TECHNISCHE
UNIVERSITÄT
WIEN
Vienna University of Technology

DIPLOMARBEIT

Solar cooling potential in housing in Libya

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Wien, Sept 2015

KURZFASSUNG

Solarenergie kann vor allem für ein Land wie Libyen ein interessanter Energielieferant sein, trotzdem ist diese Technologie dort kaum verbreitet. Insbesondere im Wohnbau ist das Potenzial der Sonne als Energielieferant noch nicht ausgeschöpft. Dies scheint vor allem darauf zurückzuführen zu sein, dass die Nutzung von Solarenergie als zu teuer in der Anschaffung und im Betrieb gilt – Energie aus fossilen Brennstoffen wird hingegen vom Staat subventioniert.

In diesem Zusammenhang beschäftigt sich die vorliegende Arbeit mit dem Potential von Solarenergie im Wohnbau in Libyen. Hierfür werden einerseits die Gründe für die geringe Verwendung dieser Technologie analysiert, andererseits wird ein Fokus auf die Möglichkeit der Wohnraumklimatisierung im Hochsommer mittels Solarenergie gelegt.

Dabei wird im Zuge dieser Arbeit besonders auch auf die längerfristige Wirtschaftlichkeit solcher Anlagen eingegangen. Es soll dabei aber nicht nur der Nutzen für den Einzelnen von Bedeutung sein, sondern auch die finanziellen und wirtschaftlichen Auswirkungen für die Gesellschaft/den Staat.

ABSTRACT

This thesis will explore the reasons behind the limited usage of solar energy as a source of power supply in the residential sector in Libya. The potential of using solar energy to achieve thermal comfort during the hot summer, in order to reduce the fossil fuel based electricity consumption, will be explored.

Although solar energy technology has been in use for decades elsewhere, there are very few applications in Libya, especially for improving the thermal performance of buildings. This is in spite of the country having an abundance of solar energy. It is believed that the main cause of the limited use of solar energy in the private sector is caused by the common assumption that such technology is expensive and not cost efficient. Electricity, which is predominantly gas- and oil based, is subsidized in Libya. This thesis will explore the possibility that, despite the initial costs of installing a solar system might be high, the long run saving in electricity bills/ costs is worthwhile. It will examine whether using solar energy will result in reducing the cost that the government has to bear in order to achieve desired indoor temperature. It will also analyse the impact on the country's economy in terms of reducing the costs spent by the public treasury on the residential electrical needs.

Keywords

Thermal comfort/ Cooling Load/ Solar Energy/ Photovoltaic/ electricity/ Cooling system/ insulation/ Cost efficiency/ Payback period/ Levelised cost of Energy/

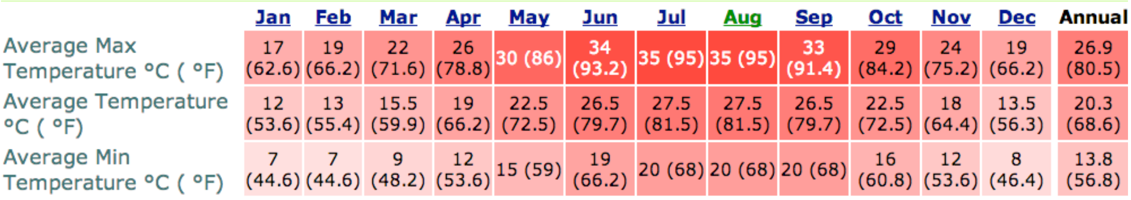
CONTENTS

1 INTRODUCTION

1.1 Motivation

Solar technology is not a new concept. The first Solar Collector was created in the 17th century. In 1839, a major milestone in the evolution of solar technology took place. Edmond Becquerel defined the "Photovoltaic effect". He observed "the production of an electric current when two plates of platinum or gold diving in an acid, neutral, or alkaline solution are exposed in an uneven way to solar radiation" (Palzm, 2010). Following the Second World War, the solar power equipments started to gain popularity and increased in demands. Solar technology has advanced a lot since then. The efficiency of solar cells has impressively improved. As a result of the evolution in the solar energy market, the usage of solar power has increased. However, its use in the residential sector, although technically feasible, is not very common. In technologically advanced countries, where climate conditions are not favorable, it is not economically feasible; and in countries like Libya, it is a topic that has yet to receive attention.

