions nor the answers are prearranged, and their produced data rely on social interaction between the researcher and the participants (Minichiello et al., 1990). The unstructured interviews are used to understand the complex behaviour of people without having presence any previous categorization, which might limit the field of investigation. The interviewers in this method depend completely on the unstructured generation of questions in the natural flow of an interaction (Patton, 2002). Unstructured interviews are directed by a study aim and objectives as well as the range of features that would be explored in the interview (Fife, 2005). This method can be used when there is no predefined theoretical framework, and thus no hypotheses assumptions and questions about the research area under investigation (Zhang and Wildemuth, 2009). Unstructured interviews tend to be used for generating data with different structures and patterns out of each interview (Zhang and Wildemuth, 2009).

The semi-structured interview is the third level of this method which has been used in this project for collecting an important data for this project. This method also called scheduled interview are specific type of interviews in which the questions posed in the interviews were predetermined as the interviews are usually directed by an interview guide, including a list of important questions to be covered (Corbetta, 2003). The semi-structured interviews are popular for their features and benefits, particularly when they were used in qualitative data collection. Because of their advantages, the semi-structured interviews have been selected to collect the detailed qualitative data used in this project. The main advantages of using the semi-structured interviews are:

- Semi-structured interviews provide more flexibility for the collected data where additional questions can be asked and the questions are open-ended encouraging research participants to give detailed responses (Gray, 2004).
- Semi-structured interviews can show real life information about the style in which people perform in their atmosphere where they are the only people who understand the live social reality (Burns, 2000).
- Semi-structured interviews allow for affecting and investigating deeply into the given situation. This helps to explore issues that arise providing an initial framework for areas under investigation. (Gorman & Clayton, 2005).
- Semi-structured interviews smooth the progress of an immediate response to a question which allow for explaining or reshape the questions in order to resolve any uncertainty if respondents are unclear about the questions (Gorman & Clayton, 2005).

The semi-structured interview has been chosen as one of the primary data collection method to gather detailed information in contributing to the major finding of the research study. Different semi-structured interviews have been carried out in this project when it has been necessary or when the required data is not available in the archives records. The semi-structured interviews in this project have included the followings and an example about the interview guide will be presented in the appendixes.

1- Semi-structured interview with the director of ESC, Jeddah branch, in June, 2013

2- Semi-structured interview with the head of Civil Engineering Department in ESC, Jeddah branch in July, 2013

3- Semi-structured interview with the deputy head of Geotechnical Engineering Department in ESC, Jazan in July 2014

4- Semi-structured interview with the director of ESC, the main branch, Riyadh in September, 2013

5- Semi-structured interview with the local council of Bain-Malik , September, 2013.

4.8 Chapter Conclusion

This study used information collected via case study strategy using different data gathering methods. These methods included local and central government archival records, documents, limited surveys, and semi-structured interviews. The collected information together with the literature review is essential to meet three of the main objectives in this study. The first objective studying the causes and current solutions suggested dealing with the electric power crisis, specifically in the remote areas in Saudi Arabia. The second objective is providing adaptive and customised design of SABIPV system for a selected village in Saudi Arabia. The last is assessing the economic, social and environment influence of using such system in the Kingdom. Using case study strategy allows for facilitating a variety of data sources with different research methods. This can guarantee that the research questions are inspected via different methods allowing data triangulation and revealing the multiple facets of the research problem. In this chapter, the research methods that selected to collect qualitative data for this research study which are documentation and interviews have been defined and discussed briefly giving examples about the sources of each method.

Chapter Five: Remote Areas in Saudi Arabia and the Electric Power Crisis: Causes and Current Solutions

5.1– Introduction

This chapter will cover the first objective of this project. Firstly, an overview about the electric power crisis in rural areas will be highlighted giving examples about the spread of these rural communities in Saudi Arabia, the number of population, population density, the source of current power supply, approximate distance from the nearest main electric grid or power plant, and the ratio that is covered from the necessary electricity needs. The reasons behind the crisis in supplying electricity to domestic remote and rural off-grid areas in Saudi Arabia will be investigated. This will also include highlighting the current used and suggested solutions.

5.2 - Remote Areas in Saudi Arabia and the Electric Power Crisis

Saudi Arabia covers more than two thirds of the Arabian Peninsula and is located between latitudes 16° and 33° N, and longitudes 34° and 56° E with estimated area of nearly 868,730 mi^2. The geography of Saudi Arabia is dominated by the Arabian Desert and associated semi-desert and shrub-land forming a number of connected deserts including the desert of Empty Quarter which covers an area of nearly 640000 km^2 in the southern part of the country and regarded as the world's largest contiguous sand desert. Rivers and lakes in the country are almost non-existent, unlike valleys which are numerous.

One of the main topographical features in the country is the Central Plateau which mounts sharply from the Red Sea and slopes steadily into the Nejd and toward the Arabian Gulf. Tihamah is a limited coastal plain parallel to the Red Sea coast which is considered as one of the most fertile areas in the country. The highest point in the country is Mount Sawda which is located in the southwest area of Asir with 3,133 m above the sea level.

Saudi Arabia can be divided into four main geographical areas which are the western mountains with a regular height of 1500 m above the sea level, the central hills with very hot and dry summers and dry and cold winters, the deserts which covers huge regions across the country with temperatures of about 50^{o} in summers, and the coastal areas with 2230 km on the Red Sea and the Arabian Gulf (Bachellerie, 2012; Hepbasli & Alsuhaibani, 2011).

A desert climate dominates on the majority of Saudi Arabia with particularly high day-time temperatures and a quick temperature decrease at night. Average summer and winter temperatures are nearly 45 °C and 10 °C, respectively in the midday. In the spring and autumn, the heat is reasonable with nearly 29 °C in the midday. The south-western area of Asir is the only exception as it is affected by the Indian Ocean monsoons which blow between October and March providing rainfall with an average of 300 mm.

Saudi Arabia has seen a remarkable urban development and rapid economic growth during the last decades due to the recovery of oil prices and the government's desire to develop some other sectors that do not rely on oil to diversify the sources of national income. This leads Saudi Arabia to be one of the major energy consumers in the Middle East, where electricity consumption is increasing annually by nearly 4%. This means that generating capacity should be amplified twice every one decade. The total consumption electricity in Saudi Arabia increased from 163150 GWh in 2006 to more than 169300 GWh in 2007. This was followed by raped increase reaching the level of nearly 194000 after just two years in 2009. In Saudi Arabia, electricity capacity and peak load have increased in parallel over the last years with a reserve boundary of 15% in average.

However, decommissioning of nearly 5 GW is predictable by the end of 2015 if the peak load continues with the current increasing level (Bachellerie, 2012; Solar energy in GCC construction, 2012; Taleb & Sharples, 2006).

The population in Saudi Arabia is relatively small compared to the geographical areas and inhabitants are distributed in general across huge areas forming small villages and rural communities on significant distances from main power supply stations. According to the available archives of Electricity Saudi Company (ESC), Jeddah, there is a crisis in Saudi Arabia in supplying enough electricity to large cities and remote areas in various parts, especially small villages near the fertile valleys which branch from the mountains of Red Sea. Figure 5.1 shows the locations of a number of distance off-grid villages that use alternative solutions, such as household or central electrical power generators.

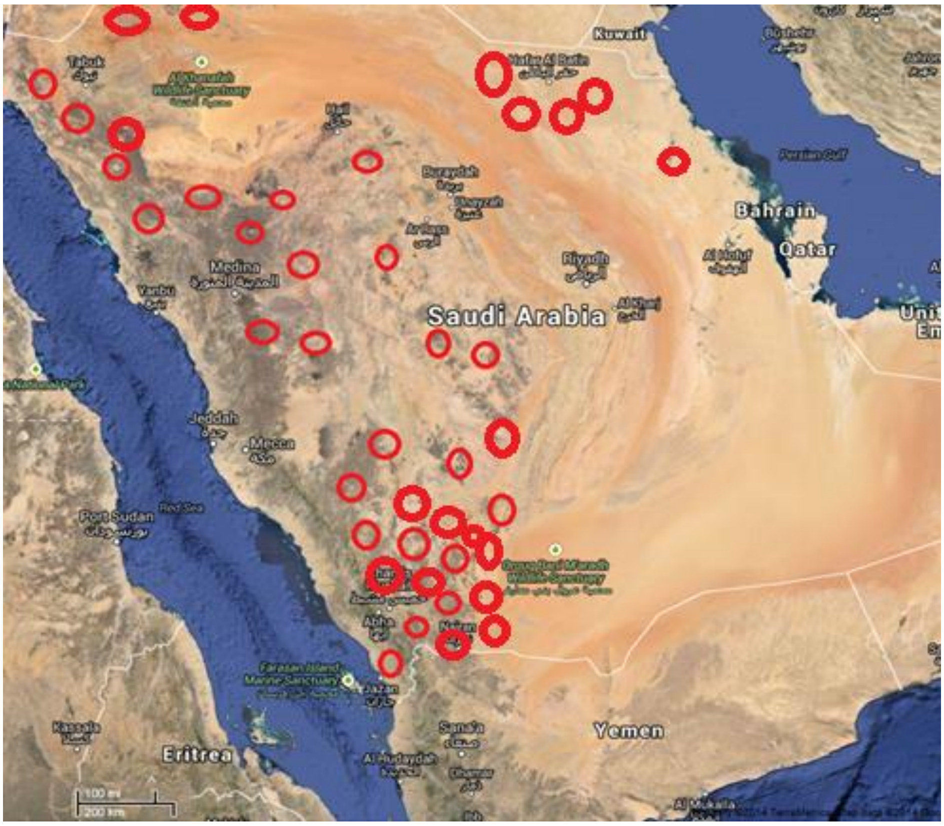


Fig 5.1: Example of the remote off-grid villages in Saudi Arabia
Data source: Archives of ESC, Jeddah

Figure 5.2 shows aerial photographs for some remote villages in the far south-west of Saudi Arabia close international border with Yemen.

Fig 5.2: Aerial photographs for some remote villages in the far south-west of Saudi Arabia close the international borders with Yemen. Data source: archives of ESC, Jeddah and Saudi Ordnance Survey (SOS), Riyadh.

According to an interview carried out by the author with the director of ESC, Jeddah branch, in June, 2013, more than 12500 rural communities were connected to the main grids in Saudi Arabia from 2008 to 2012 providing electricity to more than 1,638,000 users. However, several hundreds of rural areas still do not have electricity services. Initial research about such off-grid distance villages have been carried out by the author in the records of ESC in Jeddah showing that there are 287 off-grid remote and rural areas are distributed on the far south-west, north-west, along the fertile valleys which branches from the mountains of Red Sea, and close to the international borders of Saudi Arabia with Yemen, Oman, Jordan and Iraq. The number of population in these remote areas in common fluctuates from a few tens to several hundreds and the main activates of population are agriculture, beekeeping and grazing sheep and camels.

The majority of these areas depend mainly on the household electrical power generators even in the vital facilities if founded, such as dispensaries, schools, and police stations. Some villages with higher population have been provided with central electrical power generators which may not adequate for covering the needs of the local population and this sometimes leads to run the generators during just certain periods of the day, especially during the night.

Based on the studies applied by Alwefak Company in favour of ESC in 2010, the distribution of the houses in these areas is really to be systematic, deliberate or planned and within the same remote community, it is common to find out remote houses away from the most densely populated areas in the community of a few kilometres. This is because the majority of these neighbourhoods are distributed along narrow fertile valleys which increase the distance between private homes, especially in the case of widening the borders of properties as in the case of Saudi Arabia, where the average size of owned land in remote areas beyond the 20 hectares and the population density does not exceed the rate of one person per 10,000 square meter.

Fig 5.3: An example of the distribution of houses on huge areas in the south-west of Saudi Arabia. Data source: archives of ESC, Asear and SOS, Riyadh

Figure 5.3 gives an example of the distribution of houses on huge areas in the south-west of Saudi Arabia.

Table 5.1: Basic information about a number of remote off-grid villages in Saudi Arabia

Village No.	NOP	PD person / m^2	SCS	DMG (km)	REC
1	≈ 350	≈1/12500	HG	≈ 220	≈ 30 %
2	≈ 620	≈1/10000	HG	≈ 165	≈ 25%
3	≈ 260	≈1/18000	HG	≈ 190	≈ 25%
4	≈ 785	≈1/4500	CG & HG	≈ 145	≈ 45 %
5	≈ 390	≈1/5000	HG	≈ 195	≈ 20 %
6	≈ 485	≈1/13000	HG	≈ 245	≈ 35%
7	≈ 1620	≈1/4500	CG & HG	≈ 160	≈ 55%
8	≈ 1450	≈ 1/10500	HG	≈ 275	≈ 20%
9	≈ 1250	≈1/8500	HG	≈ 185	≈ 30%
10	≈ 1170	≈1/22000	HG	≈ 175	≈ 25%

Note: Data shown in the table are collected from the archives of ESC; Jazan

Table 5.1 gives information about some remote off-grid villages in Saudi Arabia, including the number of population (NOP), population density (PD), the source of current power supply (SCS) (Household generators (HG) or Central Generator (CG)), approximate distance from the nearest main electric grid (DMG) or power plant, and the ratio that is covered from the necessary electricity needs (REC).

REC in the table depends on different factors, such as the size and capacity of the used generators, the rate of electricity consumption, and the availability of the generator fuel. Also, the definition of the “necessary electricity needs” is not unified and changes from person to another depending on the life style, professions traded and the percentage of awareness and education. For example, according to the same studies applied by Alwefak Company in favour of ESC in 2010, air conditioning is regarded as aspects of luxury that can be dispensed with, while others consider that as a one of the basic necessities for living in such hot-climate areas. This difference in views includes almost all electrical appliances, except lights that have become the main necessities everywhere. In the following section, the main reasons behind non-availability of electricity to a number of remote and rural communities in Saudi Arabia will be discussed.

5.3 The Reasons behind Electric Power Crisis in Distance Communities in Saudi Arabia

5.3.1 The Weakness of the Financial Returns Compared to the Cost of Providing the Service

As mentioned in the previous section, the population in Saudi Arabia is comparatively small compared to the geographical areas and populations are distributed on the whole across huge areas creating small villages and rural communities on significant distances from main power supply stations. Furthermore, the distribution of the houses in the remote areas in Saudi Arabia is really to be organized or planned and they are distributed on huge areas along narrow fertile valleys. Therefore, within the same remote village, it is normal to find out smaller neighbourhoods away from the main populated areas in the village of a few kilometres. This can also be attributed to the magnitude-owned spaces in such areas which averaged about 20,000 m^2.

Connecting the isolated and remote off-grid areas to the main electricity grid is often challenge and extremely costly and requires frequent repairing. The cost of linking the rural villages to the main grid depends on several factors, namely: the distance between the village and the capable power station or main grid, the geographical nature of the area, the availability of some necessary services along the supply line, especially paved roads or affordable ways for the mechanics of installation.

According to the interview that carried out by the author with the director of ESC, Jeddah branch and based on the previous projects for connecting the rural areas to the main grids, the average cost is nearly £80,000 per kilometre and this increases to reach more than £150,000 in the case of hard topographies, such as mountain slopes, slopes of clay, sand dunes and valleys. An example of such projects is that suggested in 2012 by the main electric company in the country to the government for connecting 72 rural communities in Fayfa and Najran, in the far south-west of Saudi Arabia. This suggested project has been planned to serve about 18,000 people and applied in 5 years.

The project includes the construction of about 325 km of 33 kV distribution lines, 3200 km of 11 kV lines and 22 transfer stations (33/11 quality of 5 MVA). This is in addition to the secondary equipment, including low-voltage transformers, and connectors meters. The overall cost of this project was about £493,522,000 which means that the cost is about £27,000 for each person in the area. The expected financial returns from these villages average about £320,000 per year.

This basically means that the project failed in economic terms where the finance revenues are impossible to cover the expenses, even after a century. This led the government in Saudi Arabia to turn a blind eye on such solutions and search for better and less expensive solutions.

5.3.2 The Natural Topography of Areas

As stated by the head of Civil Engineering Department in ESC in brief interview with the author in July, 2013, the other important factor that limits providing the electricity to the majority of the remote communities, especially in the south-west of the country is the natural topography of these areas. Steep mountains, mudslides, rugged canyons, unstable rocky areas, valleys with moving silt, sand dunes, and other difficult terrain are natural barriers and inhibitors which hinder linking several areas to the main electric grid.

Fig 5.4: Electric poles in difficult topographies
(https://www.google.com/imghp)

Such difficult topographies can practically affect the extension of the electric grid where fixing the electricity poles and towers becomes complicated and unsafe at the same time. Also, the installation of transfer stations and the secondary equipment, including low-voltage transformers, and connectors meters becomes difficult and needs people with high expertise. Such requirements increase considerably the cost of such projects to be uneconomical. Figure 5.4 gives an example of the difficulties of fixing electricity poles in areas with different levels. Figure 5.5 gives examples of the difficult topography and terrain of the area.

Fig 5.5: Examples of the difficult topography and terrain in the south-west of Saudi Arabia (https://www.google.com/imghp)

This is in addition to the high cost of maintenance in these areas where the rate tends to be more than double the cost of maintenance in the flat areas. According to the maintenance records of Saudi Electric Company, Riyadh, the cost of repairing 128 km of 33 kV distribution lines and 1250 km of 11 kV lines in the mounts of Red Sea between Al Bahah, Sabt Alalayah, and An Namas during the period stretching from 2008 to 2011 is approximately double the cost of repairing 220 km of 33 kV distribution lines and 1630 km of kV lines in region of Hafar Al Batin close to the international boards with Iraq and Kuwait.

In 2013, flooding of seasonal valleys, mountain collapsing, and mudslides led to frequent interruptions in the electricity supply to wide areas in Saudi Arabia, especially in the in-grid rural and distance areas where the high voltage lines are stretched over long distances and usually well not be maintained because of the high cost of maintenance. The exorbitant repairs and maintenance carried out for re-providing the electricity included many of the high and medium voltage towers, poles and transformers, which led to heavy losses for the electricity company.

Such events have made the electricity companies realize that connecting these areas to the main electric networks would not be appropriate for both the investor and user and resorted to provide remote villages that relatively have higher population density with central electric generators and advised the residents of smaller communities to use domestic electric generators.

Figure 5.6 gives examples about the impact of mountain collapsing, and mudslides flooding of seasonal valleys in Saudi Arabia on the electrical supply lines.

Fig 5.6: Flooding of seasonal valleys, mountain collapsing, and mudslides in Saudi Arabia (https://www.google.com/imghp)

As maintained by the deputy head of geotechnical engineering department in ESC, Jazan in brief interview with the author in July 2014, sand dune encroachment has a significant impact on the power transmission lines where sands can cover the foundations and columns of mineral towers through which conductors carrying electric current. This tends to accelerate the rust and corrosion in the steel towers and reduces the lifespan strongly. Drifting and moving dunes from areas under electrical conductors reduces the interval vertical distance between conductors and ground, putting the safety of attendees desert as well as electrical networks in serious dangers.

Closing roads and terraces around the towers and columns along the electrical lines is another expected impact of sand dune encroachment which can delay the works of inspection and regular maintenance and obstruct the arrival of equipment and maintenance teams to the affected areas. Furthermore, the leakage of dust and sand into parts of electrical equipment, such as operating devices, transformers, and adopters along the overhead lines cause damaging problems.

Sandblasting works on roughing the smooth surfaces of dielectrics leading to reduce its effectiveness and makes it susceptible to the accumulation of dust and salts affecting the insulation ability of surfaces. Sandblasting works also on removing the protection layer of metal towers and columns for rust, corrosion, erosion, and oxidisation and as a consequence the design life is reduced significantly and cost of re-changed or repainted such overhead high voltage lines tends to be considerable. Figure 5.7 gives example of the impacts of Sand dune encroachment on the power transmission lines.

Fig 5.7: The Impact of sand dune encroachment and Sandstorms on the power transmission lines (https://www.google.com/imghp)

5.3.3 The Regulations of Providing the Electric Services

According to the policy regulations of the electricity companies followed in Saudi Arabia (documents of SEC, Riyadh), each locality would like to take advantages of the electricity services has to be officially registered in the administrative departments of the area as a residential area or rural community. In order to be registered as a community in Saudi Arabia, the following requirements must be available:

1- The number of population is more than 1500 distributed on an area of less than 1 square kilometre.
2- The presence of a paved road planned by the authorities and the official responsible and suitable of the mechanics of power companies.
3- The community should include at least one primary school, clinic and police point.
4- The presence of the population in the region throughout the year, not only on a seasonal basis.
5- There are not any legal issues on the ownership of the real estates and lands of the communities.
6- The area has to be within the urban plan subjects of the Ministry of Utilities

Based on the records and field studies applied by the Research Group in ESC, Nagran, in 2012, these conditions do not apply to a great deal of the rural communities in Saudi Arabia where the majority of these villages have smaller rate of population and distributed on larger areas. Furthermore, paved roads or even country roads that suitable for large cranes, equipment and vehicles may not be available in lot of areas. As for schools, clinic and police points, it is common to find that several villages share the same facilities. People in these areas are usually traveling between their houses in the agricultural and grazing areas in winter and summer, respectively which tend to be spaced and they spend several months in each area.

However, during the last a few years, these regulations have been deactivated, especially after the surge in oil prices and the increase in the national income of the country. As mentioned before, more than 12500 rural communities were connected to the main grids in Saudi Arabia providing electricity to more than 1,638,000 users. However, several hundreds of rural areas are still off-grid using local or central electric generators and this can be mainly attributed to the first two reasons, namely the rate of returns to the cost and the topography of these areas.

5.3.4 Other Reasons

According to other studies applied by Alwefak Company in favour of ESC in 2013, in addition to these reasons mentioned above, there are other sub-reasons that delay providing the electricity services to these communities which are:

1- Property problems between different administrative areas on wide areas belong to these rural communities.

2- Lack of insistence on demanding the provision of basic services in these areas because of the low awareness and education level and the transmission of the educated people to live in cities.

3- Some of these communities were built randomly without planning or permissions of the government and the provision of the basic services to these villages will increase this phenomenon unwanted by the Saudi government.

4- Low electricity prices in Saudi Arabia make the delivery of electricity service to those areas inefficient economically leading to heavy losses on the operating companies.

5- The central governing system of the administrative regions in Saudi Arabia where all the attention and services are focused and available on the provincial capital of the province and decrease as moving away the centre to the county sides.

6- Lack of encouraging the private tourism sectors in these areas, which will lead to an increase in the number of tourists and investors, thereby reducing the cost of providing services and increasing financial returns.

7- Failure to provide plans by the competent authorities to build up integrated rural villages including schools, clinics and police station for those living in random rural areas and provide safe ways to get to farms and pastures easily.

5.4 Current Solutions

After discussing the reasons behind not linking a considerable number of remote communities to the main grid in Saudi Arabia, this section will highlight the current used solutions for providing electricity and some suggested and planned solutions.

5.4.1 Household and Central Electrical Power Generators

Household electrical power generators are considered to be the most common source of electricity in the majority of the off-grid distance communities in Saudi Arabia. Initial statistics applied by the author based on the records of Saudi Electric Company in August, 2013, show that 92% from the whole number of the off-grid rural villages depends mainly on the home generators and 5% depend only on central generators where as 3% use the two solutions together (Taleb & Sharples, 2006).

In 2005, the electricity consumption in Saudi Arabia reached the level of 7 kWh per capita with annually increases of 6.2% during the period from 2005 to 2008. In accordance with the Ministry of Water and Electricity in Saudi Arabia, the residential sector consumed around 53% of the entirety electricity generated in 2007 and approximately 80% of this value is consumed for residential air conditioning due to the harsh climate conditions and design of buildings which is usually far from being energy-efficient (Solar energy in GCC construction, 2012; Taleb & Sharples, 2006).