In a hot climate such as in Libya, a high percentage of the electricity consumed in the housing sector is assumingly used for cooling the buildings during the long summer season in the months from May to October. Both the Mediterranean Sea and the Sahara Desert influence Libya's climate. It is semi-arid in the plains of the center and desert in the southern parts and the coast has a Mediterranean climate: hot and dry in the summertime, mild and rainy in the winter. In Tripoli, on the Mediterranean coast, day summer time temperature can get as high as 45°. Figure 1 shows the monthly average temperature in Tripoli.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Max Temperature °C (°F)	17 (62.6)	19 (66.2)	22 (71.6)	26 (78.8)	30 (86)	34 (93.2)	35 (95)	35 (95)	33 (91.4)	29 (84.2)	24 (75.2)	19 (66.2)	26.9 (80.5)
Average Temperature °C (°F)	12 (53.6)	13 (55.4)	15.5 (59.9)	19 (66.2)	22.5 (72.5)	26.5 (79.7)	27.5 (81.5)	27.5 (81.5)	26.5 (79.7)	22.5 (72.5)	18 (64.4)	13.5 (56.3)	20.3 (68.6)
Average Min Temperature °C (°F)	7 (44.6)	7 (44.6)	9 (48.2)	12 (53.6)	15 (59)	19 (66.2)	20 (68)	20 (68)	20 (68)	16 (60.8)	12 (53.6)	8 (46.4)	13.8 (56.8)

Figure 1: Monthly average temperature (Climatemps 2009-2015)

Libya's geographical location makes it one of the richest countries in solar energy. The country is exposed to solar radiation throughout the year with long hours during the day. The daily average solar radiation on a horizontal plane is 7.1 kWh/m²/day on the coastal region and 8.1kWh/m²/day in the southern region (Salah, 2006). Regardless to the fact that Libya is located on one of the richest parts of the world with solar energy, virtually all of the country's electricity is generated using fossil fuel, due to the fact that Libya is a major oil and gas producer.

The electric energy generated in Libya in the year 2012 was 32585 GWh, and it is predicted to keep on increasing. The fossil fuel based electricity production costs the country the expenses and the chance of putting that amount of oil into other uses or to be exported. Also, what weighs even heavier on the economy of the country is the fact that electricity is hugely subsidized, which means the treasury covers most of the expenses of the electricity production. According to the General Electric Company of Oil (GECOL), the annual electric subsidy provided to the domestic sector only reached as high as 2728.26 Million US$ in 2012 (Agha, and Zaed, 2014), this subsidy means that the public treasury sells the fuel to the GECOL for a very low price (89% of it is actual costs).

The objective of this study is to answer the question whether it is cost efficient to implement solar technology in the residential sector. It looks at the possibilities of lowering the fossil fuel based electricity consumption of the residential sector in Tripoli, Libya, by replacing some of its electrical needs by electricity generated using the abundant solar energy available. It will examine the electricity consumed by two single-family houses in the different end uses. In recent years, there have been daily blackouts due to electricity over load resulting from high usage of electricity demands during the summer period. Giving the assumption that most of the residential electricity consumption is due to the usage of air conditioning systems; this thesis would focus mainly on covering the electricity needed to satisfy the cooling demands of the buildings, in order to maintain a comfortable indoor temperature.

This study will look at the resulting cost impact of using solar energy. It will discuss the possibility of reducing the financial burden, which the current electricity system tariff puts on the public treasury, costing the country thousands of million dollars annually. It examines the profit achieved by the government by replacing the high subsidy with a grant plan, where the public treasury offers the homeowners a grant that covers some of the costs of installing the efficient equipment to generate solar energy on site.

1.2 Background

1.2.1 Electricity in Libya

Libya is a country of 6.5 million people. It is a major oil and gas producer. Relaying solely on fossil fuels, Libya doubled its electricity generation from 2000 to 2010. According to the latest 2010 World Bank estimate, 99.8% of people in Libya have access to electricity, which is the highest among African countries. With a consumption of 4,850 kWhr per capita, the total electric energy generated in 2012 was 33676 GWh (Agha, and Zaed, 2014). The residential/commercial sector commanded 50% of the total electricity sales, as shown in Figure 2.