According to studies carried out by the Department of Statistics in Saudi Electric Company in December, 2012, in rural communities, the average electricity consumption is nearly 3.2 kWh per capita in summers with air conditioning and it reduces to less than 1.8 kWh per capital in winters if gas based heating system are used. If electricity based heating system are in use, the average electricity consumption increases to reach 4.1 kWh per capita.

The size of generator depends on the power needs which can be determined as explained in chapter three in Table 3.1 and this will be discussed in details in chapter six when designing the whole PV system for a chosen rural village in Saudi Arabia. Based on the results illustrated in Table 5.1, home generators can just cover in average 25% of the necessary electricity needs in the distance areas in Saudi Arabia. This low percentage can be mainly attributed to the size and capacity of the used generators compared to the rate of electricity consumption.

Home petrol generators with power of 1.2 kW, 1.6 kW, 1.8 kW, and 2.4 kW are very common in the south-west of the country as they are low-cost and easy to repair. Home diesel generators which tend to be more powerful and can provide up to 16 kW are not desirable due to the high cost of these generators and the difficulties of repairing and also because of the lack of diesel distribution stations compared to oil. Figure 5.8 gives examples of common home generators in the south-west of Saudi Arabia.

Fig 5.8: An example of the common size of home generators in Saudi Arabia, https://www.google.com/imghp

As for the central generators provided by Saudi Electric Company for some rural villages, they are in general diesel generators with power capabilities of 100 kWh and up to 375 kWh. Table (5.2) compares the average electricity consumption of a few off-grid villages in the south-west of Saudi Arabia to the capability of the available generators. The data source is the archives of ESC, Jazan.

Table 5.2: Electricity consumption and capability of the available generators

No.	Allowed Electricity Consumption (kWh)/House	Necessary Electricity Needs (kWh)/House	Number of houses	Capability of the available generators (kW)
1	3.6	16	22	100
2	3.1	18	38	150
3	3.5	16	45	200
4	3.2	17	62	200
5	3.4	17	86	375

From the Table it is clear that nearly 25% from the necessary electric needs of the house are provided by the available central generators. This percentage can be increased to reach about 45% if integration between central and house hold generates is used.

The reason behind such significant differences between the required and allowed rate is the lack of planning when choosing the size of generators where they have been chosen just to cover very basic necessaries, such as lightning at night and pumping water during the day without taken into account increasing the number of population in the target area. Figure 5.9 give examples about the central generators used in Saudi Arabia for remote villages.

Figure 5.9: Examples of central generators used in Saudi Arabia for remote villages (https://www.google.com/imghp)

5.4.2 Connectivity with the Electrical Networks of Neighbouring Countries

According to an interview carried out by the author with the director of ESC, the main branch, Riyadh in September, 2013, one of the suggested solutions by ESC, for rural communities that located close to the international borders of the country is the linking with the electric networks of the neighbouring countries. This solution can overcome the problem of extending the high voltage lines as well as electricity columns and can provide continued electricity services to a significant number of remote villages.

This solution is common in a great deal of countries across the world and even in the Middle East where it is used in Turkey, Syria, Libya, Egypt, Lebanon, Kurdistan (Iraq), Jordan, etc. However, this solution is hard to be applied in the case of Saudi Arabia where the surrounded countries have nearly the same problem where the main cities are away from the international borders and the majority of border villages are off-grid.

A clear example is the villages in the south-east of Saudi Arabia which are close to the international borders with Yamen where the main electricity grid that capable to be used in Yamen distances about 320 km. Figure 5.10 shows the distribution of cities and villages on the international borders of Saudi Arabia and Yamen.

5.4.3 Renewable Energy

Saudi Arabia, the largest country in the Gulf region has huge potentials for exploiting solar energy with both CSP and PV technologies. This is in addition to the country’s long coasts, which are ideal for CSP solar energy to be used for producing power and water desalination plants. Saudi Arabia as the other Gulf countries is rich in renewable resources as it is rich with hydrocarbons.

Fig 5.10: The distribution of cities and villages on the international borders of Saudi Arabia and Yamen. (https://www.google.com/imghp)

In addition to the significant wind resources, geothermal and biomass from urban waste, Saudi Arabia benefits from strong regular sunshine and has vast empty areas suitable for developing huge solar power plants. Electricity generated from renewable resources, especially solar energy means that more oil and gas will be exported as domestic consumption in terms of hydrocarbons will be reduced (Solar energy in GCC construction, 2012, Taleb & Sharples, 2006).

Huge investments have been adopted by Saudi Arabia's governments throughout the last a few decades in solar technologies. This includes research and development programmers for developing the local solar energy sector and meeting the country's growing demand for power and water in recent years. Such huge demand is extremely difficult to be met via hydrocarbon fuels without reducing exportable surplus.

Solar energy is also expected to help Saudi Arabia specifically for reducing CO^2 emissions, where Saudi Arabia and the surrounded GCC countries, namely, UAE, Qatar, Kuwait, Oman and Bahrain are in the top 14 per capita emitters of carbon dioxide across the world. This can also be supported by the fact that generating electricity via solar energy, especially in areas with high solar irradiation, such as GCC region becomes more commercial with time, where the efficiency of solar energy systems tend to be significant (Solar energy in GCC construction, 2012)

The cost of the solar power systems drops dramatically due to improving technology and growing competition. Furthermore, solar power generation is naturally matched with demand patterns throughout the year where in summers air conditioning dominates the electricity demand curve, particularly in GCC countries. Producing commercially viable and low-cost solar power technology has been a common aim between the successive governments in Saudi Arabia and a number of private institutions, which led the solar energy research projects in Saudi Arabia. Power generation via PV technologies is considered as one of active and hot research areas in this country. These researches have two main objectives, namely allowing the expansion in this industrial sector to be large commercialization in near future and meeting climatic and geographical conditions. (Alnaser & Alnaser, 2011; Doukas et al, 2006).

Several factors, such as the availability of financial resources, low-cost energy, and considerable demand potential help Saudi Arabia to be an attractive market for both CSP and upstream PV manufacturing activities. One of the most promising activities is to industrialize silicon ingots and wafers to meet the requirements of the region’s solar technology markets (Bachellerie, 2012; Solar energy in GCC construction, 2012; Taleb & Sharples, 2006).

Currently, several local and natural companies, such as Mutajadedah Energy Co, Chemical Development Co Incorporated, and KCC Corp are working in poly-silicon technology project along the Gulf coast in Saudi Arabia, which is planned to provide 3350 metric tons of solar grade poly-silicon annually by the end of 2014. The annual capacity of the project is planned to be increased to 12000 metric tons by 2017. Also, manufacturing of ingots and wafers is another near future aim of this project. Saudi's solar goals appear to be the most competitive in the region, where the Kingdom plans for solar energy to form one-third of the whole electricity demand by 2032 (Bachellerie, 2012).

Despite the great attention given by Saudi Arabia of renewable energy for more than 3 decades and despite the wide planes for considering solar energy as an important energy resource, the efforts for using this great energy resource in commercially viable projects have been scattered and almost unnoticed and the main researches and investments in solar sector have concentrated on large-scale projects. Such strategic projects were driven to avoid the expected gaps in urban areas between the growing demand for electricity and supply. Meanwhile, wide range of remote areas still suffers from a severe shortage of power supply (Taleb & Sharples, 2006).

Studies about the possibility of using small-scale solar energy technologies, such as SABIPV in Saudi Arabia as a fundamental solution for supplying a wide range of remote, distant and rural areas with electricity are almost non-existent and still needs more and more investigation. This thesis planes to provide a clear prospect and reliable investigation into the potential of using BIPV technologies with different sunlight tracking sensors as an optimal solution for providing a considerable number of remote villages and rural communities in Saudi Arabia with solar energy. The project will also present the expected long-term impacts of solar energy on some important issues, especially those of countryside-to-city migration and reducing pollution. Also, more reliable and independent investigations and studies into the potentials of using solar energy technologies both PV and CSP to cover the expected decommissioning in electricity supplying are required.

Chapter Conclusion

This chapter has covered the first objective of this project providing an overview about the electric power crisis in rural areas with examples about the spread of these remote villages in Saudi Arabia, the number of population, population density, the source of current power supply, approximate distance from the nearest main electric grid or power plant, and the ratio that is covered from the necessary electricity needs. The reasons behind the crisis in supplying electricity to domestic remote and rural off-grid areas in Saudi Arabia have been explained including economical, topographic, local regulations, and other possible causes. The current used and suggested solutions have been also covered in this chapter highlighting the main features of each solution, the limitations and efforts carried out.

Chapter Six: SABIPV System for Saudi Rural Villages: Fundamental or Complementary Solution?

6.1 Introduction

In this chapter, one of the rural off-grid villages in Saudi Arabia will be chosen as a case study. The chapter will start with giving adequate information about this village including the geographical location, population density and distribution, topography, climate, solar radiation, and the current source of electricity. The chapter will also highlight briefly the reasons behind the delay of connecting this village to the main grid and the solutions suggested by the local main power company in Saudi Arabia for providing electricity services. Then, one of the houses in the village will be chosen to be used for designing Stand-Alone Building Integrated PV system. The design will include sizing the main components of the system including the panels and tracking system, storage system, inverter, and charge controller. The amount of energy expected to be provided with the design SABIPV system will be compared with the necessary electricity consumption to investigate whether the designed system can be used as a fundamental or complementary power source in the remote community in Saudi Arabia.

6.2 Case Study: Al Rakabah Village

6.2.1 General and Important Information

Al Rakabah is a small village located in the District of Bani Malik,Jizanin the south-western part of Saudi Arabia. The centre of village is located on latitude of 17.317968^o and longitude of 43.169661^o and the village stretches over vast areas. The village is bordered from the north by Addayer and from the south-west by Viva Mounts. From the west, it is bordered by Al Hojfah, Al Qateel and Al Sheban. As for the south, the village stretches reaching That Almesk close to Saudi Arabia's southern border. The heights in this area start from 2100 m reaching 2980 m in the highest regain above the sea level. This height is close to the highest point in the country which is Mount Sawda located in the southwest area of Asir with 3,133 m above the sea level. Figure 6.1 shows the geographical location of Al Rakabah.

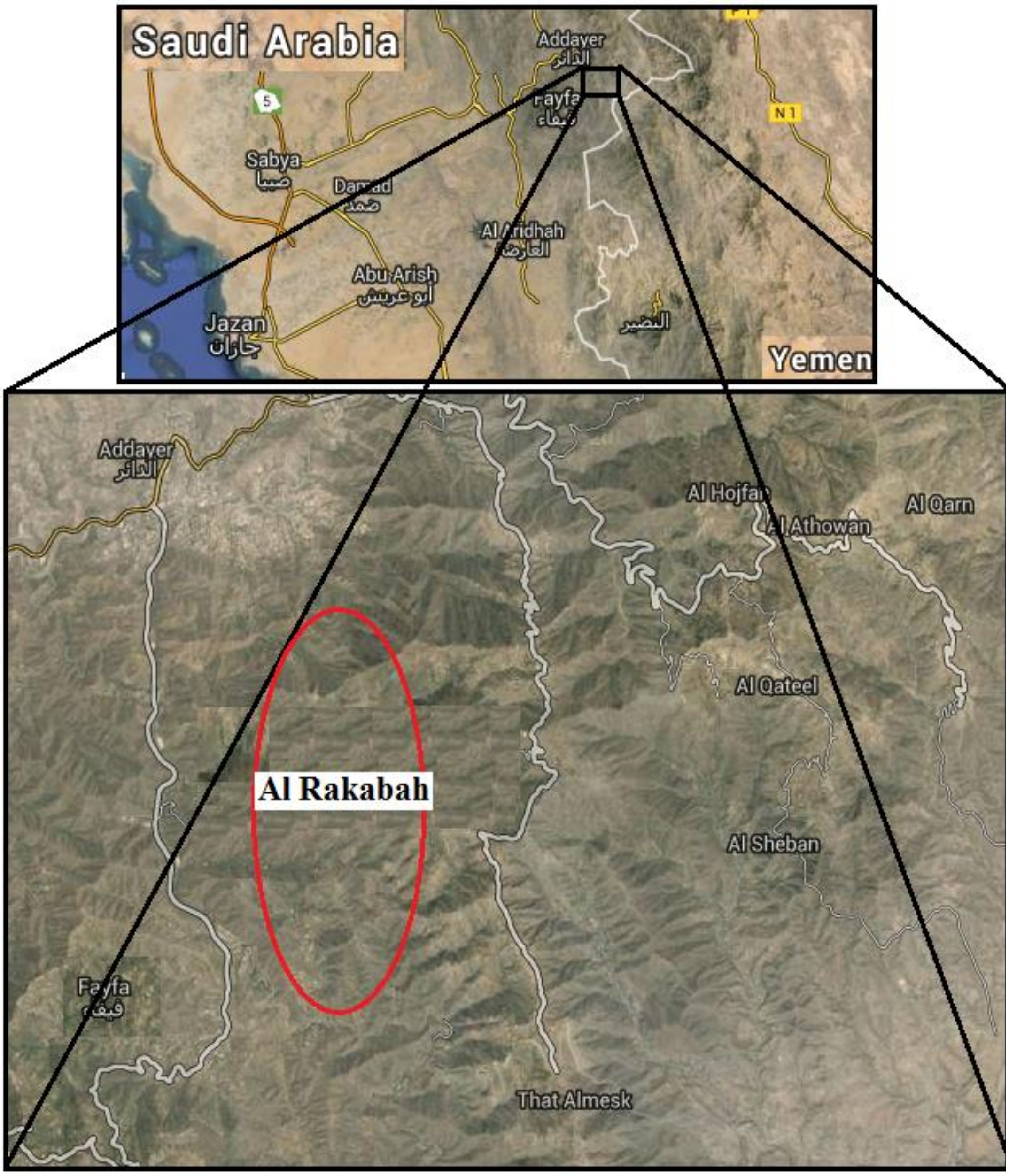


Fig 6.1: The geographical location of Al Rakabah, (https://www.google.com/imghp)

The village can be divided into five main geographical areas which are the eastern rocky mountains with an average height of 2500 m above the sea level, the central mountain ranges with fertile slopes and an average height of 2750 m above the sea level , narrow fertile valleys that stretch between the highlands with an average height of 2150 m above the sea level, rocky mountains with an average height of 2500 m above the sea level, rugged mountains and steep on the west side of the village which are interspersed by fertile valleys with sandy clay soil, and finally, southern highlands and valleys which characterized by the large disparity in the heights where the difference in heights can reach the range of 1000 m in no more than 150 as a horizontal distances. Figure 6.2 gives examples of the different topography and terrain of the village.

Fig 6.2: Examples of the different topographies of AlRakabah, https://www.google.com/imghp

During the last decade, the area experienced frequent mountain collapses, mudslides, flooding, and flow of muddy valleys which led to plunging large agricultural areas and destroy crops. Figure 6.3 gives examples about mountain collapses, mudslides, flooding, and flow of the valleys in Al Rakabah.

Fig 6.3: Mountain collapses, mudslides, flooding, and flow of the valleys in Al Rakabah, (https://www.google.com/imghp)

The distribution of the houses as well as farms in this village is completely unsystematic and unplanned even in the centre of the village which has the highest relatively population density as can be seen from Figure 6.4. The number of population is nearly 1400, which is significantly small compared to the whole area of village nearly (80 km^2). The population density in this area is nearly 1 person for 6 Hectares. This is because the majority of farms and houses are distributed along narrow fertile valleys which increase the distance between private houses. The average area of farms in this area is nearly 40 Hectares where the number of owners (families) in the village is approximately 200 only. Figure 6.4 gives example of the bounders of farmers and the distribution of houses in the valleys.

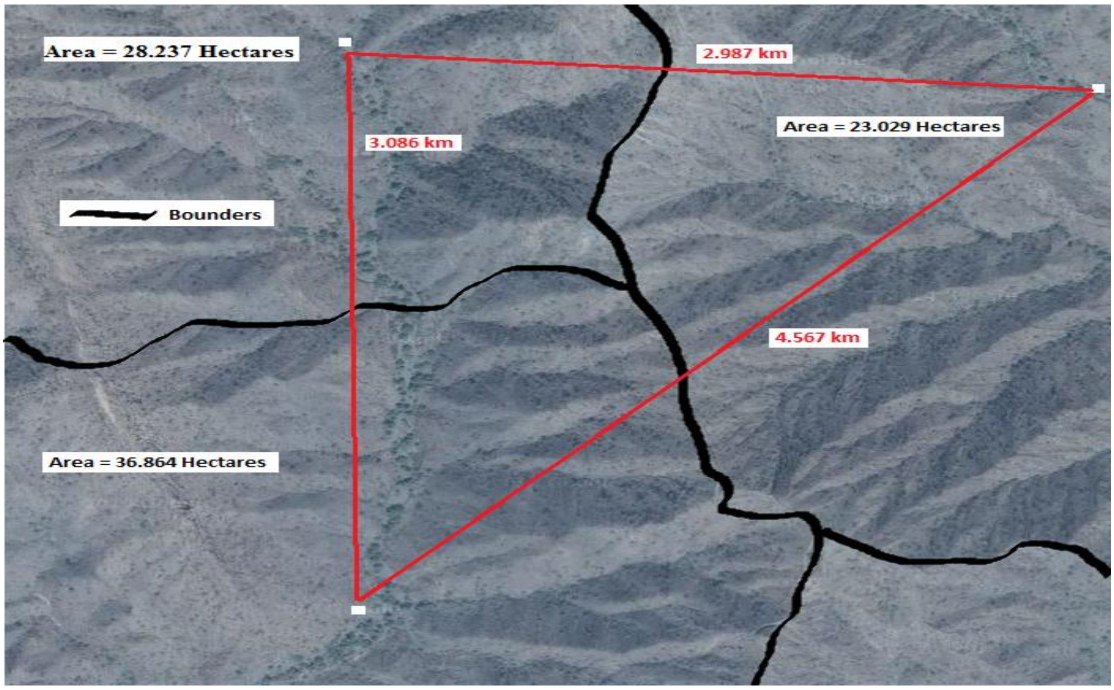


Fig 6.4: Example of the size of farms and the distances between houses, (https://www.google.com/imghp)

According to a privet study applied by AFNAN Company for the benefits of Saudi Electric Company in 2012 (the study is available in the main archive of ESC, Jazan), connecting this village to the main electricity grid will be extremely costly in terms of installation as well as repairing. This has been attributed to the length of the suggested power lines inside the village which exceed 180 km of 11 kilo-voltage lines in addition to 165 km of 33 kV distribution lines and a number of transfer stations (33/11 quality of 5 MVA) with overall cost of £62,170,000. This means that the cost is about £45,000 per person. The expected financial returns from the suggested network average about £50,000 per year. This shows the significant differences between the cost and the returns which is an important reason for the success of any in economic terms.

Such local network is extremely huge and costly compared to the number of target users. The study has attributed the high cost of installation and maintenance also to the hard geographical nature of the area which increases the insurance of workers as well as mechanics due to increasing the risk and the accident rate in such areas and the unavailability of the necessary services along the supply line. Figure 6.5 shows an example of the high risk faced the staff of SEC on a similar hard topography area close to Fayfa Mount.

Fig 6.5: The high risk of working in hard topographic areas (https://www.google.com/imghp)

The regulations followed in Saudi Arabia for providing electricity services to the remote areas have also worked on disabling connecting this village to the main grid. Al Rakabah has not officially registered in the administrative departments of the area as a residential area or rural community until now. This is because the number of population is less than the minimum required number and distributed on an area bigger than that required. Also, the area does not include any paved road planned by the authorities and the official responsible and suitable of the mechanics of power companies. The other important reason is big legal issues on the ownership of the lands in this village where more than 13% from the whole agriculture area in the village are still legally disputed. Houses in this area have been built randomly without planning or permissions of the government and providing electricity services to this village will increase the phenomenon of random villages and communities which were fought by the Saudi governments during the last two decades.

The regulations and the economical and topographical reasons have made SEC believes that connecting this village to the main grid would not be appropriate for both the investor and user and advised the residents of the community to use domestic electric generators which is the only source of electricity in this village and can just cover in average 25% of the necessary electricity needs of each house. Figure 6.6 gives an example of using home petrol electricity generators 1.8 kW in Al Rakabah, which is very common in the area due to the low-cost and easy repairing.

Fig 6.6: Home petrol electricity generators 1.8 kW used in Al Rakabah (https://www.google.com/imghp)

In general, in this section, general and important information about Al Rakabah village chosen as a case study has been given including location, topography, distribution and density of population, some statistics about connecting the village to the main grids, and the reasons hindering providing electricity services. In the following section, very important information about solar radiation that necessary for designing SABIPV system for houses in the case study area will be discussed in details.

6.2.2 Solar Radiation and Design Data

The weather in the area in general is very hot and dry in summers and wet and cold in winters as it is affected by the Indian Ocean monsoons which blow between October and March providing rainfall with an average of nearly 300 mm. Average summer and winter temperatures are nearly 32 °C and 23 °C, respectively in the midday. In the spring and autumn, the heat is reasonable with nearly 28 °C in the midday. Figure 6.7 shows the average midday temperature throughout the year in Al Rakabah.

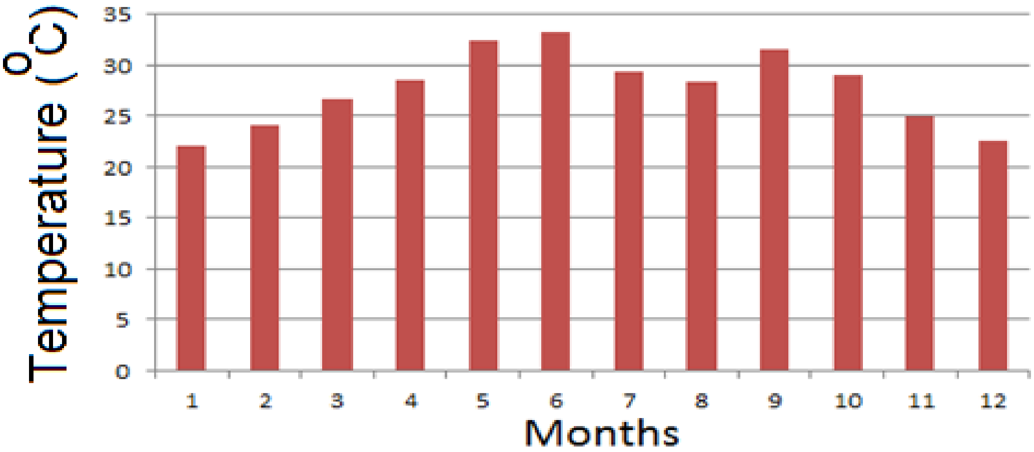


Fig 6.7: The average midday temperature throughout the year in Al Rakabah.

As mentioned in chapter three, two quantities are often used to measure solar radiation, namely irradiance and irradiation. The first is defined as the density of the power which is received by a surface (W/m^2). The second provides more details and defined as the density of the energy that received by a surface over some period of time such as an hour or a day (kWh/m^2/day).The village is located on an area that has one of the highest rates of solar radiation across the world with solar irradiance rate of nearly 350 W/m^2 and solar irradiation rate of nearly 6 kWh/m^2/day. Figure 6.8 shows the distribution of solar irradiance across the world in 2014 and Figure 6.9 shows world solar irradiation map.

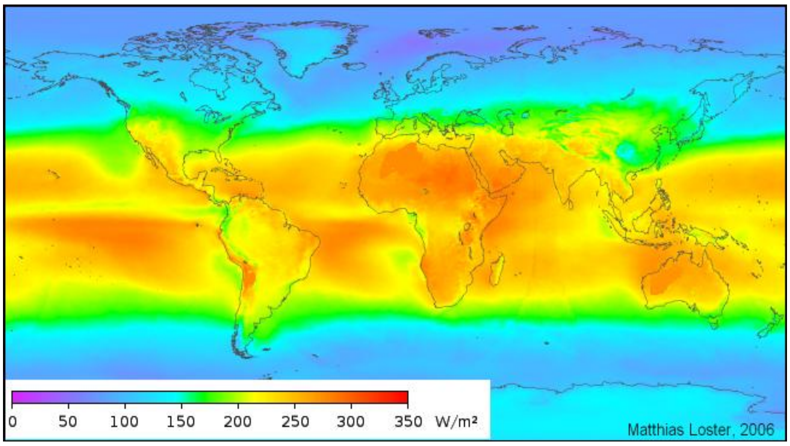


Fig 6.8: Worldwide solar radiation (Solar irradiance, 2014)

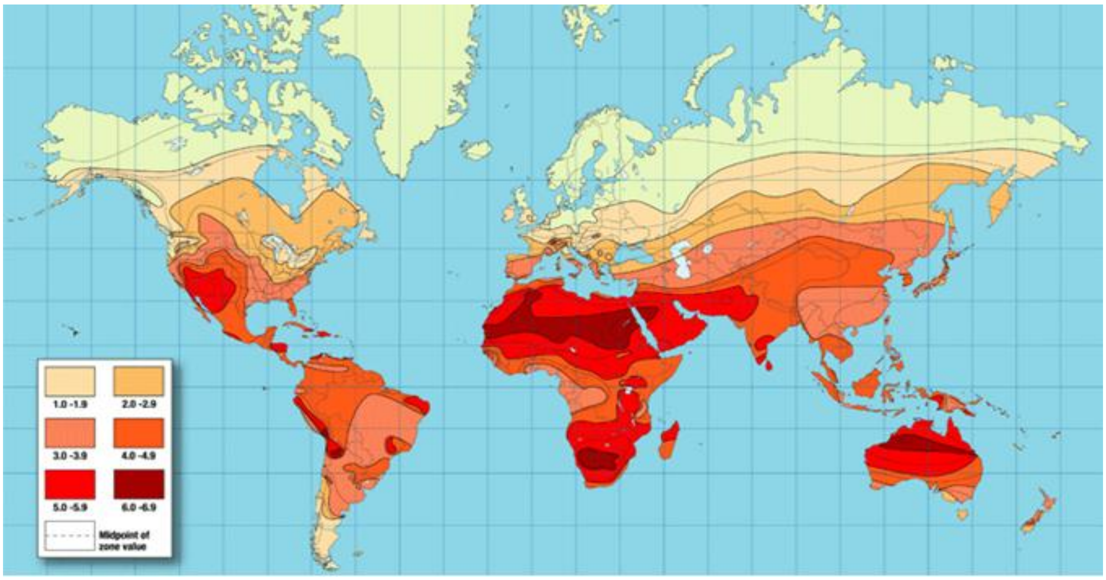


Fig 6.9: World solar irradiation map, (https://www.google.com/imghp)

To determine precise rate of average yearly solar isolation for the village, GPS based coordinates of different sites across the village (diagonal corners of a region) have been taken from the Saudi Ordinary Survey. Coordinates with accuracy of a few metres can be used as solar irradiation tends to be the same for vast areas. Therefore, code stand-alone GPS technique can be adequate for such task. Solar irradiation has been estimated by NASA Surface Meteorology and Solar Resource website.

The user can get for any site estimated values of the monthly minimum, average and maximum solar irradiation in kWh / m^2 / day at ground level with different tilt angles. From the website, the user can choose the suitable tilt angle of the panels and show the distribution of solar irradiation across the year. This is in addition to providing the minimum, average and maximum daytime temperatures at the location of the system and the actual solar irradiation measurements. The reference in the website is SSE Methodology for detailed discussion of the methodology for deriving the SSE horizontal surface insolation from satellite observations.

The monthly average amount of the total solar radiation in Al Rakabah that incident on the earth horizontal surface is shown in Figure 6.10. The illustrated amount is averaged for each month over 22-year period from Jul 1983 to Jun 2005. Each monthly averaged value is evaluated as the numerical average of 3-hourly values for the given month. The monthly average amount of the total solar radiation named also as global horizontal radiation averaged about 6 kWh/m^2/day with standard deviation (3 Sigma) of nearly 1kWh/m^2/day.

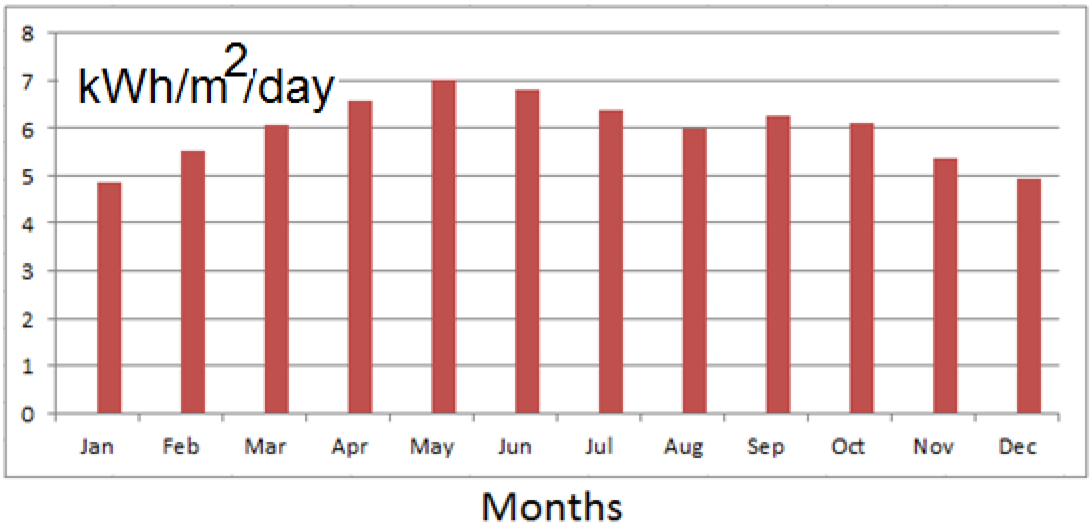


Fig 6.10: The monthly average amount of the total solar radiation that incident on horizontal surface

Comparing to Figure 6.9, it can be noted that solar radiation follows in general the amount of temperatures where the solar radiation is often proportional to the the temperature. It is also clear that there is a little drop in the temperatures as well as the solar radiation in July and August compared to the regular decreasing of these values from May to December. This can be attributed to blowing of winds Arabian Sea's cold wind and Horn of Africa's cold wind on this region in these two months.

The monthly average amount of the midday solar radiation incident on a horizontal surface at the surface of the earth for each month in kW/m^2 is shown in Figure 6.11. Also these values are the average of the same 22-year period mentioned before for each month.

Each monthly averaged value is assessed as the numerical average of the 3-hourly values, one per day, at the time (GMT) closest to local solar noon. The time used is within 1.5 hours of local solar noon. The monthly averaged clear sky insolation in kWh/m^2/day that incidents on a horizontal surface at the surface of the earth when the cloud cover is less than 10% is shown in Figure 6.12.The monthly average of the number of days with an average cloud cover less than 10% is shown in Figure 6.13.

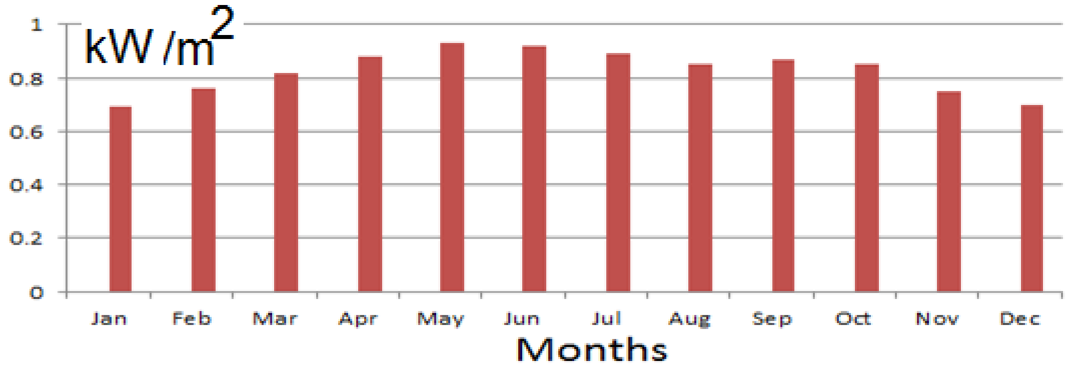


Fig 6.11: The monthly average amount of the midday solar radiation

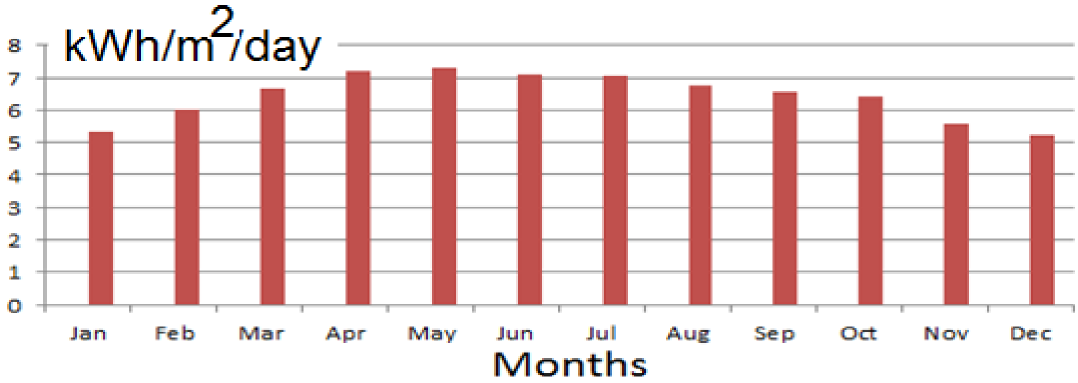


Fig 6.12: The monthly averaged clear sky insolation

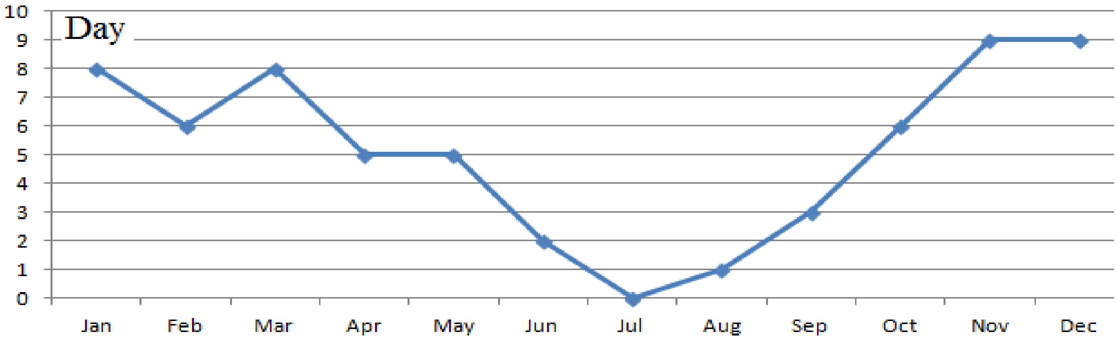


Fig 6.13: The monthly average of the number of clear sky days for each month

It is clear from Figure 6.13 that the number of clear sky days in winters is significant compared to summer months which is useful to balance the relative dropping of solar radiation on winter months.

The monthly averaged diffuse solar radiation incident on a horizontal surface of the earth under all-sky conditions with the direct radiation from the sun's beam blocked by a shadow band or tracking disk for is given in Figure 6.14. The annual average is 1.68 kWh/m^2/day with standard deviation (3 sigma) of 0.25. The monthly average amount of normal solar radiation incident on a surface oriented normal to the solar radiation for each month along the year averages about 6.67 kWh/m^2/day and presented in Figure 6.15.the relationship between Figure (6.15) and Figure 6.13 is clear where the amount of normal radiation increases with increasing the number of clear sky days.

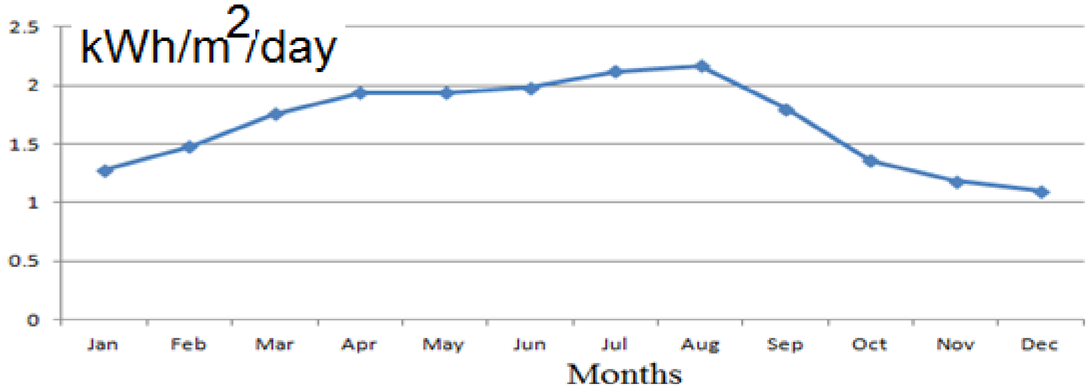


Fig 6.14: The monthly averaged diffuse solar radiation incident on a horizontal surface

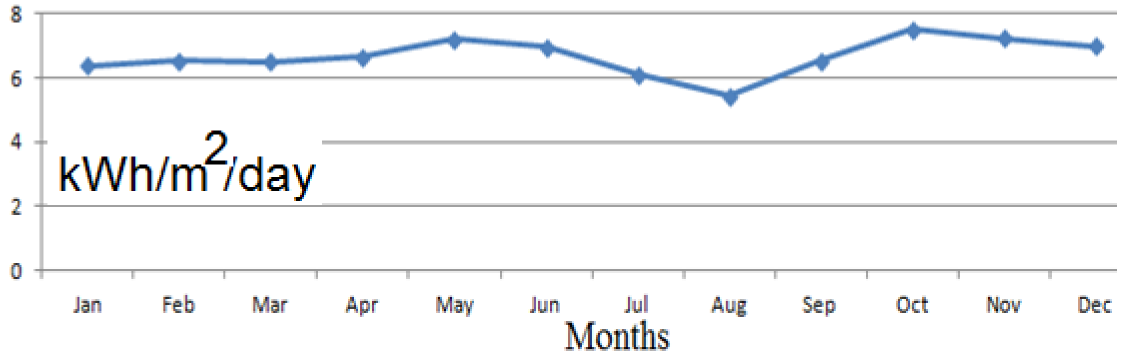


Fig 6.15: The monthly averaged normal solar radiation incident on a surface oriented normal to the solar radiation for each month

The monthly average amount of the total solar radiation incident on a horizontal surface at the surface of the earth for 3-hour intervals of GMT during the given month (kW/m^2) is illustrated in Table 6.1. It is clear from the Table that the maximum amount of radiation is at 09 GMT Time which is the midday time in the village (3 hours from GMT time).

Table 6.1: Monthly averaged insolation (kW/m^2) incident on a horizontal surface at indicated GMT times (3 Hours from local time)

GMT Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00	-	-	-	-	-	-	-	-	-	-	-	-
03	0.01	0.01	0.03	0.05	0.07	0.06	0.05	0.04	0.04	0.04	0.03	0.01
06	0.39	0.44	0.51	0.59	0.62	0.57	0.53	0.52	0.56	0.57	0.51	0.44
09	0.69	0.76	0.82	0.88	0.93	0.92	0.89	0.85	0.87	0.85	0.75	0.70
12	0.45	0.52	0.56	0.55	0.57	0.56	0.52	0.47	0.51	0.48	0.42	0.42
15	0.03	0.04	0.05	0.06	0.07	0.07	0.07	0.05	0.04	0.02	0.01	0.02
18	-	-	-	-	-	-	-	-	-	-	-	-
21	-	-	-	-	-	-	-	-	-	-	-	-

The monthly averaged solar noon which is the time, in which the sun is due south in the northern hemisphere or due north in the southern hemisphere, is shown in Figure 6.16. It is important to note that during polar winter the sun may be below the horizon at solar noon but this is away from the location of the case study.

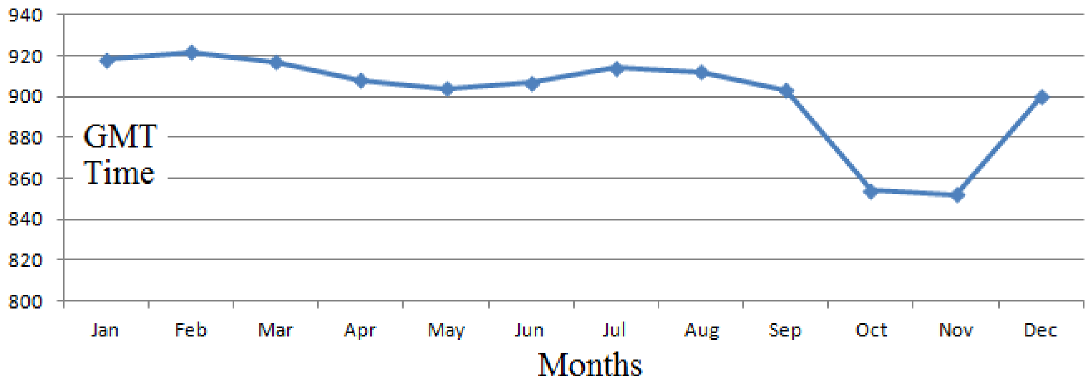


Fig 6.16: The monthly averaged solar noon

The number of hours between sunrise and sunset is another important factor should be taken into account when designing PS system where it affects the overall amount of power generated. The monthly averaged daylight hours is shown in Figure 6.17. It is clear from the chart that the daylight hours average about the half of the day (12 hours) with slight change of one hour during the year. This slight change is attributed to the closeness of the area from the equator where the farer the location from the equator both in North or South direction, the more differences in the daylight hours across the year.

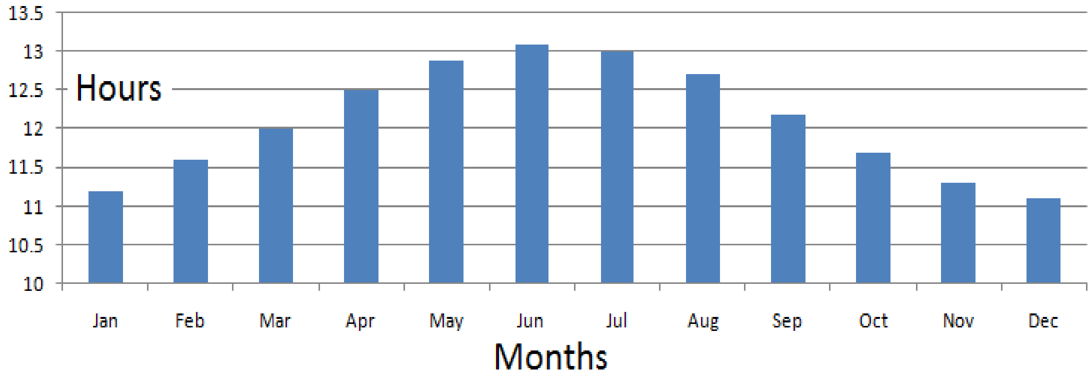


Fig 6.17: The monthly averaged daylight hours

The monthly averaged declinations another factor tends to be taken into account when designing PV systems. The declination is the angular distance of the sun north (positive) or south (negative) of the equator. Declination changes across the year from 23.45° north to 23.45° south and reaches the minimum/maximum at the southern/northern summer solstices. The determination of monthly averaged declination for each month is based on the monthly average day. Figure 6.18 shows the monthly averaged declination in degrees for each month.

The sunset hour angle is the angle that the earth has rotated between the time of solar noon and sunset. Note that the earth rotates 15° with respect to the sun each hour. The determination of monthly averaged sunset hour angle for each month is based on the monthly average day. The monthly averaged sunset hour angle is shown in Figure 6.19.

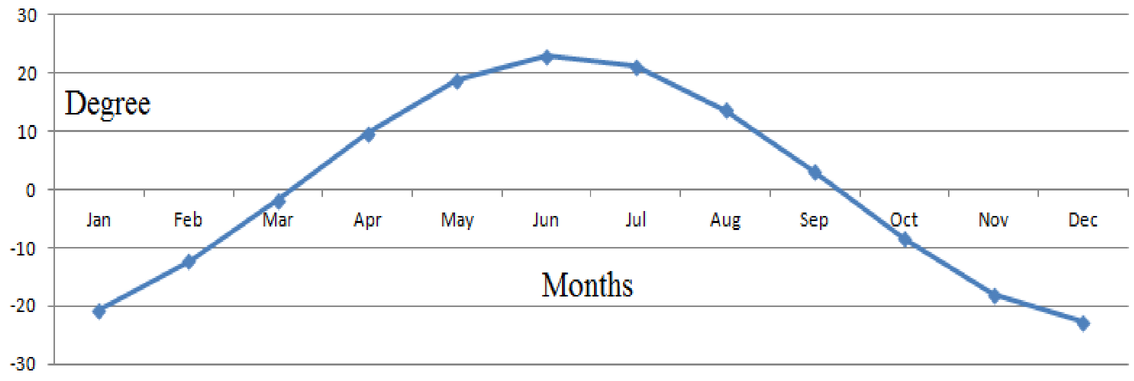


Fig 6.18: The monthly averaged declination in degrees for each month.

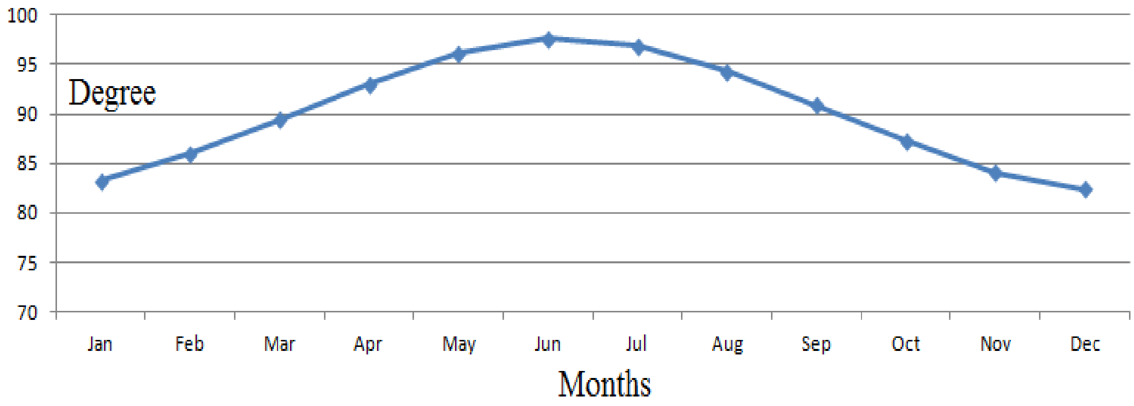


Fig 6.19: The monthly averaged sunset hour angle

The maximum vertical angle of the sun above the horizon is also important, especially in the case of using two axis rotation tracking sensors with the PV panels. In the case of single tracking rotating sensor, the vertical angle of the sun above the horizon does not taken into account where the PV panels following the sun along the East-West path only.

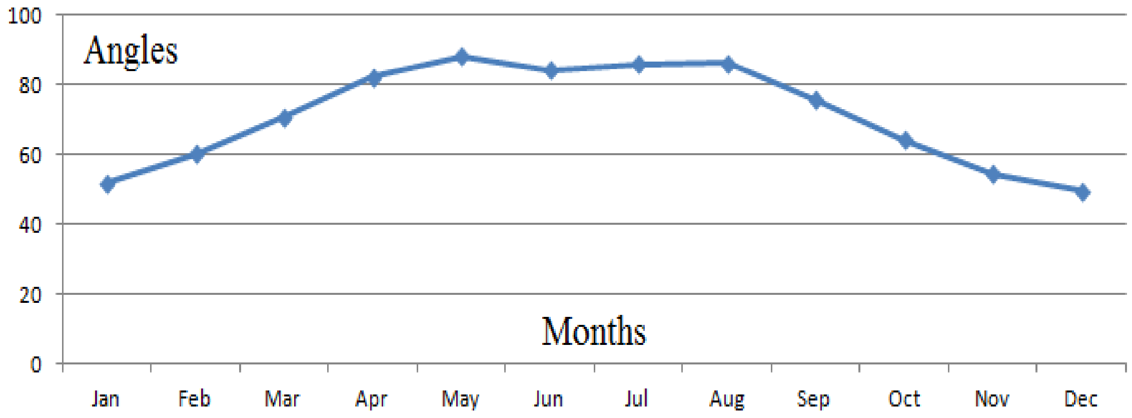


Fig 6.20: The maximum monthly averaged solar angle relative to the horizon

The maximum monthly averaged solar angle relative to the horizon is shown in Figure 6.20.