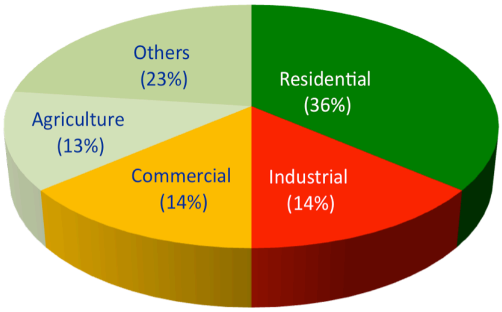
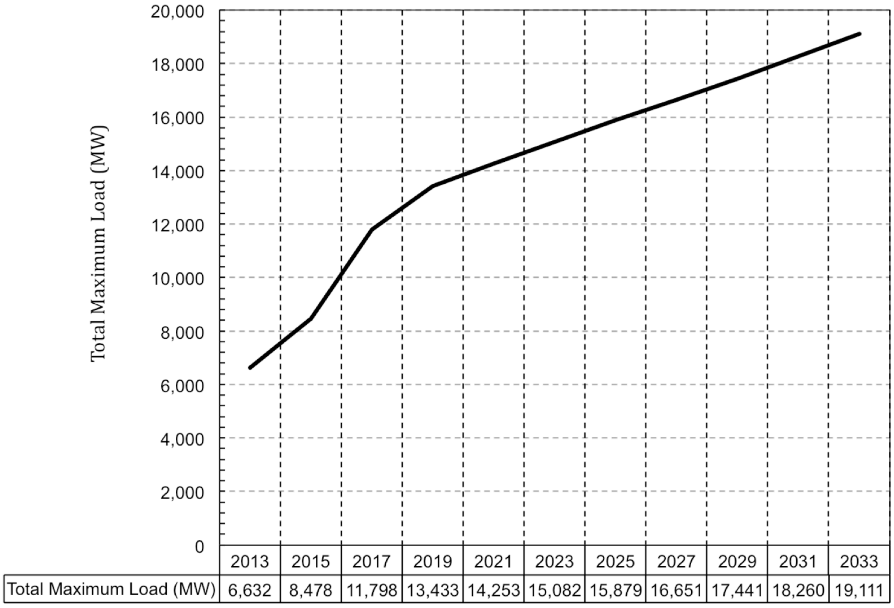


Figure 2: Percentage of Electricity consumption in different sectors (Zaroug, 2013)

In Libya, the annual consumption per capita has reached 4860 kWh and the total electrical consumption has reached 7480 MW. It is predicted that it would carry on increasing to reach 13839 MW in 2020 and 19,111 MW by 2033. Figure 3 shows the predicated future loads by the General Electricity Company of Libya (GECOL).



	2013	2015	2017	2019	2021	2023	2025	2027	2029	2031	2033
Total Maximum Load (MW)	6,632	8,478	11,798	13,433	14,253	15,082	15,879	16,651	17,441	18,260	19,111

Figure 3: Predicted future electric consumption) (Agha, Zaed, 2014).

The electricity sector in Libya is facing huge challenges to maintain the growing demand of electricity, which is growing by more than 10% per year. Due to the security situation and the political instability that the country has been going through since 2011, there has been no substantial work in the electricity sector, this lead to an acute power shortage in terms of transmission as well as generation capacity.

There have been some steps taken towards employing solar energy as a renewable energy source in Libya, such as using PV systems in rural areas for lighting and for water pumping. For example, a water-pumping project was started in 1983, where 10 PV systems with a peak power of 40 kWp were installed for irrigation at El-Agailat, located on the coastal region. However, no serious efforts have been taken to integrate solar energy into the building sector in order to ease the load of the sector's usage of fossil fuels-based electricity and to achieve a more ecologically friendly architecture.