Figure 6.21 compares the monthly average amount of direct normal radiation incident on a surface oriented normal to the solar radiation (Direct Normal) and the monthly average amount of total solar radiation incident on a surface tilted at the optimum angle relative to the horizontal and pointed toward the equator (OPT). Figure 6.22 shows monthly averaged optimal angle for which the monthly averaged total solar radiation is a maximum.

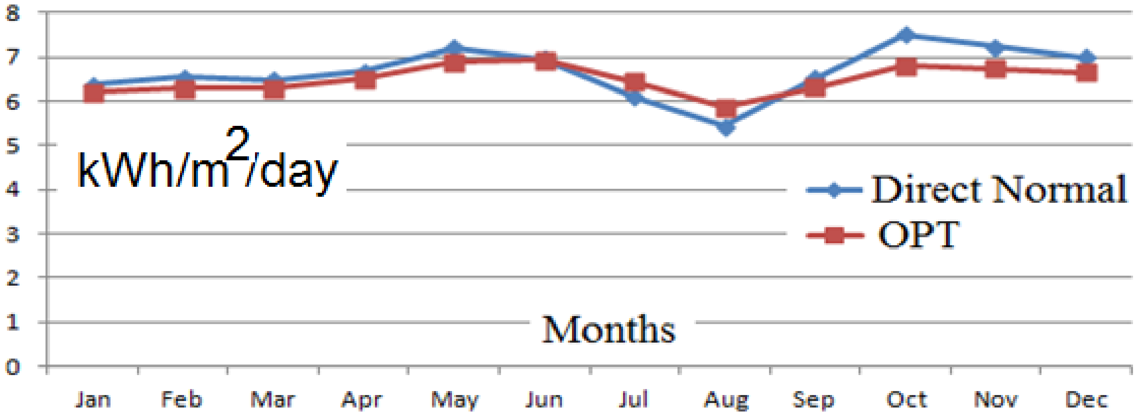


Fig 6.21: Direct Normal VS. OPT

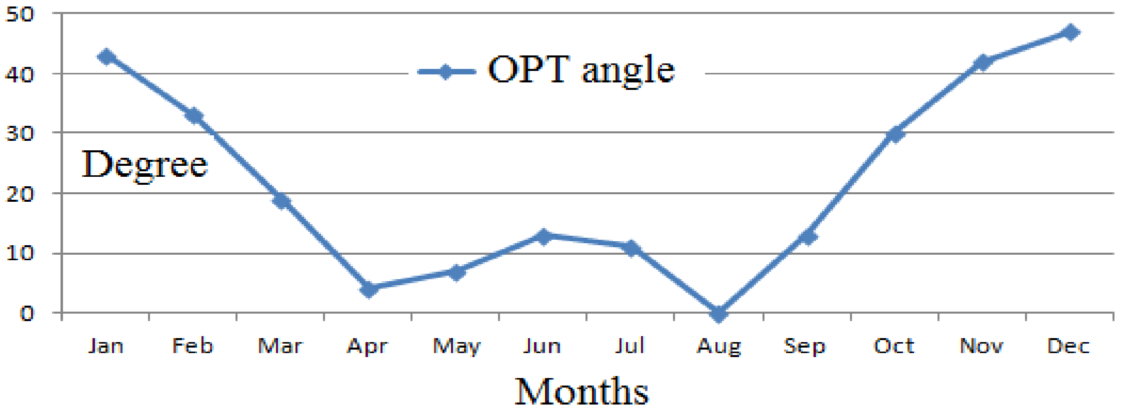


Fig 6.22: The monthly averaged OPT angle

The minimum available insolation over a consecutive-day period is another important factor must be taken into consideration when designing SABIPV system where it is used for sizing the storage system. The minimum available insolation over a consecutive-day period as a percentage of the expected average kWh/m^2 value over the same consecutive-day period is illustrated in Table 6.2.

Table 6.2: The minimum available insolation over a consecutive-day period (%)

Al Rakabah	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Min/1 day	33.3	33.5	26.6	13.1	41.5	47.1	44.7	45.4	57.6	27.8	22.9	31.5
Min/3 day	44.7	43.0	43.7	36.0	52.8	55.6	72.4	67.1	79.2	40.8	55.7	52.3
Min/7 day	61.0	56.1	72.0	60.9	74.1	72.4	80.3	79.9	86.8	53.2	71.1	64.7
Min/14 day	73.7	67.6	77.3	75.6	83.0	78.9	87.3	88.9	90.9	63.3	78.2	77.8
Min/21 day	80.7	74.0	82.7	86.3	85.9	84.3	89.6	89.6	92.5	75.0	80.4	82.0
Min/Month	83.9	81.4	89.3	89.6	91.7	86.8	92.1	90.9	94.4	81.7	82.9	89.2

The other two important factors of sizing the storage system of SAPVS are Solar radiation deficits below expected values incident on a horizontal surface over a consecutive-day period (kWh/m^2) and the equivalent number of black days (no-sun) or that must be supplied by the storage backup system. These two factors are shown in Figures 6.23 and 6.24, respectively. These parameters will be used in designing the SABIPV system in the following section.

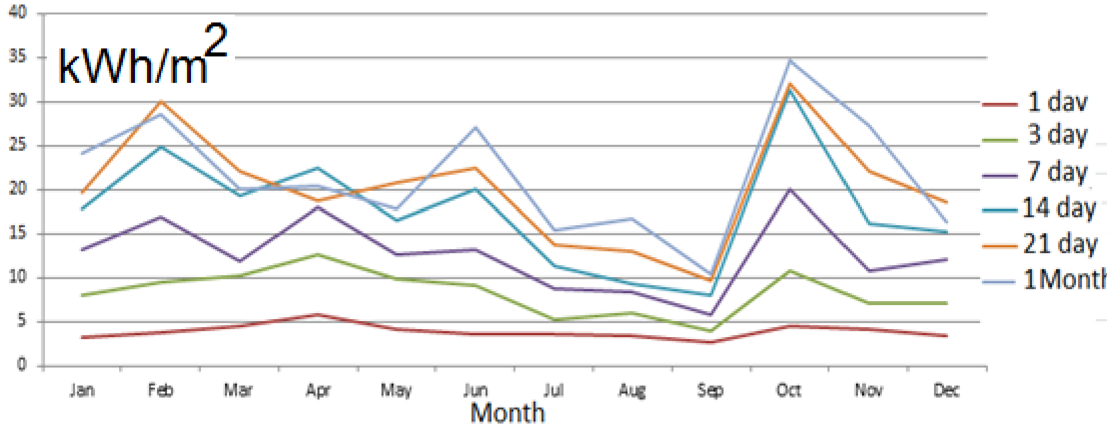


Fig 6.23: Solar radiation deficits below expected values incident on a horizontal surface over a consecutive-day period

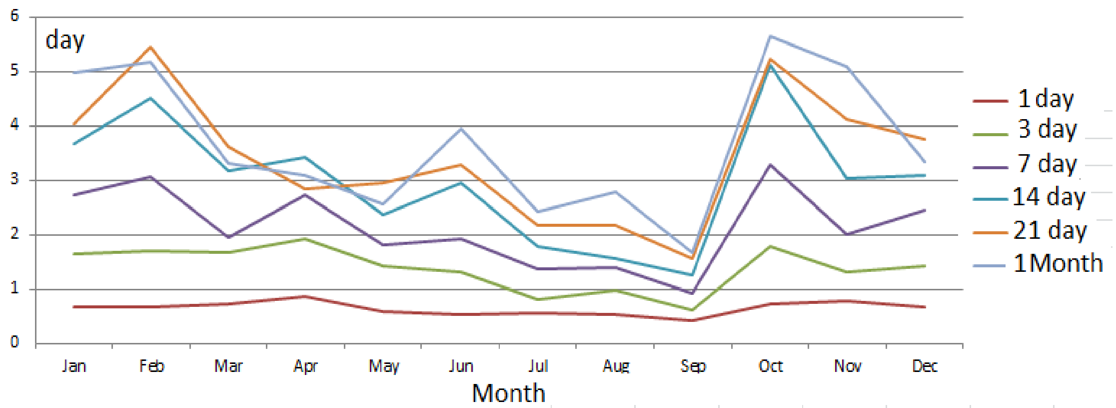


Fig 6.24: The equivalent number of black days (no-sun) or that must be supplied by the storage backup system

For sizing surplus-product storage systems, available surplus insolation over a consecutive-day period should be known. The amount of surplus insolation over a consecutive-day for a period of 1, 3, 7, 14, or 21 days as a % of the expected average kWh/m^2 value over the same consecutive-day period (%) is shown in Figure 6.25.

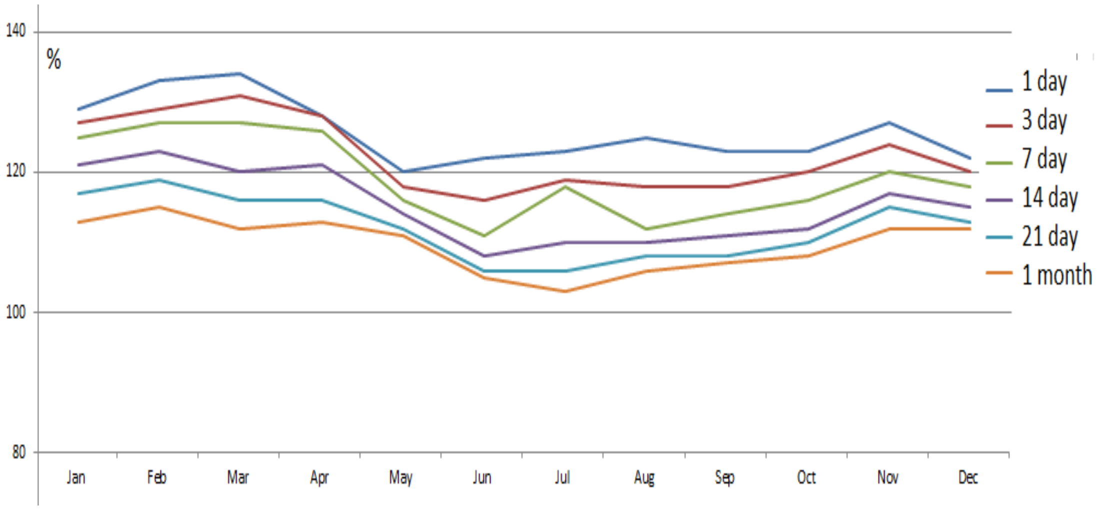


Fig 6.25: Surplus insolation over a consecutive-day period

More information can also be extracted from NASA website about cloud in the chosen location. Monthly averaged daylight cloud amount during daylight for a given month is illustrated in Figure 6.26. Also, the monthly averaged cloud amount at indicated GMT times at 3-hour intervals is shown if Figure 6.27. The monthly averaged frequency of cloud amount at the midday (12:00 in Al Rakabah time, 09 GMT) is shown in Figure 6.28 with less than 10% (clear skies), between 10 - 70% (broken-cloudy skies), and greater than or equal to 70% (near-overcast skies)

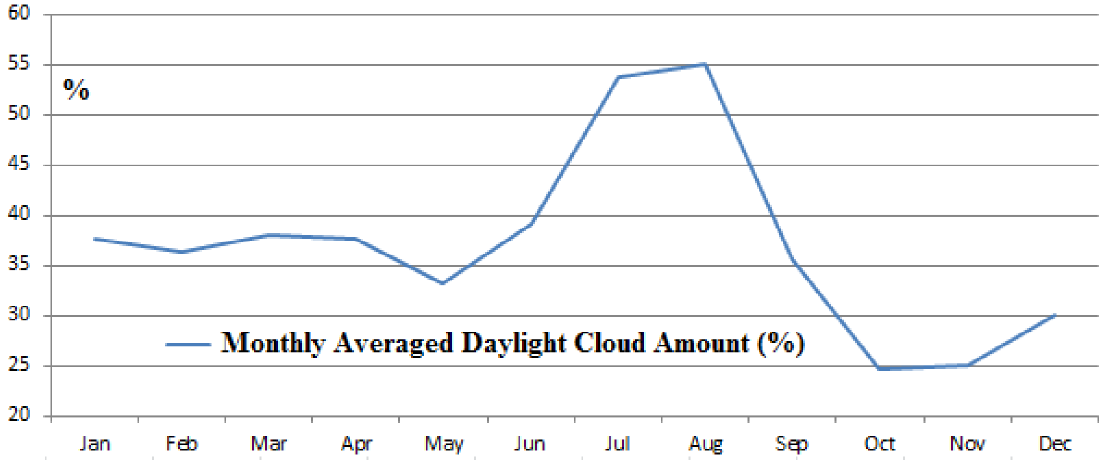


Fig 6.26: Monthly averaged daylight cloud percentage during daylight

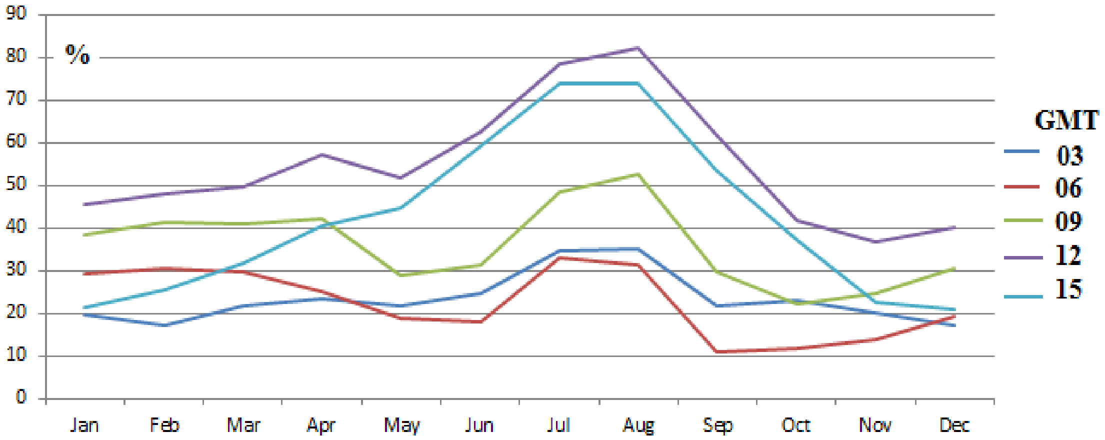


Fig 6.27: Monthly averaged cloud percentage at indicated GMT (3-hour intervals)

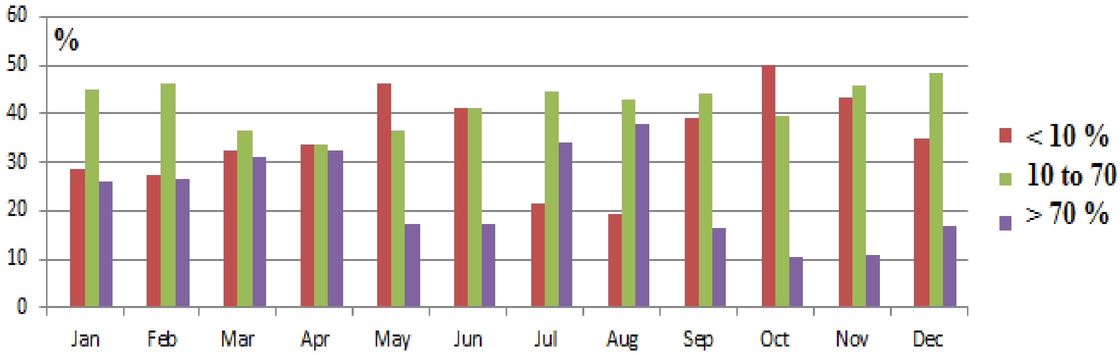


Fig 6.28: Monthly averaged different cloud percentage at midday

The monthly averaged cooling and heating degree days above and below 18° C are shown in Figures 6.29 and 6.30, respectively. Temperature values are for 10 meters above the surface of the earth. The monthly average of the accumulation of degrees when the daily mean temperature is above/ below 18 degrees is calculated as following:

Above: for the days of a given month, sum the quantity [((Tmin + Tmax) / 2) - 18]. When (Tmin + Tmax) / 2 > 18.

Below: for the days of a given month, sum the quantity [18 - (Tmin+ Tmax) / 2]. When (Tmin + Tmax) / 2 < 18.

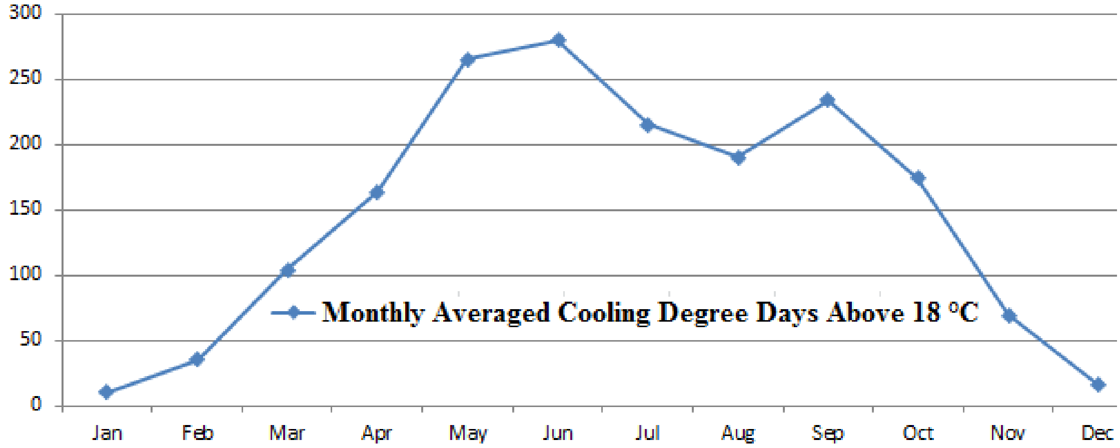


Fig 6.29: Monthly averaged cooling degree days above 18 C^o

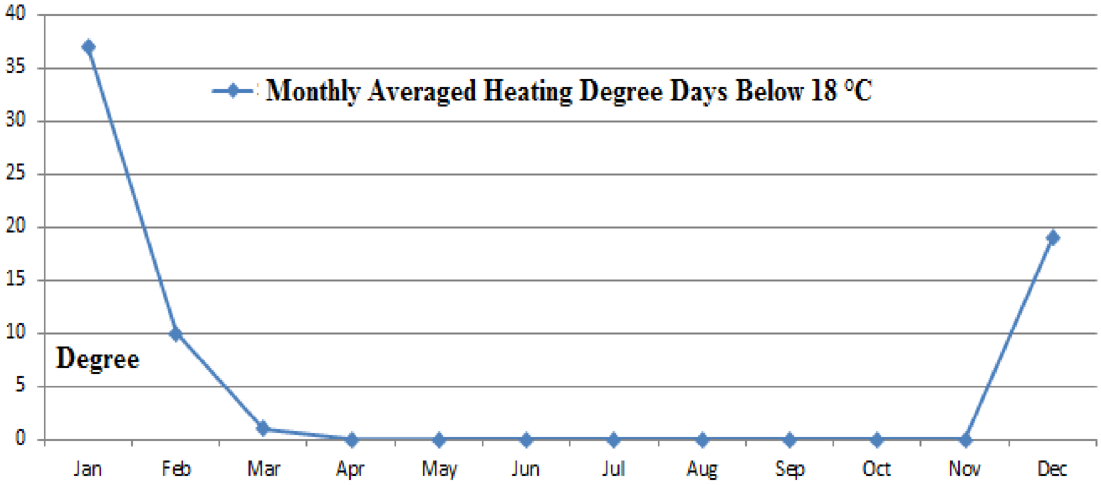


Fig 6.30: Monthly averaged cooling degree days below 18 C^o

The monthly average of the accumulation of degrees when the daily mean temperature that below 10 degrees is zero across the year. This is also the case of the monthly averaged frost days which is zero thought the year. The dew point is the temperature to which the parcel must be cooled at constant barometric pressure, for the water vapour component to condense into water, named dew. When the dew point temperature decreases below freezing, it is named the frost point. The monthly average dew/frost point temperature values for 10 meters above the surface of the earth which is a normal height for SABIPV system to be fixed is shown in Figure 6.31.

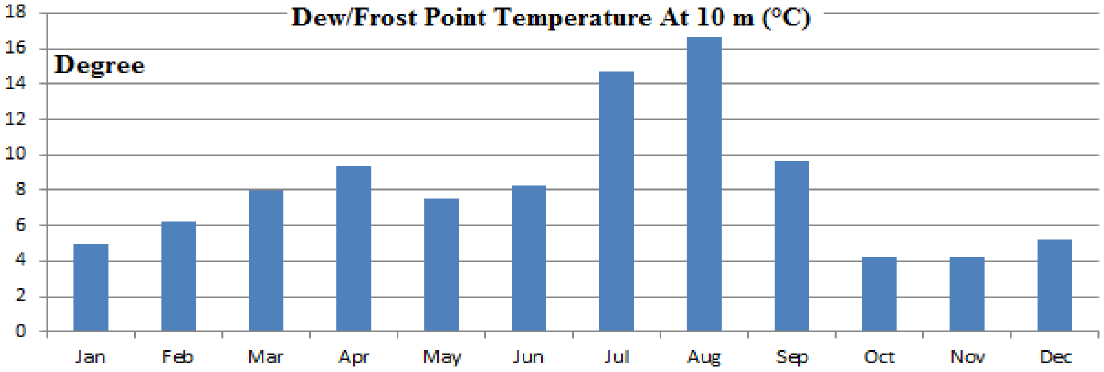


Fig 6.31: Dew/frost point temperature values are for 10 meters above the earth

Information about wind speed is also important for SABIVP system where the wind load on panels must be taken into account for designing the system frame. The monthly averaged wind speed at 10 m above the surface of the earth is shown in Figure 6.32.

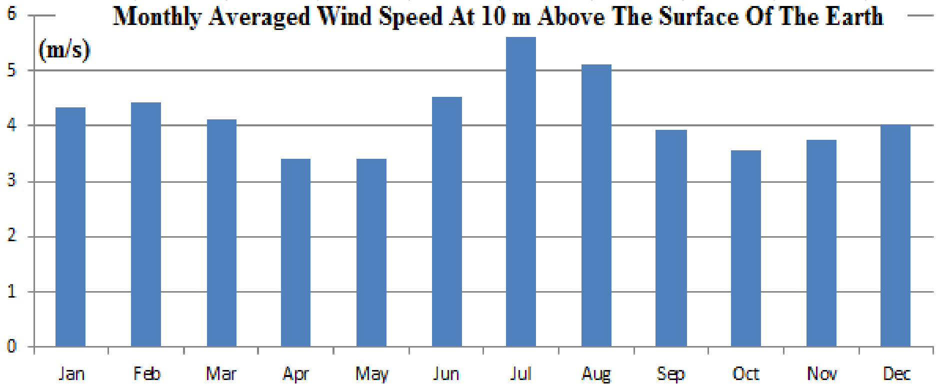


Fig 6.32: Monthly averaged wind speed (m/s)

6.3- Design SABIPV system

6.3.1 Design concept

SABIPV system consists in general of PV panels, cables, mounting or fixing frame, an inverter, charge controller, and storage system. The PV panels are fixed on the frame in rows and the number of panels depends on the required amount of power, the efficiency of the PV cells, the solar irradiation, and sun tracking system (fixed or rotated panels).To generate as much electricity as possible, PV panels should be subjected to the direct sunlight as long time as possible. The power generated by panels is stored in the storage system. Batteries are often used to store direct current electrical energy to be used when the required power is more than that generated or at night where no power can be

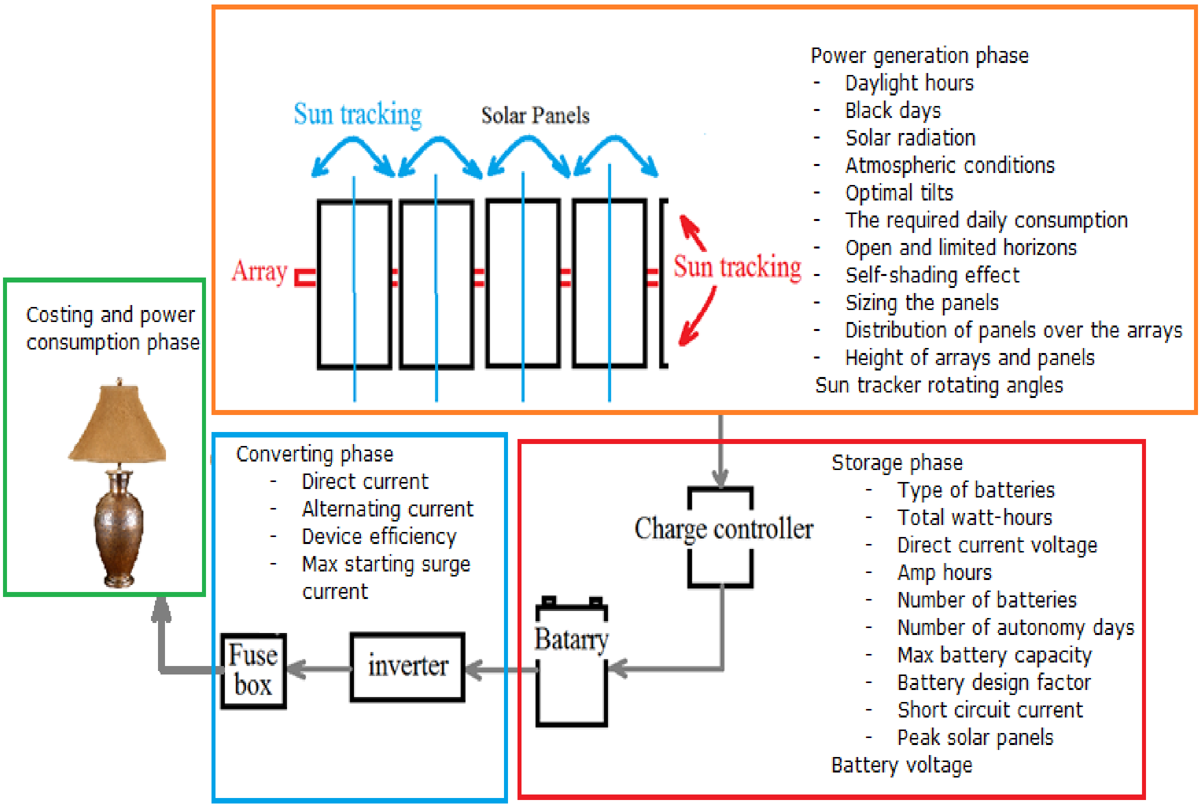


Fig 6.33: SABIPV system: design concept

provided. Charge controller is used to control the battery voltage in storage system and the flow of current from the solar panel to the battery. When the battery is full, the charge controller stops flow the generated electricity to the battery avoiding overcharging damages. The inverter is used to change direct current generated by SABIPS to alternating current to run loads working on alternating current. The inverted current passes throughout a fuse box to the connected devices. A dedicated metering box can also be used to measure the electricity rate generated by the panels. Figure 6.33 shows the main components of SABIPV system and design concept.

6.3.2- Sizing the System Components

Designing a perfect stand-alone building integrated PV system includes sizing each element in the system, namely: solar array, controller, inverter and storage system. In this section, a brief description of designing these elements will be discussed as more details will be given in chapter five.

- PV panels and Sun-Tracking System

The first step of designing the system is to determine the size of PV panels that can provide the required electricity consumption. The size of PV panels depends on the solar isolation for the area in which the system will be installed, the efficiency of PV cells used, the required rate of power, type of sun tracking system (fixed panels, one/two axis rotation sensors), the daylight hours, the equivalent number of black days (no-sun), and daylight cloud percentage during daylight. As seen from section 6.2.2, the intensity of the solar radiation at any location across the world depends on latitude, topography, season, daytime, and atmospheric conditions, such as clouds, dust, and water vapour.

From Figure 6.21, which compares the monthly average amount of direct normal radiation incident on a surface oriented normal to the solar radiation (Direct Normal) and The monthly average amount of total solar radiation incident on a surface tilted at the optimum angle relative to the horizontal and pointed toward the equator, it is clear that the two values are nearly the same which means that it not necessary rotate the array of panels continually using a sun tracker system in the North-South direction. The tracker can be set to rotate the array only one time per month by the optimal angles shown in Figure 6.22.

It can be noted from Figure 6.22 that the differences between the maximum and minimum optimal tilts equal to the summation of earth rotating angles in north and south directions (23.3° N + 23.3° S = 46.6°) and when the optimal angle is zero, this means that the Sun path is in the same plan with the latitude of the chosen area (The Sun is perpendicular on the horizontal surface). Figure 6.34 shows the tilt angle of PV array relative to the relative to the horizontal and pointed toward the equator

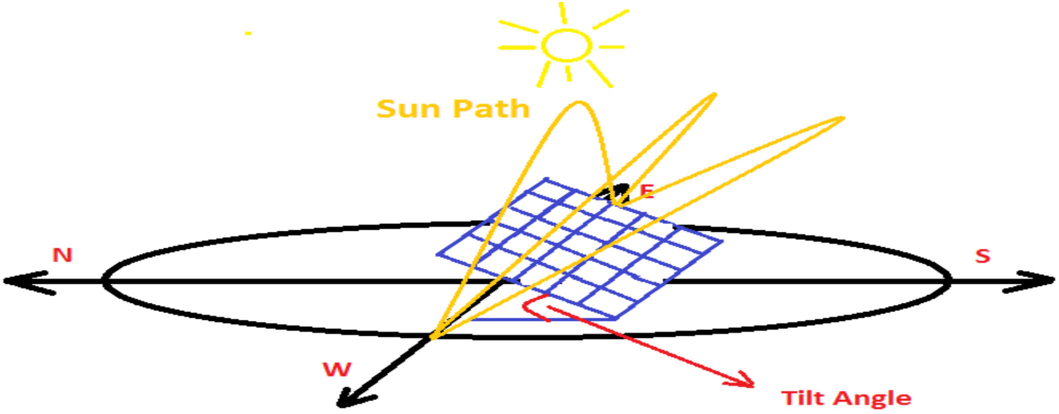


Fig 6.34: The array tilt angle relative to the horizontal and pointed toward the equator

If it is impossible to rotate the array with the optimal angle, the average optimal angle of the whole year should be used instead which is 21.7°. However, this will reduce the efficiency and the lost amount of irradiation can be calculated as the differences between the amounts of optimal irradiation shown in Figure 6.21 and the amount of irradiation attended with sloped modules. This last can be estimated from the interpolation between the amount of irradiation with optimal angle and that incident on horizontal surface (see Figure 6.10). For example, in January, the averaged irradiation that incident on horizontal surface is 4.86 kWh/m^2/day and with optimal angle is 6.21. The lost in irradiation due to the differences between the optimal tilt (43^o) and the annually averaged tilt (21.7^o) can be calculated as:

The lost = 6.21- ((6.21-4.86) x 21.7 / 43 + 4.86) = 0.7 (kWh/m^2/day)………………6.1

To design the system with the amount of solar irradiation achieved with the optimal angle, the system must be provided with effective sun tracking system to rotate the arrays as well as the panels in North-South and East-West directions, respectively. The sun tracking system that recommended for the suggested SABIPV system is an active two axes rotating system which is able to rotate the arrays with the monthly optimal tilt in the sun path direction and also rotating the panels to follow the sun during the day as shown in Figure 6.35.

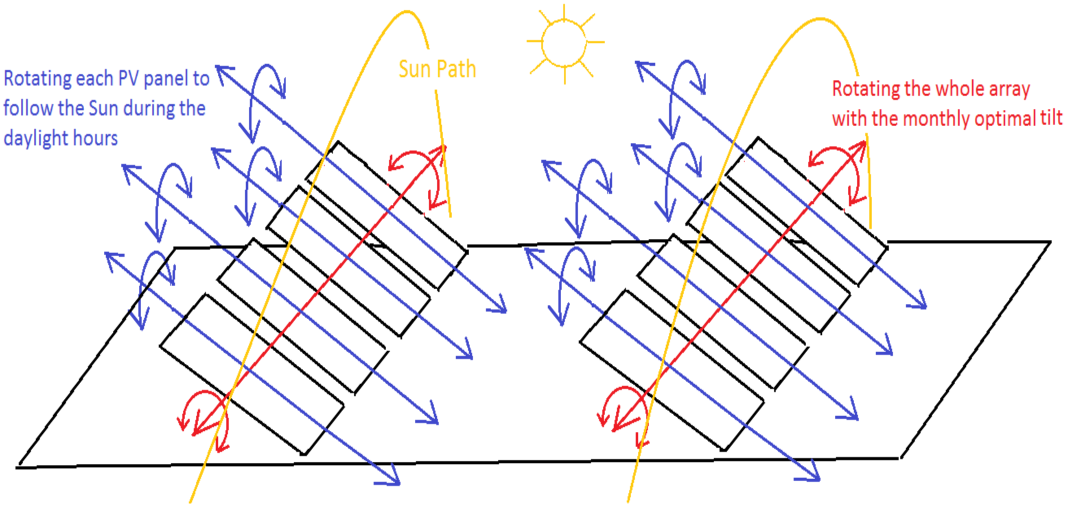


Fig 6.35: Rotating arrays and panels with two axes sun tracking system

As for the rotating angle of panels used to follow the Sun in the East-West directions during the day, it depends on the visible portion of the sun path and the number of daylight hours. Theoretically, the visible portion of the sun path from the perspective of any fixed on the Earth is 180 degrees during an average of 12 hours period. From Figure 6.17, the monthly averaged daylight hours in Al Rakabah is 12 hours which means that the panels should be rotated around the Blue Axis (see Figure 6.35) by 15° per hour. However, due to local horizon impacts, this portion might be reduced.

In Al Rakabah and in any mountainous area, the impact of the local horizon tends to be considerable, especially for buildings located in Valleys and surrounded by high mounts in the east-west direction where the visible portion of the sun path from the perspective of these buildings decreases significantly to reach less than 120° in some cases. This means that there will be a waste of about 6 daylight hours per day, three hours after sunrise and three at the end of the day before sunset. In the case of buildings located on the top of mounts, the impact of the local horizon tends to be neglected. Figure 6.36 shows the impact of the local horizon on the visible portion of sun path in Al Rakabah.

Fig 6.36: The Impact of the local horizon on the solar irradiation (https://www.google.com/imghp)

Although, passive solar tracking systems have several advantages over active systems, such as the low-cost, no need for regular maintenance or power, active sun tracker has been chosen for the designed BISAPV system. This is because passive solar tracking systems tend to be heavy and inactive in the morning and evening where the temperature is limited. Also, PV arrays provided with passive tracker should be flexible to be rotated under the weight impact which reduces the resistance of the panels to the wind impact. From Figure 6.32, the monthly averaged wind speed reaches about 5.5 m/s (19.8 km/h) but the design area tends to experience strong winds, especially on the top of mounts where the horizons are open in all directions.

By providing the system with the two axes sun tracking system, the Impact of receiving the sunlight with an incident angle will be avoided and the monthly averaged amount of solar irradiation shown in Figure 6.21 can be used directly in the design steps. This can be noted clearly from equation 3.2 which presents the mathematical relationship between the sunlight intensity (λ), the angle of incidence (i), and power generation (P).

From the equation, the highest power generated can be obtained when the angle of incidence is zero (cos (0) = 1) and no power can be achieved when the sunlight is at a 90 degree to the normal (cos (90) = 0). This means that with fixed solar panels, significant power is lost during the day as the PV cells and the sunlight will not be perpendicular to each other. Single axis sun trackers are also limited in terms of rotating the solar array in North-South direction which reduces the amount of receiving irradiation as shown above. The role of two axes tracking system is to keep the angle of incidence within a certain range as much as possible to increase the sunlight intensity and consequently the power generated.

However, the solar cells can only convert a specific percentage of the received sunlight to electricity and this is known as the cell efficiency. The typical crystalline silicon cell which is common in GCC countries and currently manufactured in Saudi Arabia can convert about 22% of the received light to electricity. Therefore, the amount of solar irradiation must be multiplied by the cells efficiency to get the design amount which will be used for sizing the PV panels. Figure 6.37 shows the design monthly averaged amount of solar irradiation across the year (Al Rakabah).

The design amount of solar irradiation = OPT * cells efficiency (22 %).................6.2

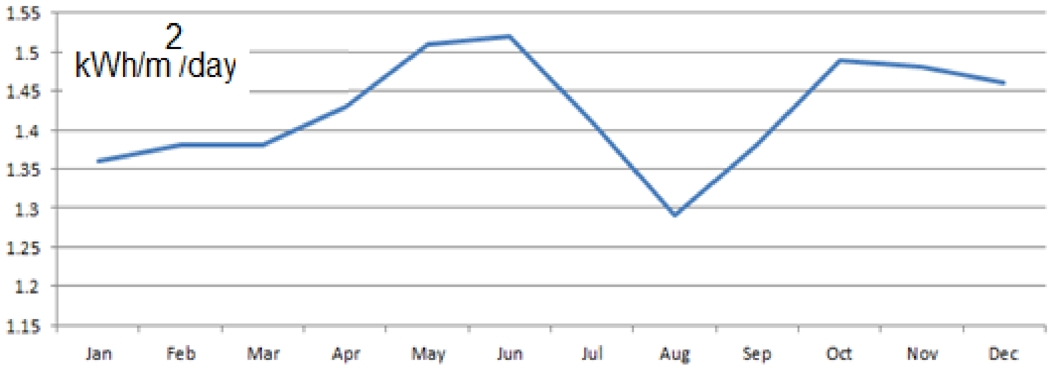


Fig 6.37: The design monthly averaged amount of solar irradiation (Al Rakabah)

After determining the design averaged monthly amount of irradiation in the Al Rakabah, the second step is to find out the daily total power and energy consumption of all typically domestic loads that need to be powered by the solar system, such as lighting, computers, radios, TV, garden devices, air conditioner, fridge, etc. In fact, the energy consumption depends on several factors and differs from house to another based on the number and ages of occupiers, size of the house, season, and home activates. These factors are considerably variable in Al Rakabah and each house can be considered as a specific case. In this study, an average amount of power consumption of 10 houses with different expected electricity requirements has been determined by the author based on field study and will be used for determining the average size of PV panels.

To find out the power and energy consumption for each house, the power rating in Watts of each and every used electrical device and the number of using hours of each piece of equipment have been recorded. Then, the Watt-hours needed for all appliances have been added together to determine the total daily energy consumption in Watt-hours. Table 6.3 illustrates the daily total power and energy in summers determined by the author for a selected house occupied by one family of 12 persons. The house has an area of 300 m^2, one floors, 6 bedrooms, two living rooms, large kitchen, 3 bathrooms, and store for agricultural equipment. Figure 6.38 shows the selected houses.

Table 6.3: Determining the required daily power and energy consumption

Electrical device	No. of devices	Power (Watt/device)	hours/day	Energy Wh/day
Fluorescent lamp bedrooms	5	40	3	600
Fluorescent lamp living rooms	6	40	6	1440
Fluorescent lamp kitchen	3	40	4	480
Fluorescent lamp bathrooms	4	25	2	200
Fluorescent lamp store	2	60	2	240
Fan	3	250	3	2250
Refrigerator	1	550	12	6600
TV flat screen	2	180	5	1800
Air conditioner	1	2500	6	15000
Desk top computer	1	600	3	1800
Lap top computer	1	250	4	1000
Sat TV receiver	2	250	5	2500
Microwave	1	1000	0.25	250
Water pump	1	2500	1	2500
Water boiler (not for heating)	3	1500	2	9000
Washer machine	1	1200	1	1200
Mobiles (charging)	7	6	1	72
Total daily energy consumption = 46.932 kWh/day				46932

The energy consumption in summer is the highest among the year where the air conditioning and fans are used extensively as seen from the Table. The electric consumption in winters is the lowest among the other seasons where the heating systems used in the village are based on gas only. Using the same steps illustrated in Table 6.4, the total averaged daily energy consumption in winters is 40.834 kWh/day and in spring and autumn is in average between summers and winters. Figure 6.39 shows the total averaged daily energy consumption in the four seasons in Al Rakabah.

Fig 6.38: The selected houses (The black square is the house in table 6.4)

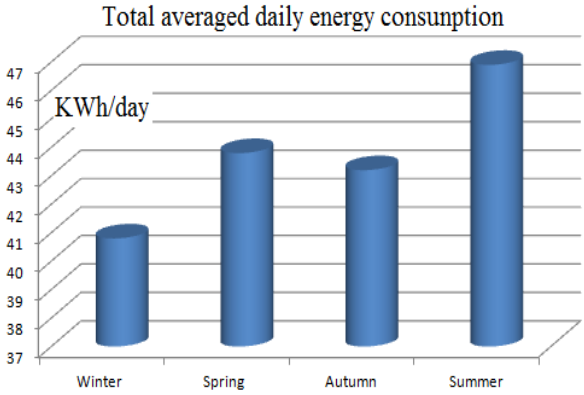


Fig 6.39: The average demotic Energy Consumption in Al Rakabah

For save and reliable design, the maximum amount of the daily total energy consumption should be used for finding out the size of PV panels which is that of summer time. This amount should be multiplied by a design factor which depends on the efficiency of the system and expected rate of losing the energy. Generally, the calculated daily energy consumption is often increased by 30% to 50% to get the total Watt-hours/day which should be provided by the panels. In this project, a design factor of 40% will be used as the efficiency of the local manufactured solar cells recommended for the system is not highly reliable. From that, the design daily energy consumption amount equals to (46.932 * 1.4 = 65.705 kWh/day).

The surface area of PV panels in m^2 that is required to provide the design daily energy consumption amount can be calculated as:

The surface area of PV panels (m^2) = the design amount (kWh/day) / the minimum value of the design monthly averaged amount of solar irradiation (see Figure 6.37).

The surface area of PV panels = 65.705 (kWh/day) / 1.28 (kWh/m^2/day) = 51.33 m^2 ………………………………………………………………………………........…..…6.3

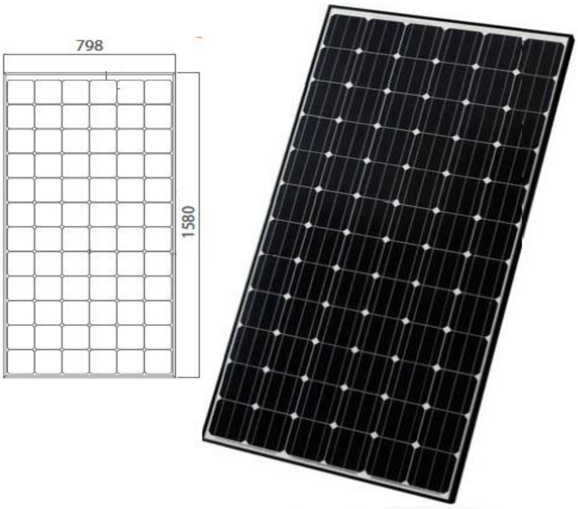


Fig 6.40: Solar panel diminutions, https://www.google.com/imghp

The number of panels required to cover this area depends on the size of the available panels. As the solar cells are small, PV panels with different sizes are available in the market and specific sizes can be orders as well. In this project, PV panels that are local manufactured by Solar Sun-Edison Company will be used in the design as it is famous and available in Saudi markets. The size of these panels is 1.58 m x 0.798 m with an area of 1.26 m^2. Based on that, the required number of panels is the surface area of PV panels divided by the surface area of each panel which equals to 41 panels. This is the minimum number of PV panels required and increasing the number of PV panels will help the system for better performance and longer battery life. On the other hand, using less number of PV panels that required reduces the efficiency of the system significantly, especially in cloudy periods which might affect the battery in terms of life period and effectiveness.

After determining the total number of panels, it is the time now to distribute the panels in arrays on the roof of the house. The dimensions of the house are 20 m x 15 m with flat and empty roof. The roof is surrounded by walls with a height of 2 m as the roof is used in social events, especially in summer nights. Figure 6.41 shows the house roof and the diminutions.

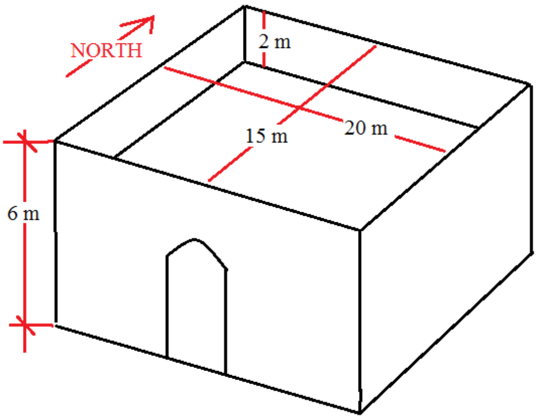


Fig 6.41: The diminutions of house

To distribute the panels perfectly on the roof and to guaranty the panels are perpendicular with the sunlight across the day, the North direction has been determined on the roof using adjustable compass set to a declination of 0° and found to be 8 degrees. The declination is the differences between the two North Poles: the geographical and the magnetic North Pole. The geographical pole is the point at 90° northern latitude which is shown on most maps. The magnetic pole is the point where the magnetic field lines are vertical and enter the Earth. The observations showed that the azimuth of is as shown in Figure 6.42.

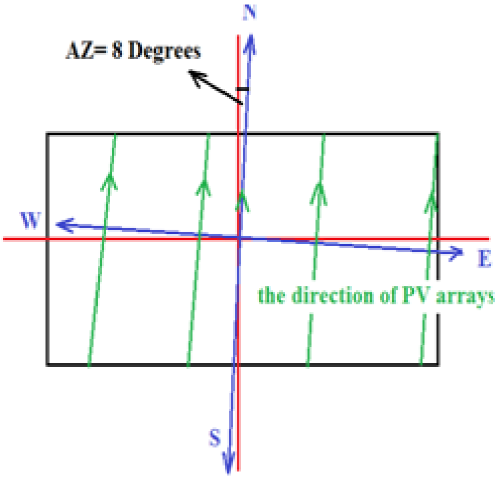


Fig 6.42: The North direction

The direction of the PV arrays is parallel to the North direction and the number of PV panels in each array depends on the width of the house, the width of the panel and the maximum OPT angle that is used to rotate the array in North-South direction. If only one array is used in each line, the number of panels in each array equals to 18 panels (15 /

0.798). This means that to provide the house with the minimum number of panels, 2 arrays of 18 panels and one array of 5 panels should be used. However, using one array for each line is not practical as this array should be rotated in the North-South direction with the averaged monthly OPT angle. The maximum OPT angle as seen from Figure 6.23 is 47^{o} and this means that northern pole of the array should be rise by 10 m (15 / cos (47)) which is logically unaccepted. Therefore, the length of each array should be limited for reasonable changing in the length of the northern pole.

Each line in this house will be designed to include 4 arrays with 3 panels each. This means that each line will include 12 panels. As mentioned above, more panels should be used for better performance and reliable functionality. Therefore, the house will be designed with 4 lines including 16 array and 48 panels. Figure 6.43 shows the initial distribution of the arrays and panels on the roof of the house.

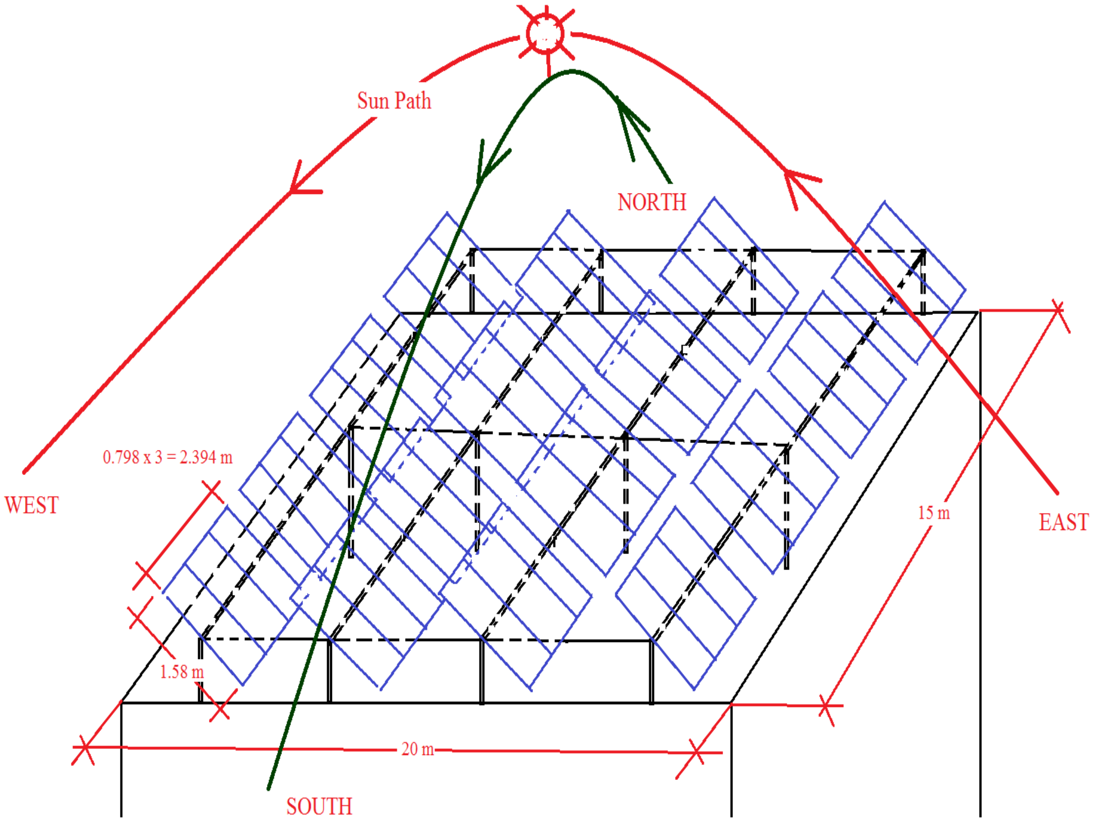


Fig 6.43: The initial distribution of the arrays and panels on the roof of the house.

As multi PV panels are connected together to form solar PV array, any shading on a single module can affect the performance of the whole solar PV system. Some shading in the early morning and evening may not reduce the overall power generated. However, in mid-day when the sunshine intensifies, shading can affect the performance of a solar PV array significantly and preferably should be avoided. However, in the case of the chosen house, the only shading should be considering is the panels self-shading where no neighbouring constructions, faraway tall buildings, and snow and the horizon is open in all directions. Dust can also have a significant impact on the system performance but the rotating of panels and arrays can help to clean it. Such temporary shading can also be reduced considerable using the solar PV array self-cleans. Some systems are provided with cleaning system including tiny water pumps and electrical wipers. However, this can increase the cost of the system.

When fixing a number of arrays in the system frame as in the case of this house, self-shading impact can be caused by the row of panels at the front, especially in early morning and evening. Space requirements and shading losses can be reduced throughout optimal design with calculated tilt angles and distances between the module rows. When the arrays are fixed close to each other, each array will shade a part of the next, causing further losses. On the other hand, increasing the distance between arrays significantly can cancel out the self-shading impact but at the expense of space and number of models.

The mathematical relationship between array width *(w)*, tilt angle, the Sun elevation angle *(γ)* and the distance between the arrays (*d)* has been discussed in chapter three and explained in equation 3.4 and Figure 3.12. In the case of rotated panels and designing the models to follow the sun making an incident angle of nearly zero, equation 3.4 can be rewritten as:

$$d = W / \sin(\gamma) \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 6.4$$

As the impact of the local horizon in the case of the chosen house is nearly neglected, the visible portion of the sun path will be used as180 degrees during an average of 12 hours period. However, as can be seen from the equation, the distance between the panels is function of the minimum shadow angle and the smaller the shadow angle, the bigger the distance between arrays. This means that balance between the shadow angle and the number of arrays should be used.

In this system, the minimum shadow angle in East-West direction that will be used is 15^{o}. This means that the arrays will stop rotating when the Sun elevation angle is 15^{o} both in East and West directions (when sunrise and sunset). With the minimum sunlight elevation angle of 15^{o}, the distance between the arrays is nearly 6 m (1.58 / sin (15)). This means that the required distance for fixing 4 lines of arrays is 18 m which is less than the length of the house (20 m). The self-shading has also an impact in the North-South direction where the arrays will shadow each other when they are rotating with the OPT angle. Using equation 3.5, the minimum distance between arrays in the North-South direction can be determined with maximum Sun tilt angle ($\gamma = 90^{o} - 47^{o} = 43^{o}$) and W = 2.394m. Based on that, the distance between arrays in North-South direction equals to 3.5 m. As 4 arrays are required in this direction, 11.5 m is the distance required to fix these arrays with intervals of 3.5 m which is less

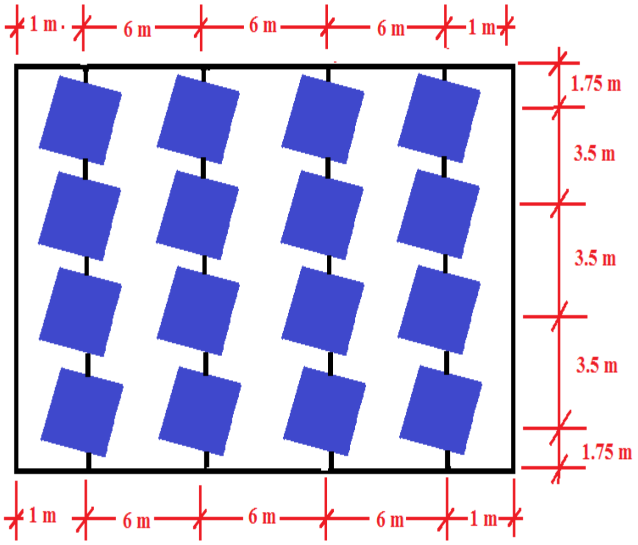


Fig 6.44: The distances between arrays

than the width of the house. The distances between the arrays in East-West and North-South directions and the fixing points on the roof are shown in Figure 6.44.

As for the height of the frame’s poles, the height of southern poles of each array is fixed and for the northern poles is changeable as the arrays are rotated with the monthly OPT angle. Figure 6.44 shows the minimum and maximum heights of southern and northern poles of each array and Figure 6.45 shows how the arrays are rotated to be parallel to the North direction.

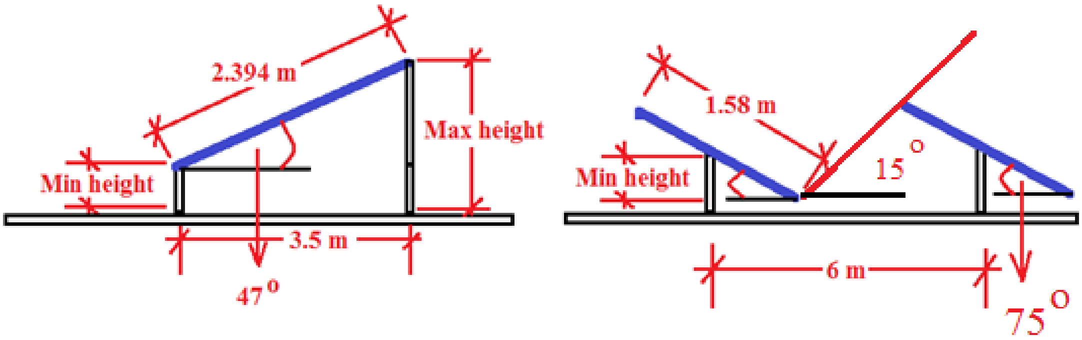


Fig 6.44: The minimum and maximum heights of poles

The minimum height of the frame can be calculated as following where:

$\gamma = 90-15 = 75^o$ ………………………………………………………………….....6.6

The minimum height of the pole = (the width of array / 2) x sin (75) = 76 cm ………………………………………………………………………………………..6.7

Poles with height of 80 cm are recommended in such case to leave enough space for the air to be circulated and to avoid the fraction between the edged panels with the wall. When the OPT angle is zero in August (see Figure 6.23), the height of the frame in northern and southern wall will be the same (80 cm). The height of the frame will be increased in the northern direction reaching the maximum height in December where the

OPT angle is nearly 47^{o}. The maximum height in the northern direction can be determined as:

The maximum height = the minimum height + array width x sin (47) = 2.55 m…6.8

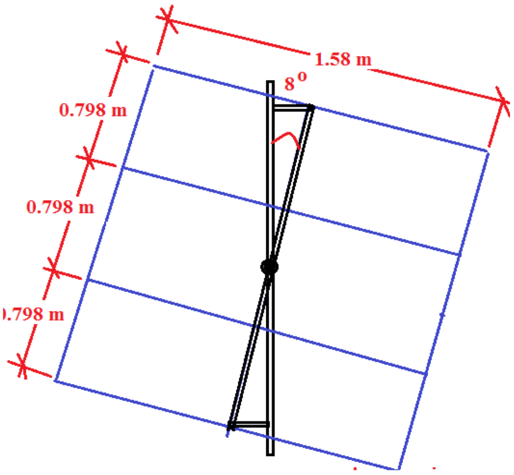


Fig 6.45: Array rotating with the North

In the cases of houses located in the mount's shadows where the local horizon becomes limited, the minimum rotation angle in the East-West direction should be increased. For example, if the open sky view in an area is 120^{o} with mount shadow of 30^{o} in the East and West, this means that the sun can be seen after nearly 2 hours from the sunrise and is hidden before nearly 2 hours from the sunset. In such case, the minimum panel rotations in East-West direction that should be used is 30^{o} as rotating the panels less than this is pointless. Reducing the sun path portion from 180 to 120 will reduce the average daily irradiation amount.

However, as the efficiency of the system is often low in early morning and evening due to weak solar insolation as can be seen from Table 6.1, the impact of such shading can be overcome by increasing the number of arrays in the East-West direction where the minimum rotation angle used (30^{o}) reduces the distance between rows to be 3.16 m compared with 6 m in the case of using minimum sun elevation angle of 15^{o}. This means that 6 rows of arrays can be fixed in the East-West direction instead of 4 rows with sun elevation angle of 15^{o}. This means that 72 panels can be fixed on the house. Increasing the number of panels will help to collect more solar irradiation in the high insolation hours and the amount of generated power might be more than that of the designed system with 4 rows of solar arrays. However, this will increase the cost of the system where more panels are used and more effective storage system is required for the longer dark hours.

In some cases, the area of the roof may not adequate for the required number of panels or the house may not be able to carry out the dead load of the system and the live load caused by the wind load on the area of panels. In such cases, ground fixed system can be used where the frame of each array can be fixed in the house surrounded areas or even in the nearest open horizons place to decrease the number of panels as much as possible and consequently the overall cost of the system.

In general, in this section, sizing the solar panels has been carried. Firstly, the required energy consumption has been determined based on a field study with 10 different houses in Al Rakabah. Then, one of the houses has been used as a study to design SABIPV system. The ideal size of PV panels has been determined based on the required electric energy and on the irradiation rates in the area which has been discussed in the previous sections. The size and distribution of arrays on the house's roof have been illustrated with details. Finally, different scenarios might be faced for sizing and fixing the solar arrays have been discussed with suggested solutions.

- Solar Batteries, Regulator, and Inverter

Sizing the batteries of solar PV system is regarded as one of the most important step of designing the system. The type of batteries that is recommended for solar PV system is deep cycle battery, which is specifically designed to be discharged to low energy level and rapid recharged. These batteries can be cycle charged and discharged continually for years. The size of battery should be large enough to store sufficient energy to operate the electrical domestic devices at night and cloudy days. Most batteries live longer with shallow cycled discharging of only about 20% of their capacity. A moderate design can save the deep cycling for occasional use. This means that the battery bank should be approximately five times the daily load to provide power continuously for five days without any solar power generating or battery recharging.

To determine the total battery Amp hours, the total Watt-hours required by all loads should be used. This value is divided by the direct current system voltage giving the amount of Amp hours required to run all loads for a given period. The number of needed batteries can be calculated from equation 3.10. The total Watt-hours per day required by all loads (Whd) is 65.709 kWh/day. The number of autonomy days that needed the system to operate without generating power by PV panels (D_{aut}) is 6 days as seen from Figure 6.25 where in October, it is possible to get about 6 back days. As for the nominal battery voltage (B_{vol}), 48V deep cycle batteries (OPzS solar power) are available in Saudi markets and started to be manufactured locally. This type of batteries can provide up to 4700Ah with size of 75cm x 40cm x 55cm as seen in Figure 6.46. Based on the assumption that the battery will never be discharged less than a specific rate, say 20%, B_{loss} will equal to the remains of the battery's capacity (80%). The design constant of the battery depth of discharge (D_{cha}) will be used as 0.6 which is common with the deep cycle batteries. Based on that, the number of batteries required is:

Fig: 6.46: 48V deep cycle OPzS battery, https://www.google.com/imghp

Number of batteries = (65709 x 6 / (0.6 x 0.8 x 48)) / 4700 = 3.6 ………………...6.9

In such case, it is better to use 4 batteries where the temperature tends to have an impact of the battery efficiency. Also, using more batteries increases the storage capacity which reduces the required charging rate of batteries and reflects positively on battery life. The batteries should be kept in save place away from rain and as close as possible to the solar panels and the house to avoid the long connections and cables.

Choosing the appropriate solar regulator or charge controller is the next step in designing the SABIPV system. The role of this device is to regulate the direct current from solar modules to avoid overcharging batteries. A charge controller includes a low voltage disconnect feature, which senses the battery voltage and if the battery voltage reaches a pre-determined cut-off voltage level or overcharging, the supply will be switched off. Solar regulator helps also to prevent the battery from feeding back into the solar panel when the modules stop working due to darkness. Solar regulators are rated by the amount of electric current they can receive form the solar panels. Also, the solar regulator should be capable of handling the total short circuit current of a solar panel. The capacity of solar regulator should be bigger than the minimum to allow for more PV panels to be added to the system when necessary. With large SABIPV system such as that designed in this project, it is recommended to distribute the solar array on the batteries where each group of arrays is connected to separate battery. This is because connecting the whole panels to the storage system with one charger regulator will be hard due to the significant amount of minimum controller output required. In this project, each raw of arrays will be connected to one of the four batteries used and provided with separate charger controller. The size of the charger regulator can be calculated as:

Controller size = (short circuit current (SCC) + peak solar panels (Watt)/battery (Volt) …………………………………………………………………………..……..6.10

As for the short circuit current, it is 8.3 Ampere for each panel. As the panels are connected in parallel in each raw, the total SCC will be the same which is the minimum controller input current. The peak solar for the system is in the midday in May as shown in Table 6.1 and equals to 0.93 kWh/m^2. As each raw has 4 arrays and each array has 3 panels with efficiency of 22% and an overall surface of 15.12 m^2 (12x1.26 m^2), the total peak solar is 3.09 KW (15.12 x 0.93 x 0.22). With 48 V batteries, the minimum controller output current is 64.45 Amp. This means that 4 charger controller with minimum input of 3.8 Amp and nearly 70 Amp minimum output should be used in the system; one for each raw of arrays and one battery. Figure 6.47 shows the recommended charge controller with 70A/4080W, environment: -40 to 40C, dimensions of 14.87" x 5.95" x 4.00".

Fig 6.47: Large charge controller
https://www.google.com/imghp

Choosing the suitable inverters for the system is based mainly on the maximum anticipated alternating current load to be supplied. The design capacity should cover the combined maximum load for all alternating current electrical devices running at the same time. Converting direct current to alternating current results in a loss of efficiency for the inverter reducing the energy with nearly 20% depending on the quality and efficiency of the inverter used. The design capacity of the inverter can be determined from equation 3.9. The design capacity should takes into account the maximum starting surge current of the equipment running simultaneously.

from Table 6.4, the maximum load can be determined by adding the loads of devices that are expected to be used in the same time. Estimated calculation can give a maximum load of 6700 W including 5 lamps, air conditioner, fan, refrigerator, water boiler, desk and

Fig 6.48: SAJ 20kW solar inverter,
https://www.google.com/imgh

lap top computers, 2 TV, 2 receivers, and mobile charging. The maximum starting surge current in these devices is 5000W for the air conditioner. From equation 3.9, the design capacity of the inverter is 14625W ((6700+5000)/0.8). Figure 6.48 shows the recommended solar inverter for this system which has capacity of 20 kW with suitable domestic size and dimensions of 50 cm x 30 cm x 10 cm.

In general, in this section, sizing the storage system, inverter, and charge controller has been discussed. The design shows that four 48V batteries with 4700 Amp can cover the required electricity consumption for 6 days without any charging from the solar panels. As the minimum output rate of the available charge controller is limited, each battery has been provided with separate controller and each battery has been connected to one raw of arrays. High capacity inverter has been used with the system to power the whole number of devices working at the same time. The design has included just the main components of the SABIPV system as the main point is to see whether it is possible to cover the whole home electric consumption in the remote villages in Saudi Arabia using solar energy. The design showed that it is possible to power large house such as that used in the study case using SABIPV system, but to decide whether the system can be used as fundamental solution for a considerable number of remote off-grid areas, the cost of the system should be determined and compared with the cost of connecting these areas to the main power grid.

6.4- SABIPV Systems for Rural Villages in Saudi Arabia: Fundamental or Complementary Solution?

In the previous sections, the possibility of designing a large SABIPV system for a chosen house in Al Rakabah has been discussed technically. However, this is not adequate to see whether the designed system can be considered as a fundamental solution for the problem of providing the remote villages is Saudi Arabia with electricity services. To complete the picture, the designed SABIPV system should be cost and compared with the cost of the traditional suggested solutions to check if it is cost-effective. In this section, an estimated cost of the designed system will be calculated based on the prices in Saudi markets and available prices in the websites. The cost of each component of the main components well includes the installation and guarantee for 10 years. The cost will not include cables as they tend to be provided with the panels. Table 6.4 shows the individual cost of each components and the overall cost of the whole system.

Table 6.4: The individual cost of each components and the overall cost of the system

Component	**Number**	**Individual averaged cost £**	**Total component averaged cost £**
Panel	48	210	10080
Battery	4	11670	26680
Inverter	1	2280	2280
Charge controller	4	700	2800
Dual axis sun tracker	16	130	2080
Frame & extra light requirements	-	-	2000
The overall cost of the designed system			£ 65,920

This estimated cost can be reduced significantly if low quality equipment is used but this tends to reflect on the life span of the devices. For example, the high quality batteries chosen for the system are guaranteed for 10 years with expected life span of up to 15 years. Low-cost batteries with the same size (Voltages and Amp) are also available in the markets with expected life span of only 5 years and price of £5850. One of the important factors that can reduce the overall cost of the system is the wholesale price where buying a significant number of devices to cover the whole village will decrease the prices.

Manufacturing these devices locally can also reduce the overall cost of the installed systems where the cost of labour is low in Saudi Arabia and the vat is zero. This is in addition to cancelling out the cost of importing and customs.

As the designed system serves one family consisting of 12 persons, the estimated cost of providing solar energy for each person is nearly £5500/capita and as the number of population in the village is nearly 1400, the estimated cost for providing the whole village with solar energy is nearly £7,690,000. Comparing to the cost of linking the village to the main grid which has been mentioned in section 6.2.1, the cost of using solar energy for providing electricity to remote mountainous villages with vast areas, low population, and difficult topographies is considerably less. The cost of using SABIPV systems for Al Rakabah is nearly 12% of the cost of gridding the village to the main grid and nearly £ 54 million can be saved and invested in other subjects such as education or heath care. Here, we are just token about one village and if this all the off-grid areas have been taken into account, the differences between the solar energy and the traditional solutions will be considerably significant. This can lead to one clear conclusion which is that the stand-alone building integrated PV system (SABIPV) is a cost-effective, powerful, and fundamental solution for all off-grid areas in Saudi Arabia including remote villages and rural communities and providing the same level of electricity services that can be achieved in urban on-grid areas.

6.5- Chapter Conclusion

In this chapter, one of the rural off-grid villages in Saudi Arabia has been chosen as a case study giving adequate information about this village, such as the geographical location, population density and distribution, topography, climate, solar radiation, and the current source of electricity. The reasons behind the delay of connecting this village to the main grid and the solutions suggested by the local main power company in Saudi Arabia for providing electricity services have been highlighted briefly. Then, the potential of designing a SABIPV system that is able to provide one of the houses in the village with a level of electricity similar to that available in on-grid urban area has been discussed in details. The design has included sizing the main components of the system, namely the panels and tracking system, storage system, inverter, and charge controller. The amount of energy expected to be provided with the design SABIPV system has been compared with the required electricity consumption to investigate whether the designed system can be technically used as a fundamental or complementary solution in such remote off-grid areas and rural community in Saudi Arabia. Then, the economic side has been investigated by comparing the estimated cost of the designed system with the cost of linking the village to the nearest main grid. The investigations have shown that the Stand-Alone Building Integrated PV system can be used as a highly cost-effective, powerful, and fundamental solution for providing all off-grid areas in Saudi Arabia including remote villages and rural communities with the same level of electricity services that can be achieved in urban on-grid areas**.** Such solution is expected to have a significant impact on different vital issues in Saudi Arabia which will be the focus of the following chapter.

Chapter Seven: Using SABIPV System for Saudi Rural Villages: The Expected Impacts

7.1 Introduction

In this chapter, the expected impact of using SABIPV systems for Saudi rural villages and remote communities will be discussed. This will include the expected environmental, economic, social and security impacts. Starting with environmental impact, reducing pollution and greenhouse gas emissions, the expansion of agricultural land and reduce desertification, and reducing the influence of high-voltage electrical lines on living organisms will be examined. Then, some economic impacts will be considered including providing adequate electricity service at lower cost, offering more job opportunities for people in remote areas, increasing agricultural and handicraft products, and developing of tourism sector in rural areas. After that, social impacts will be studied counting reducing the rate of migration from rural areas to the cities, reducing the slum areas in cities and its impact on reducing the rate of crimes, poverty, ignorance, the low level of morality, and health and environmental problem.

7.2 Environmental Impact

7.2.1 Reducing Pollution and Greenhouse Gas Emissions

Pollution levels have risen over the years across the world, especially in the Middle East due to a large amount of petroleum. Saudi Arabia is the main producer and exporter of petroleum and oil generally with more than 25% of the global oil reserves. Saudi Arabia has seen express economic growth and has become one of the major energy consumers in the Middle East, where electricity consumption is increasing annually by nearly 4%. This means that generating capacity should be amplified twice every 10 years. In 2006, the total consumption of electricity reached 163.151 GWh and increases regularly reaching nearly 193.472 GWh in 2009 with annually increasing rate of more than 10 GWh. In 2005, the Saudi Arabia reached the population of about 23 million and electricity consumption of nearly 7 kWh per capita. This last increased annually by 6.2% during the period from 2005 to 2008 meanwhile population grew yearly by 2.2% during the same period. In accordance with the Ministry of Water and Electricity in Saudi Arabia, the residential sector consumed around 53% of the entirety electricity generated in 2007 with nearly 95.11 GWh and approximately 76 GWh of this value is consumed for residential air conditioning due to the harsh climate conditions and design of buildings which is usually far from being energy-efficient (Bachellerie, 2012).

The rest of the whole electricity produced in 2007 was distributed between industrial sector, government and the commercial sectors as 18%, 11.7% and 11.4%, respectively. On the other hand, during the period of 2004 to 2007, the commercial sector was found as the most rapidly growing area in terms of consuming electricity with annually increasing of 12 %. This is followed by households, government, and industry with yearly growing of 7.5%, 6%, and 2.4% in this order. In Saudi Arabia, electricity capacity and peak load have raised hand in hand over the last years with a reserve margin of 15% in average. However, decommissioning of 5 GW is expected by the end of 2015 if the peak load continues with the current growing rate (Bachellerie, 2012).

During the last decades, oil industrial sector in Saudi Arabia's has grown considerably producing large negative impacts on the environmental and pollution along the country's long coastline and the problem is increasing over the years reaching the rate of 43 ug/m3 in 2011. CO^2 emissions in Saudi Arabia is regarded as one of the highest rates across the

Fig 7.1: Air pollution in Saudi Arabia, https://www.google.com/imghp

world with nearly 332.7 million tons/year in 2005 and increased regularly reaching 410.5 million tons/year in 2009 with annually growing rate of nearly 20 million tons. This can be attributed to rapid industrial development and the level of economic activities which are positively correlated of environmental pollution. The high concentration of industrial activities in Saudi Arabia, and accordingly the high level of CO^2 emission from industrial processes and electricity power stations, is probable to perceive increased environmental pollution as Saudi Arabia continues to come forward from a developing to a developed country (Bachellerie, 2012). Figure 7.1 gives examples of air pollution in Saudi Arabia.

According to a study carried out by SEC in 2014, around 50% of the CO^2 emissions in Saudi Arabia are accounted for by the power and electricity sector, followed by the transport sector and the industrial/ construction sector. CO^2 emissions in Saudi Arabia that caused by providing electricity to the residential sector only reached the level of 108 million tons/year in 2014. The number of those whom benefit from the electricity service of SEC in 2014 across the country was 24, 222,130 from a total population of nearly 28 million which led to a CO^2 emissions rate of 4.35 tons/year/capita from only the residential sector. This is regarded as one of the highest rates across the world representing about 0.34% from the world total CO^2 emissions and put Saudi Arabia in the top 14 per capita emitters of carbon dioxide across the world. Figure 7.2 shows the air pollution resulted from petroleum based power stations in Saudi Arabia.

Fig 7.2: Petroleum power stations and air pollution, https://www.google.com/imghp

Solar energy is expected to help Saudi Arabia specifically for reducing CO^2 emissions and decreasing pollution and greenhouse gas emissions. For example, a small village, such as Al-Rakabah with a population of nearly 1400 if gridding with the main electric network can increase the amount of CO^2 emissions by nearly: 1400 x 4.35 = 6090 tons/year. As mentioned in chapter 5, more than 12500 rural communities were connected to the main grids in Saudi Arabia from 2008 to 2012 providing electricity to more than 1,638,000 users. With 4.35 tons/year/capita CO^2 emissions rate, connected these rural communities to the oil based power stations increased the CO^2 emissions with nearly 7.125 million tons/year which could be avoided using solar energy.

Several hundreds of off-grid rural areas still do not have electricity services due to the reasons mentioned in chapter 5. In the south-west, north-west, along the fertile valleys which branches from the mountains of Red Sea, and close to the international borders of

Saudi Arabia with Yemen, Oman, Jordan and Iraq, there are 287 off-grid remote and rural areas and this number is just based on initial research carried out by the author. With an average population number of 1000, providing these villages with SABIPV systems can prevent the emission of nearly 1.25 million tons/year As the of CO^2 comparing with using local or central electric generators or linking the villages to the oil based power stations.

In general, using SABIPV systems for rural off-grid villages in Saudi Arabia can help to reduce the emission of CO^2 considerably comparing with the alternative planned or currently used solutions, namely the costly connecting with oil based power stations and home or central electric generators.

7.2.2 The Expansion of Agricultural Land and Reduce Desertification

Desertification is term used to describe one of the land degradation forms in which relatively dry land areas become gradually more arid starting with losing bodies of water and following by losing the vegetation cover and wildlife. Desertification is caused by different factors, such as climate change, pollution and human activities and it is regarded as a considerable worldwide ecological and environmental problem. The direct cause of this phenomenon is the removal of most vegetation which is driven by a number of individual or combined issues, such as drought, global warming, tillage for agriculture, overgrazing and deforestation for fuel or construction materials.

Vegetation cover plays a significant role in determining the biological structure of the soil and in many environments, the level of erosion and runoff reduces considerably with increased vegetation cover. Losing the water content in the soil makes it unprotected and dry which help to blow the soil surfaces away under the impact of wind or are washed away by water floods. This leaves unproductive lower soil layers in the sun which are not suitable for growing vegetation.

Total desertified areas in the world amounted to about 46 million square kilometres including approximately 13 million square kilometres in the Arab world in the north of Africa and the Arabian Peninsula. The desertification has a catastrophic impact on the economic situation of the country leading to the loss of huge amount of agricultural crops and regular increasing in their prices. Impacts of desertification appear in most parts of and can be monitored through the transformation of many agricultural areas and fertile valleys to barren and dry land due to the lack of rain, over-attrition of water sources, and the migration of those working in agriculture from their farms to the cities because of the lack of the necessary services in these rural areas, especially electricity, education and health. Neglect of agricultural lands led to productive land deterioration and doubling impacts of desertification in these areas. Examples of desertification on fertile valleys in Saudi Arabia in spite of exposure to the relatively high rain amounts is the valleys of the Mecca, such as Fatima and Naaman, and the valleys of the southern region, such as the valleys of Bisha. Figure 7.3 shows example of the land desertification in Saudi Arabia.

Fig 7.3: Land desertification in Saudi Arabia,
https://www.google.com/imghp

With respect to desertification in Saudi Arabia, Saudi Arabia is classified within the arid regions severely affected by the increasing impacts of desertification on all regions except the south-western region, which lies within the semi-arid region because of the multiplicity of the rainy seasons and high amounts of rainfall. With regard to the phenomenon of desertification in Saudi Arabia, Saudi Arabia is the leading Arab states that have established a specialized centre for studying the desertification and anti-desertification long time ago and King Saud University has had the honour to be the leader of this centre. Prince Sultan Research Centre for environment, water and desert has carried out different studies on methods of fighting against desertification in Saudi Arabia and encourage private research to find the best ways to preserve the fresh water through modern technology, especially remote sensing techniques.

One of the methods suggested for fighting desertification is increasing the vegetation cover in the lands on the bounders with desert and enhancing the quality of the semi-desertified lands by increasing agricultural areas. Providing the necessary services in remote and rural areas can play a significant role in this matter and the best example about that is Dawaser valley where linking the area to the main electricity grid increased the agricultural areas considerably as seen in Figure 7.4. In 1986, the area was off-grid with considerable degraded services in terms of electricity, education and health which led to the immigration of a good deal of farmers to surrounded cities. In 1991, the electricity services started to be provided in the area leading to increase the agricultural area significantly. This progress has continued reaching the optimistic levels in 2000 with nearly 10 times the areas enhanced in 1995.

In general, providing the necessary services, especially electricity to off-grid remote and rural areas using solar systems, such as SABIPV system can help significantly to increase the agriculture areas and vegetation covers and as a consequence increasing the

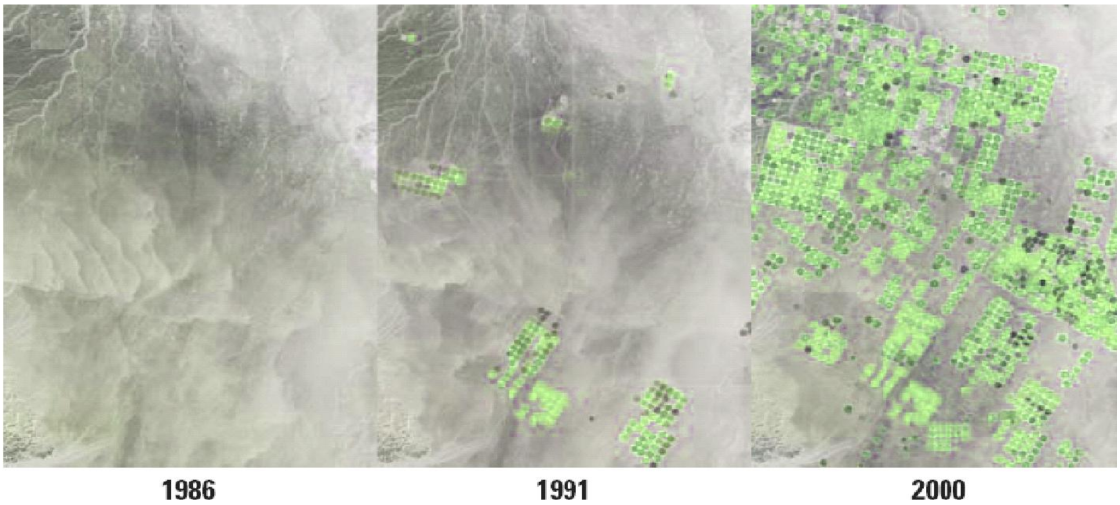


Fig 7.4: Increasing agricultural areas with providing electricity services, https://www.google.com/imghp

agricultural products, reducing the impact of desertification, and reducing the cost of the expensive project of fighting desertification.

7.2.3 Reducing the Influence of High-Voltage Electrical Lines

By increasing population of Saudi Arabia and growing the industrial sector, towns are expanding and many structures build up near high voltage power transmission lines. The increase of power consumption and the distribution of population across huge areas have increased the need for transmitting huge amount of power over long distances. Large transmission lines with high voltage and current levels generate huge values of electric and magnetic field stresses which have an impact on the human being and the surrounded objects at ground surfaces. The electricity system produces exceedingly low frequency electromagnetic field and non-ionizing radiations which have health impacts. In addition to that, the electrostatic coupling and electromagnetic interference of high voltage transmission lines have impact on plants (Epidemiology, 2002).

There are lots of supporting documents and research paper discusses the impacts of Electric and magnetic fields on humans, plants, animals along with vehicles, fences, and buried pipes under close to these lines. For more details, the user is referred to: (British Medical Journal, June, 2005; Epidemiology, 2003 Jul; 14(4):413-9; Epidemiology, 2002 Jan; 13(1):9-20). The impact Electric and magnetic fields generated by high voltage power transmission lines includes short term health problem, such as Headaches, Fatigue, Anxiety, Insomnia, Prickling and/or burning skin, Rashes, Muscle pain. This is in addition to the expected long term human health impacts and risks, such as damaging DNA, Cancer, Leukemia, Neurodegenerative disease, Miscarriage.

The other important impact is that on maintenance worker of high voltage power transmission lines. For providing continuous and uninterrupted supply of electric power, maintenance operations of power lines tend to be carried out with systems energized or live. These live power lines generates electric fields and magnetic fields which may affect the health of live line workers and cause a number of diseases by affecting almost all parts of the human body. Such electric fields and current densities generated by high voltage power transmission lines can affect humans of all ages and causes short term and long term health problem and sometimes death. This is in addition to the expected damage of agricultural and forest lands where high power transmission lines pass where high power transmission lines affects the growth of plants and the bio-chemical changes in this plant.

Mitigating the impact of high voltage power transmission lines via the current used methods, such as Line Shielding, Line Configuration and Compaction, Grounding, Providing Right of Way, and Maintaining Proper Clearance, are extremely costly and are not guaranteed for less impacts. Using solar energy and providing the rural communities with SABIPV systems can reduce these harms considerably where there will be no need for extending the high voltage power transmission lines from the main power stations to these remote villages.

7.3 Economic Impact

7.3.1 Provide Adequate Electricity Services at Lower Cost

Using solar energy and providing the remote areas with SABIPV systems would create a massive opportunity for Saudi Arabia to shift away from supplying oil based electricity reducing local oil consumption considerably. According to the archives of SEC, Jeddah, in 2010, the cost of the domestic oil consumption in the power stations in Saudi Arabia reached about Saudi Arabian Riyals (SAR) 134 billion compared to SAR 6.5 billion in 1985. Following the current trends, and according to forecasts applied by ESC, domestic oil consumption in Saudi Arabia can reach more than 3 billion barrels/annum in 2030 which will affect the amount of oil exporting extremely. The costs of CO^2 emission should also be taken into consideration when costing the domestic oil consumption which will increase the overall cost significantly.

This is in addition to the high cost of extending the electric grid to the remote and rural areas, especially mountainous regions where the cost of the installation and maintenance tends to be doubled. For example, as seen in chapter 6, in the case of Al-Rakabah village, linking the area with the main grid will cost more than 8 times the cost of providing the village with the designed SABIPV system which can provide the same level of electricity services provided with the main electricity grid.

An example is the projects suggested in 2012 by SEC to the government for connecting 72 rural communities in Fayfa and Najran, in the far south-west of Saudi Arabia to serve about 18,000 people living in 1485 houses. As mentioned in chapter 5, for carrying out the whole project, construction of about 325 km of 33 kV distribution lines, 3200 km of

11 kV lines and 22 transfer stations (33/11 quality of 5 MVA) are required. This is in addition to the secondary equipment, including low-voltage transformers, and connectors meters. The overall cost of this project was about £493,522,000 which means that the cost is about £27,000 per capita in the area with expected financial returns of about £320,000 per year. Such huge differences between the cost and the returns show how such project is unsuccessful in economic terms. This led the government in Saudi Arabia to turn a blind eye on such solutions and search for better and less expensive solutions. Using SABIPV system instead of the suggested project is extremely cost-effective and fundamental solution where the approximate cost is (1485 x 65,900) approximately £ 97 million which is about 20% of the suggested project’s cost.

The saved money can be spend on reconstructing the remote areas and providing the necessary services in rural communities, such as education, health, road networks, transportation, agriculture, tourism, light industry and institutions of civil society which will benefit the residents of these areas in particular and the entire country in general.

7.3.2 Provide Job Opportunities For Residents in Remote Areas

Unemployment means that there are a number of persons in the community who have the ability to work but they do not find jobs due to the lack of employment opportunities in the community. Unemployment is considered to be a social scourge and economic problem and it has negative impacts on both the individuals and the society. The number of unemployed in Saudi Arabia differences considerably between the government statistics and the private independent statistics. According to the Department of Statistics in Saudi Arabia, there were more than 629,000 unemployed in 2014 which forms about 12% from the local workforce. However, Hafiz, the independent institute of statistics claims that the number of unemployed in 2014 in Saudi Arabia was nearly 1.9 million and the unemployed rate is about 36% and 20% from them hold university degrees. According to Hafiz, in remote areas, the percentage of unemployed reaches in some villages 45% and reduced to 18% in the best cases in harvests which led the majority of workforce to leave these areas and migrate to cities and as a consequence the display will be more than demand and this increases the unemployed rate in cities.

In addition to the migration from rural areas to cities, many reasons play a significant role in rising the unemployed rate in Saudi Arabia, especially in rural areas, such as low education level, lack of linking education with the labour market requirements, imbalance in the structure of the national economy, increasing population by more than the growth rate in GDP, Foreign labour, the demand of reducing the number of service workers for many reasons, such as privatization.

Using solar energy and providing the remote areas with SABIPV systems can provide more opportunities for the residents to work in their villages and reduce the need for migrating to cities. The job opportunities will include education services, health services, transportation, tourism sector, and institutions of civil society. This is in addition to the main sector in these areas which is the agriculture where providing electricity services help to increase the agriculture areas and as a consequence increase the agricultural products and the based light industrial and handicraft products. This will reflect considerably on the life quality of villagers and local residents of rural areas as well as on the economy of the country.

7.3.3 The Development of Tourism Sector in Rural Areas

These days, tourism represents an integrated industry, including planning, investment, construction, and marketing and distribution. Tourism becomes a multi-stage industry and it interacts with and depends on other sectors of the economy. Therefore, tourism is considered as a contributing factor to the developing and growing the economy, especially in the field of infrastructure. This led the developed countries to pay much attention for developing the tourism sector and provide additional reasons for its tourist attractions to meet the needs of different categories of tourists, both local and international. This has helped to increase the contribution of tourism sectors in the gross domestic outputs and puts these countries in the forefront of the most attractive tourist countries in the world. This is in contrast to many developing countries that have not yet reached that level of tourism attracting and the contribution of tourism sector in national and local economies is still limited.

It is clear that tourism in Saudi Arabia is currently a relatively large weight industry. With regard to tourist facilities and the number of tourists, the kingdom is considered as the biggest tourist destinations in the Middle East as well as the largest generator of foreign tourism in the region. Saudi tourism is characterized by relatively high capacities to attract large numbers of tourists. According to Tourism Information and Research Centre, the total number of inbound tourist trips to the kingdom reached about (194.71) million trips, while the total number of departing tourist flights is (114. 211) million trips during the year 2012. The inbound tourism expenditure amounted to about SAR (31) billion, compared to approximately SAR (141) billion on domestic tourism, and SAR (2141) billion expenses for local tourism. The number of overnight local and expatriate tourists was about (274 792) million spent the equivalent of SAR (1.40) billion riyals with recorded hotel occupancy rate of about (03%) compared to approximately (01%) of furnished residential units.

According to the World Bank, approximately 14.3 million people visited Saudi Arabia in 2012, making it the world's 19th most visited country. Potential tourist areas include the Hijaz and Sarawat Mountains, Red Sea diving and a number of ancient ruins. With regard to the number of jobs provided by the tourism sector, the number of jobs until the end of 2012, according to Tourism Information and Research Centre in Saudi Arabia, is one million direct jobs, and 231 thousand indirect jobs.

However, the tourism sector in Saudi Arabia is largely based around religious pilgrimage where the visitors of the holy places in Mecca and Medina forms more than 75.8% from the whole number of visitors and about 19.6% for business. During the last a few years, the local tourism has started to be engorged by establishing some traditional festivals and occasions in local tourism areas to draw attention to such these attractive areas. However, the absent infrastructures and weak services, such as electricity, road networks, hotels, restaurants, and emergency response in these areas prevent developing the tourism sector in wide areas in Saudi Arabia.

An example of that is Faif Mountain in the south of Said Arabia which has almost all tourism attractions, such as the worm weather, mountainous lakes and caves, beautiful sightseeing, the eyes of mineral water, areas above the clouds, and historical castles. However, due to the degraded services in this area, especially electricity where house electric generators are the only method used, the tourism sector in this area is disabled and the number of local tourists does not exceeds a few hundred who come from the surrounded areas and villages to visit their relatives in this area. Using solar energy systems, such as SABIPV system in such tourism attraction areas can help to provide the electricity to the necessary services in the tourism sector in the area, such as hotels, restaurants, emergency response, security, and night activates. Figure 7.5 gives examples of the tourism attractions in Faif Mountain.

Fig 7.5: Examples of the unexploited tourism attractions in Fifa Mountain, https://www.google.com/imghp

7.4 Social Impacts

7.4.1 Reduce the Rural-Urban Migration

According to some local research carried out by King Saud University, in 2012, the rate of migration of Saudi workforces from the countryside to the cities is expected to exceed 74% from the whole number of local workers in remote and rural areas and the rest linked by place of work or study. This can be noted when visiting the rural areas where the presence of young people is considerably low compared to the elderly whom reject the migration because of social considerations and their association with the place. Such high rate of migration is expected to have an impact on the demographic, economic, social and cultural characteristics of the population.

Economic incentives, employment opportunities that improve immigrant income, educational, health, social services, and entertainment and lifestyle are classified as important attractive factors for the majority of those immigrate from rural communities to big cities. The south-west of Saudi Arabia has one of the highest country-to-city migrating rates and experiences the migration of the majority of the hand workers due to the reasons mentioned above in addition to the considerable differences in the lifestyle between these mountainous rural and agricultural areas and urban areas.

Such high rate migration is expected to have a negative impact on the development in different regions in Saudi Arabia through a direct impact on the distribution of the population and their attributes. Moreover, service agencies may face difficulty in providing the necessary services in the event of a growing population resulted in the rural exodus, in addition to a rise in real estate prices in those cities and the proliferation of slum areas in cities.

Also, countryside-to-city migration usually includes the better educated and the most active population whom have the ability to compete in the labour market. This will deprive rural areas from human produced power which will adversely affect the rural development in general and agricultural sector in particular. Accoutring to an interview with the local council of Bain-Malik carried out by the author, the rural-urban migration during the last decade had considerably negative impacts on the agricultural sector of the area located in the south-west of the country where the percentage of those who were employed in agriculture decreased from 22.2% before immigration to 1.4% during 10 years and 40.1% of those who were employed in agriculture and immigrate to the cities are still retain their farms but untapped.

To overcome this problem, the agricultural sector and the light industrial products that based on it should be developed which can help to reduce the high rate of immigrants and ease population pressure on cities. This can help to create good jobs, and keep the main economic source in the countryside with an infusion of some modifications according to agricultural activities. Also, it is imperative that economic development plans balance between urban and rural requirements and distributed across the whole country. This should include expanding the agricultural areas and rehabilitation of neglected and untapped lands which depend mainly on providing the necessary services to these rural areas and encouraging the remigration from big cities to countryside, especially for young workforces. As mentioned before, providing the remote areas with solar energy systems, such as SABIPV system can help in increasing the agricultural areas, encouraging the tourism sector, and providing the necessary services, such as opening schools, clinics, and emergency response. This will be reflected positively on the number of the available job opportunities in rural and remote areas which works on reducing the need for leaving to big cities.

7.4.2 Reducing the Proportion of Slum Areas in Cities

A slum is a high density populated urban unofficial community regarded as substandard housing and squalor. Slums are different in size, location, and architecture and other characteristics from country to country but common in lack reliable sanitation services, supply of clean water, reliable electricity, timely law enforcement and other basic services. Slum residences vary from shanty houses to professionally-built dwellings but in general with poor-quality design or construction. Slums tend to be constructed illegally on agricultural and desert lands or unplanned and unregulated state lands that located on the outskirts of the city. Slums often arise spontaneously in cities and are not subject to the standards of modern urban so they cannot interact with the requirements of modern life or provide basic services which lead to generate chronic problems, such as transportation, public health, environment, and security.

The main reasons behind the proportion of slum in cities are the high population growth rates, the flow of migration from the countryside to cities and the disability of cities to receive all these numbers migrate from remote and rural areas, decrease in the number of residential units and increased demand as a result of the rapid migration from the countryside to the city. Furthermore, major cities have become highly attractions as a result of the concentration of services and in return, rural towns and villages become severe expulsion as a result of the scarcity of services and lack of job opportunities. The other reason is the high prices of apartments and residential land in the official areas which enjoy public utilities, such as pure water, sewage, electricity, and paved streets.

Saudi Arabia had one of the highest rates of rural-urban migration during the last decades as well as high rate of population growth rounded about 2.5% which means that the number of population is doubled every 28 years. Saudi Arabia has a huge shortage of housing where according to Jeddah Chamber of Commerce and Industry, the kingdom must build at least one million new homes in the next five years to meet this increasing need. To address the growing need and overcome the problem of slums in big cities, Saudi Arabia plans to spend US $35 billion on construction including building new factories, schools, doubling desalination capacity, increasing electrical generation and distribution.

A slum phenomenon spreads in almost all big cities in Saudi Arabia, such as Riyadh, Jeddah, Mecca, Medina, Al-Ahsa, and Dammam. For example, in the Red Sea city of Jiddah , the second biggest city in the country, the high rate of immigration from the villages and rural areas of Red Sea's mountains and the lack of property shortage, especially affordable homes, has led to the creation of more than 50 big slums and unplanned settlements in the city that housing more than 1.2 million people and comprise a third of its built-up area, according to municipality Figures. Figure 7.6 shows a number of Slums south-east of Jeddah. The Jeddah Municipality plans to decrease this number of people to nearly the quarter by building more high density developments in the city as part of its Jeddah Strategic Plan.

Fig 7.6: Slums in Jeddah the second city in Saudi Arabia

As mentioned in the previous section, using solar energy systems, such as SABIPV system for rural areas in Saudi Arabia can help to reduce the rate of countryside to city migration and as a consequence, can help to reduce the propagation of slums in cities and overcome the related problems, such as the spread of poverty, ignorance, crime rate, the low level of morality, and health and environmental problem.

7.5 Other Expected Impacts

In addition to the expected positive impacts mentioned above of providing the rural villages and remote communities in Saudi Arabia with SABIPV systems, more general and long term advantages can be expected, such as:

- Increasing the education and awareness levels in rural areas by providing schools and watching the TV educational programmes.
- Improving the individual and community health level by providing local hospitals which reflects in general positively on the other sectors, such as industry and agricultural.
- Maintain the original customs and traditions of each region and protection them from extinction due to migration to cities.
- The well distribution of population across the state area ensures good monitoring and high level of security where unoccupied and empty areas tend to be used for purposes detrimental to the interests of the country.
- Covering the roofs of buildings with the arrays of panels can reflect the sun away from the roofs which can relatively decrease the need for air conditioning providing wide shadowed areas. These unexploited areas can be used in social activities, such as weddings and local small and light industrial projects, such as spinning, weaving, knitting, sewing and pottery.

7.6 Chapter Conclusion

In this chapter, the expected impact of using SABIPV systems for Saudi rural villages and remote communities has been discussed. It can be concluded from the chapter that using solar energy and providing the rural areas and remote communities in Saudi Arabia can help in terms of environment in reducing pollution and greenhouse gas emissions, the expansion of agricultural lands and reducing desertification, reducing the influence of high-voltage electrical lines on living organisms. As for the expected economic impacts, SABIPV system can help in providing adequate electricity service at lower cost, offering more job opportunities for people in remote areas, increasing agricultural and handicraft products, and developing of tourism sector in rural areas. Socially, the advantages of using the system can include reducing the rate of migration from rural areas to the cities, reducing the slum areas in cities and its impact on reducing the rate of crimes, poverty and ignorance, the low level of morality, and health and environmental problem.

Chapter Eight: Conclusions and Recommendations

This chapter provides the reader with the main conclusions that are extracted from this thesis and some recommendations that can help to improve this work.

8.1 Conclusions

A number of natural resources can be exploited for deriving energy, such as the sun, wind, water flow, tides, waves and deep heat generated within the earth. Recently, renewable resources especially that extracted from solar have been significantly encouraged mainly for environmental worries, such as climate change mitigation and global warming, coupled with high oil cost and security and economic matters. The crucial need of energy in human development has also been another important drive pushing the rapid progresses in renewable technologies, which results in both large-scale strategic projects for covering wide urban and rural areas and simple systems suitable for individual buildings. Solar energy is a suitable solution for providing electricity, especially for off-grid areas and momentary constructions where the electricity network, if available, might be inconvenient or highly pricey to be connected. Using solar energy is increasing progressively even in gridded areas as the cost of solar electricity tends to be limited in the installation cost.

Solar energy has become a widely desired option, especially in high solar radiation areas. The Middle East, especially Gulf region is an ideal geographical area for solar power where it has one of the highest solar irradiation rates across the world. Also, the design of houses in GCC countries are suitable for SABIPV systems where they have extended flat roofs for providing more shadows and allowing the air to be circulated. The population in GCC countries is significantly small compared to the geographical areas and populations are distributed mostly throughout huge areas forming small villages and rural communities on substantial distances from the main power networks.

In Saudi Arabia, there is a crisis in supplying enough electricity to the large cities and domestic remote area in various parts in the country. Wide range of remote areas still suffer from a severe shortage of power supply due to: the prohibitive cost of connecting such distant areas to the main electric grids, the financial returns futile and the difficulty and high cost of maintenance works. This problem becomes significant during summers because of the high air conditioning electricity demands. Gridding the isolated and remote off-grid areas to the main electricity grid are challenge and exceptionally overpriced. This is in addition to the expected environmental impacts, such as raising the pollution rates in the area and the safety influences of extending the high voltage lines over huge areas. On the other side, the lack of the necessary infrastructure services, particularly electricity and the looking forward for better level of prosperity lead people who live in countryside and remote areas usually to immigrate to in-grid areas which has several short and long-term negative impacts on economic, social and security sides.

Although GCC countries have been undertaking solar energy projects for more than 3 decades and despite the wide planes for considering solar energy as an important energy resource in these states generally and in Saudi Arabia particularly, the efforts for using this great energy resource in commercially viable projects have been scattered and almost unnoticed. Also, more reliable and independent investigations and studies into the potentials of using solar energy technologies both PV and CSP to cover the expected decommissioning in electricity supplying are required.

In this project, the opportunity of using small-scale solar energy technologies, such as Stand-Alone Building-Integrated PV systems has been investigated as an optimal solution for providing solar energy to a great deal of off-grid areas in Kingdom of Saudi Arabia and the expected short and long-term impacts of such solution have been studied. From this study, the following points can be concluded:

1- The main reasons behind the crisis in supplying electricity to domestic remote and rural off-grid areas in Saudi Arabia can be summarised as:
    - The weakness of the financial returns compared to the cost of providing the service where the population density in Saudi Arabia is considerably small and residents are distributed over huge areas creating small communities on vast distances from vital areas. Furthermore, these rural villages in general are really to be organized or planned and they are distributed along narrow fertile valleys which increases the distances between houses in the same community to reach a few kilometres in average. This increases the cost of gridding the rural villages to the main grid comparing to the expected financial returns from such small populations. Also, gridding such remote areas requires the availability of some necessary services along the supply line, especially paved roads or affordable ways for the mechanics of installation which are not available in the majority of Saudi rural communities and providing these services will increase the cost significantly. The studies show that linking the rural mountainous areas to the main grid is unsuccessful in economic terms where the finance revenues are impossible to cover the installation and maintenance expenses.
    - The natural topography of areas which is regarded as one of the main factors limits providing the electricity to the majority of the remote communities, especially in the south-west of the country. These areas are common with steep mountains, mudslides, rugged canyons, unstable rocky areas, moving

silt, sand dunes, and other difficult terrain which hinder linking the villages to the main electric grid.

- The regulations of providing electric services in Saudi Arabia where the policy regulations of the electricity companies requires for providing the electricity for any community to be officially registered in the administrative departments of the area as a residential area or rural community. This registration requires the number of population to be more than 1500 distributed on an area of less than 1 square Kilometre, the presence of a paved road planned by the authorities and the official responsible and suitable of the mechanics of power companies, the community should include at least one primary school, clinic and police point, the presence of the population in the region throughout the year, not only on a seasonal basis, there are not any legal issues on the ownership of the real estates and lands of the communities, and the area has to be within the urban plan subjects of the Ministry of Utilities. These conditions are not fit the majority of the distance areas in Saudi Arabia.
- Property problems between different administrative areas on wide areas belong to these rural communities.
- Lack of insistence on demanding the provision of basic services in these areas because of the low awareness and education level and the transmission of the educated people to live in cities.
- Some of these communities were built randomly without planning or permissions of the government and the provision of the basic services to these villages will increase this phenomenon unwanted by the Saudi government.

- Low electricity prices in Saudi Arabia make the delivery of electricity service to those areas inefficient economically leading to heavy losses on the operating companies.
- The central governing system of the administrative regions in Saudi Arabia where all the attention and services are focused and available on the provincial capital of the province and decrease as moving away the centre to the county sides.
- Lack of encouraging the private tourism sectors in these areas, which will lead to an increase in the number of tourists and investors, thereby reducing the cost of providing services and increasing financial returns.
- Failure to provide plans by the competent authorities to build up integrated rural villages including schools, clinics and police station for those living in random rural areas and provide safe ways to get to farms and pastures easily.

2- One of the rural off-grid villages in Saudi Arabia has been chosen as a case study which is Al Rakabah. This last is a small village located in the District of Bani Malik, Jizanin, the south-western part of Saudi Arabia. Important information about this village that related to designing the SABIPV system has been illustrated and discussed, such as the geographical location, population density and distribution, topography, climate, solar radiation, and the current source of electricity. The potential of designing a SABIPV system that is able to provide one of the houses in the village which includes a family of 12 persons with a level of electricity similar to that available in on-grid urban area has been investigated in details. The design has included sizing the main components of the system, namely the panels and tracking system, storage system, inverter, and charge controller. The amount of energy expected to be provided with the design SABIPV system has been compared with the required electricity consumption to investigate whether the designed system can be technically used as a fundamental or complementary solution in such remote off-grid areas and rural community in Saudi Arabia. The design showed that it is possible to power a large house such as that used in the study case using SABIPV system providing the whole electricity requirements. Also, the economic side has been investigated by comparing the estimated cost of the designed system with the cost of linking the village to the nearest main grid. The study has shown that the estimated cost of providing the normal level of electricity services via solar energy for each person in the village is nearly £5500/capita which is nearly 12% of the cost of gridding the village to the main grid. This means that nearly £ 54 million can be saved and invested in other subjects such as education, infrastructures or health care. This is just for one village and if all off-grid areas have been taken into consideration, the differences between the cost of utilizing solar energy and traditional oil based solutions will be considerably significant. This can lead to one clear conclusion which is that the Stand-Alone Building Integrated PV system is a cost-effective, powerful, and fundamental solution for all off-grid areas in Saudi Arabia including remote villages and rural communities and providing the same level of electricity services that can be achieved in urban on-grid areas.

3- The expected impacts of using SABIPV systems for Saudi rural villages and remote communities have been investigated including a number of environmental impacts, such as reducing pollution and greenhouse gas emissions, the expansion of agricultural land and reduce desertification, and reducing the influence of high-voltage electrical lines on living organisms, a number of economic impacts, such as providing adequate electricity service at lower cost, offering more job opportunities for people in remote areas, increasing agricultural and handicraft products, and developing of tourism sector in rural areas, and a number of social impacts, such as reducing the rate of migration from rural areas to the cities, reducing the slum areas in cities and its impact on reducing the rate of crimes, poverty, ignorance, the low level of morality, and health and environmental problem. The main conclusions are:

- CO^2 emissions in Saudi Arabia is regarded as one of the highest rates across the world with nearly 332.7 million tons/year in 2005 and increased regularly reaching 410.5 million tons/year in 2009 with annually growing rate of nearly 20 million tons. Around 50% of the CO^2 emissions in Saudi Arabia are accounted for by the power and electricity sector reached the level of 108 million tons/year in 2014 and this put Saudi Arabia in the top 14 per capita emitters of carbon dioxide across the world. Solar energy is expected to help Saudi Arabia specifically for reducing CO^2 emissions and decreasing pollution and greenhouse gas emissions where this study has shown that gridding a small village, such as Al-Rakabah with a population of nearly 1400 with the main electric network can increase the amount of CO^2 emissions by nearly 6090 tons/year and the 12500 rural communities with populations of 1,638,000 that were connected to the main grids in Saudi Arabia from 2008 to 2012 increased the CO^2 emissions with nearly 7.125 million tons/year which could be avoided using solar energy. Generally, this study expects that using SABIPV systems for rural off-grid villages in Saudi Arabia can help significantly to reduce the emission of CO^2 comparing with the alternative planned or currently used solutions, namely the costly connecting with oil based power stations and home or central electric generators.

- The expansion of agricultural land and reduce desertification where Saudi Arabia is classified within the arid regions severely affected by the increasing impacts of desertification on all regions except the south-western region, which lies within the semi-arid region because of the multiplicity of the rainy seasons and high amounts of rainfall. One of the methods suggested for fighting desertification is increasing the vegetation cover in the lands on the bounders with desert and enhancing the quality of the semi-desertified lands by increasing agricultural areas. Providing the necessary services in remote and rural areas, especially electricity can play a significant role in this matter and using SABIPV system can help considerably to increase the agriculture areas and vegetation covers and as a consequence increasing the agricultural products, reducing the impact of desertification, and reducing the cost of the expensive project of fighting desertification.

- Reducing the influence of high-voltage electrical lines where large transmission lines with high voltage and current levels generate huge values of electric and magnetic field stresses which have an impact on the human being and the surrounded objects at ground surfaces. The electricity system produces exceedingly low frequency electromagnetic field and non ionizing radiations which have health impacts, such as Headaches, Fatigue, Anxiety, Insomnia, Prickling and/or burning skin, Rashes, Muscle pain. This is in addition to the expected long term human health impacts and risks, such as damaging DNA, Cancer, Leukemia, Neurodegenerative disease, Miscarriage. In addition to that, the electrostatic coupling and electromagnetic interference of high voltage transmission lines have impact humans, plants, animals along with vehicles, fences, and buried pipes under close to these lines. Using solar energy and providing the rural communities with SABIPV systems can reduce these harms considerably where there will be no need for extending the high voltage power transmission lines from the main power stations to these remote villages.

- Provide adequate electricity services at lower cost where the cost of extending the electric grid to the remote and rural areas, especially mountainous regions including installation and maintenance tends to be doubled. The study shows that the estimated cost of providing the normal level of electricity services via solar energy is nearly 12% of the cost of gridding the village to the main grid. The saved money can be spend on reconstructing the remote areas and providing the necessary services in rural communities, such as education, health, road networks, transportation, agriculture, tourism, light industry and institutions of civil society which will benefit the residents of these areas in particular and the entire country in general.

- Provide job opportunities for residents in remote areas. The number of unemployed in Saudi Arabia differences considerably between the government statistics and the private independent statistics from 12% to 36% from the local workforce, respectively. The percentage of unemployed reaches in some rural villages 45% and reduced to 18% in the best cases in harvests which led the majority of workforce to leave these areas and migrate to cities and as a consequence the display will be more than demand and this increases the unemployed rate in cities. Using solar energy and providing the remote areas with SABIPV systems can provide more opportunities for the residents to work in their villages and reduce the need for migrating to cities. The job opportunities will include education services, health services, transportation, tourism sector, and institutions of civil society. This is in addition to the main sector in these areas which is the agriculture where providing electricity services help to increase the agriculture areas and as a consequence increase the agricultural products and the based light industrial and handicraft products. This will reflect considerably on the life quality of villagers and local residents of rural areas as well as on the economy of the country.

- The development of tourism sector in rural areas. It is clear that tourism in Saudi Arabia is currently a relatively large weight industry. However, the tourism sector in Saudi Arabia is largely based around religious pilgrimage where the visitors of the holy places in Mecca and Medina forms more than 75.8% from the whole number of visitors and about 19.6 % for business. During the last a few years, the local tourism has started to be encouraged by establishing some traditional festivals and occasions in local tourism areas to draw attention to such these attractive areas. However, the absent infrastructures and weak services, such as electricity, road networks, hotels, restaurants, and emergency response in these areas prevent developing the tourism sector in wide areas in Saudi Arabia. Using solar energy systems, such as SABIPV system in such tourism attraction areas can help to provide the electricity to the necessary services in the tourism sector in the area, such as hotels, restaurants, emergency response, security, and night activates.

- Reducing the rural-urban migration where the rate of migration of Saudi workforces from the countryside to the cities is expected to exceed 74% from the whole number of local workers in remote and rural areas and the rest linked by place of work or study. Such high rate of migration is expected to have an impact on the demographic, economic, social and cultural characteristics of the population. Economic incentives, employment opportunities that improve immigrant income, educational, health, social services, and entertainment and lifestyle are classified as important attractive factors for the majority of those immigrate from rural communities to big cities. The south-west of Saudi Arabia has one of the highest country-to-city migrating rates and experiences the migration of the majority of the hand workers due to the reasons mentioned above in addition to the considerable differences in the lifestyle between these mountainous rural and agricultural areas and urban areas. Providing the remote areas with solar energy systems, such as SABIPV system can help in increasing the agricultural areas, encouraging the tourism sector, and providing the necessary services, such as opening schools, clinics, and emergency response. This will be reflected positively on the number of the available job opportunities in rural and remote areas which works on reducing the need for leaving to big cities.

- Reducing the proportion of slum areas in cities where Saudi Arabia had one of the highest rates of rural-urban migration during the last decades which led to the wide spread of slum areas across the main cities and the business centres.. A slum phenomenon spreads in almost all big cities in Saudi Arabia, such as Riyadh, Jeddah, Mecca, Medina, Al-Ahsa, and Dammam. This has led to generate chronic problems, such as transportation, public health, environment, and security. Using solar energy systems, such as SABIPV system for rural areas in Saudi Arabia can help to reduce the rate of countryside to city migration and as a consequence, can help to reduce the propagation of slums in cities and overcome the related problems, such as the spread of poverty, ignorance, crime rate, the low level of morality, and health and environmental problem.

- Increasing the education and awareness levels in rural areas by providing schools and watching the TV educational programmes.

- Improving the individual and community health level by providing local hospitals which reflects in general positively on the other sectors, such as industry and agricultural.

- Maintain the original customs and traditions of each region and protection them from extinction due to migration to cities.

- The well distribution of population across the state area ensures good monitoring and high level of security where unoccupied and empty areas tend to be used for purposes detrimental to the interests of the country.

- Covering the roofs of buildings with the arrays of panels can to reflect the sun away from the roofs which can relatively decrease the need for air conditioning providing wide shadowed areas. These unused areas can be used in social activities, such as weddings and local small and light industrial projects, such as spinning, weaving, knitting, sewing and pottery.

8.2 Recommendations and Future Work

Based on the research reported in this thesis and the conclusions deduced from the results of the study, the following recommendations are being made for possible future work:

- The generalization of this study to include the majority of the areas in Saudi Arabia which have different topography, climate, and solar radiation. This will help for more investigations on the capability of the SABIPV systems to be used as a fundamental solution for providing the rural and remote areas in the country with the suitable level of electricity service.
- Designing software that is able to design a whole PV system automatically based on simple information provided with the user where the software should be provided with a data base including all the required designing data which can be downloaded from the internet based on the geographical location of the chosen building.
- Comparing the suggested solution with central solar system even that based of PV panels or using concentrating solar technique. This can help to provide a clear view about the limitations and advantages of each system for rural and remote areas.
- Comparing the designed system with the integration of solar and deasil generators in terms of functionality, cost, and reliability.
- Investigating the possibility of using the SABIPV system in urban areas as a fundamental or conventional system for providing electricity services and reducing the load on the oil based power stations.
- Investigating the opportunity of creating power distribution integrating system between buildings which works on exporting the exceeded power between stand-

alone systems. This can helps on increasing the functionality and reliability of the system providing better performance.

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Appendixes

Table (A.1): A brief description of the interviews carried out in this project

Interviewee	Interviewer	Interview date	Questions about:	Used in section:
The director of ESC, Jeddah branch	The author	June, 2013	1- The number of rural communities that connected to the main grids in Saudi Arabia recently. 2- Number of users in these villages. 3- The locations of the off grid areas in Saudi Arabia. 4- The average cost of connecting rural areas with hard topographies to the main grid. 5- Previous projects including mountainous areas and the overall cost. 6- The annual expected financial returns from these villages. 7- The economical value of such projects.	3.2
The head of Civil	The author	July, 2013	1- The important factors that limit providing the	3.3.2

Engineering Department in ESC, Jeddah branch			electricity to the majority of the remote communities, especially in the south-west of Saudi Arabia. 2- How the natural topography limits providing the electricity services in mountainous areas. 3- The relationship between the hard natural topographies and the overall cost of the installation and maintenance.	
the deputy head of Geotechnical Engineering Department in ESC, Jazan	The author	July 2014	1- The impacts of sand dune encroachment on the power transmission lines. 2- The dangerous side impacts of this problem. 3- How can this delay the works of inspection and regular maintenance? 4- The impact of the leakage of dust and sand into parts	3.3.2

			of electrical equipment. 5- The impacts of sandblasting on the protection layer of metal towers and columns for rust, corrosion, erosion, and oxidisation. 6- The related safety issues.	
The director of ESC, the main branch, Riyadh	The author	September, 2013	1- The suggested solutions by ESC for rural communities that located close to the international borders of the country. 2- The advantages and limitations of the suggested solutions. 3- Examples of using the suggested solutions successfully in the other countries. 4- The possibility of applying such solution in the case of Saudi Arabia. 5- Examples for explaining the difficulty of using the	5.4.2

			suggested solution.	
The local council of Bain-Malik	The author	September 2013	1- The rural-urban migration during the last decade in the south-west of Saudi Arabia. 2- The negative impacts of the rural-urban migration on reducing the percentage of those who were employed in agriculture sector. 3- The suggested solutions for overcome such harm impacts. 4- How can providing the electricity services to these areas help to reduce the impacts of the rural-urban migration? 5- The impact of the rural-urban migration on priding the slum areas on the cities.	7.9.1 7.9.2

Table (A.2): A brief description of the unpublished documents used in this project

Document name	Document type	Date of use	Description
Archives of Electricity Saudi Company, Jeddah	Archive	2013/2014	Archives of Electricity Saudi Company, Jeddah is considered as one of the biggest archives in Saudi Arabia where Jeddah is one of the first cities in the area that has been provided with the electricity services and it has included the main branch of the ESC until 1990 when moved to the capital city of Saudi Arabia. Archives of Electricity Saudi Company, Jeddah is an accumulation of historical records and contains primary source documents that have accumulated over the company lifetime. These archival records are unpublished and are quite distinct from libraries with regard to their functions and organization. The archives include records about everything carried out or faced by the company from 1932 up to the time of

			using these records by the author in 2014.
Archives of Electricity Saudi Company, Jazan	Archive	2013/2014	Archives of Electricity Saudi Company, Jazan is considered as one of the most important archives in this project where they include some of the required information about the selected village (the study case). The archives in Jazan are relatively limited where the branch of the ESC in this city was opened in 2000. However, using the digital archiving in this branch has facilitated the research saving time and efforts. Archives of Electricity Saudi Company, Jazan is an accumulation of historical records and contains primary source documents that have accumulated over the company lifetime and digitally organized. These archival records are unpublished.
Archives of Electricity Saudi Company, Asear	Archive	2013/2014	Archives of Electricity Saudi Company, Asear is another important archive in this project where before opening the Jazan branch, all the records about the selected case study

			and the surrounding areas were archived in Asear branch. The archives in Jazan are also limited compared with those of Jeddah and Riyadh where they are an accumulation of historical records and contains primary source documents that have accumulated from 1968 up to the date of doing this research. These archival records are unpublished and manually organized.
Maintenance records, Maintenance Department, Saudi Electric Company, Riyadh	Records	2013/2014	The maintenance records in Maintenance Department, Saudi Electric Company, Riyadh covers all the works carried out by the Maintenance Department at the SEC. The records are divided into two parts, the old records which are manually recorded and organized; and the new records which are digitally recorded and organized. The first group includes all the records and works carried out between 1935 and 2000 and the second group includes the rest of the records up to the date of this research. The main branch of SEC includes also

			copies from the archives and records of the other branches but they were not accessible for the author.
Saudi Ordnance Survey (SOS), Photogrammetry Department, Riyadh	Archives	2013/2014	Saudi Ordnance Survey includes the historical ordnance survey maps and Records that created or maintained by the Ordnance Survey as the national mapping agency of Saudi Arabia. The nature of Ordnance Survey's work means that the maps and provided records are a useful source for researching many different aspects of the history and presents of Saudi Arabia during the 20th and 21th centuries. The new records and maps are digital where aerial photogrammetric cameras are used with navigation sensors including Global Positioning System and Inertial Measurements Units. The old maps are terrestrial maps where ground surveying equipments have been used. However, they are now available as scanned digital maps which might be useful for low accuracy engineering

			applications.