Aside from the economic benefits of using solar energy, replacing some of the fuel-fuel based electricity would have ecological benefits. Fossil fueled power stations, are major CO_2 emitters. Libya's CO_2 emission is estimated to be around 60.7 Million tons CO_2, which is about 0.2% of the world's total emission (*Zaroug, 2013)*. Figure 4 shows the contribution of different sectors to the total country's CO2 emission:

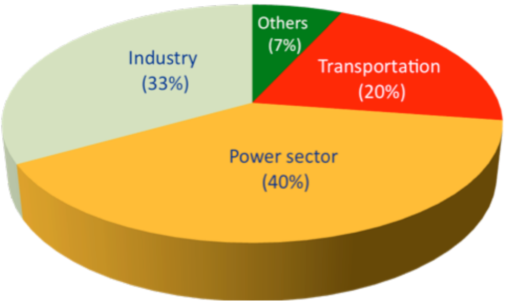


Figure 4: CO2 emission (Zaroug, 2013)

Subsidy system:

The electricity sector in Libya is highly subsidized which causes the electricity tariff to be very low as compared to neighboring countries. Subsidy can be defines as "direct or indirect government intervention so that the selling prices of a product (or commodity or services) to the consumer is reduced. In other words, the price of the product will be set by the government and will not be subjected to the forces of supply and demand" (Agha, and Zaed, 2014). The government in this case sets the selling price of the product (electricity in this case) for the consumers, and covers the difference between the selling price and actual cost price of the production of electricity.

Everyone in Libya, regardless of their economic situation, nationality, whether an owner of public or private businesses, benefit from the subsidized price of electricity. The level of subsidy is about 42% if the cost is evaluated according to the local fuel prices. However, since fuel prices are also highly subsidized in Libya, the electricity subsidy if evaluated according to the international fuel prices goes up to 89% (Agha and Zaed, 2014). Figure 5 shows the prices of electricity for the different categories of consumers.

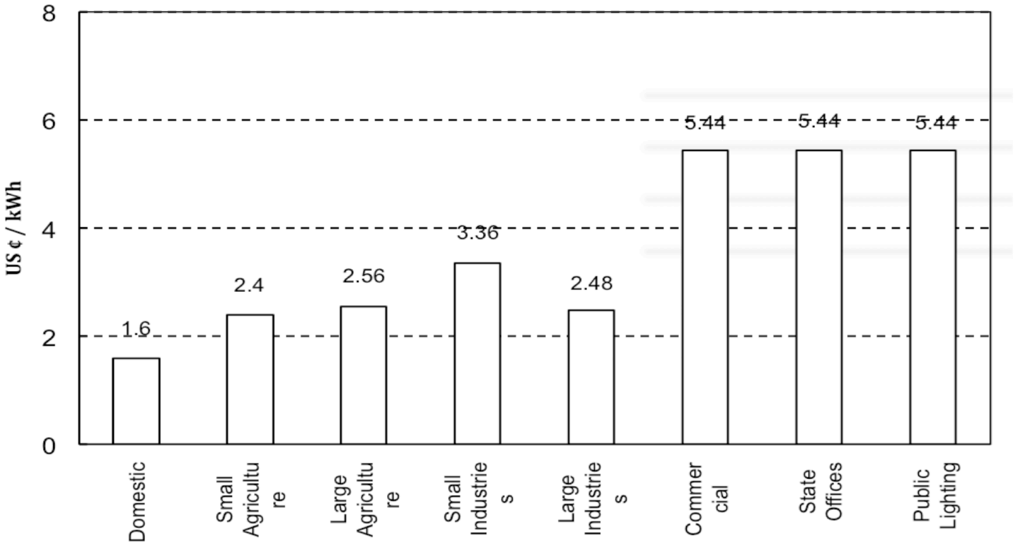


Figure 5: Prices of electricity for different consumers (Agha and Zaed, 2014).

The legalization that is established by the General Electric Company of Oil (GECOL) states that the company is to provide electricity services for all consumers at a set price for the units they consume (prices are shown in the previous graph). It also states that the public treasury will cover any cost differences resulting from the price set for selling and the actual cost of electrical energy generating, production and transmitting. According to the previous graph, 1 kilowatt per hour only costs the consumer 1.6 US cents due to the 89% subsidy. This means that the consumers only pay 11% of the actual price of production. The total cost of producing 1kWh is **14.55 US cents**, meaning that the government pays **12.95 US cents** per 1 kilowatt.

According to the GECOL, although the subsidies to the electricity sector would benefit all types of consumers, it does so in varying degrees, and the highest subsidies are provided to the domestic sector reaching 3327.5 Million Libyan Dinar (2728.62 Million US$). Figure 6 shows the burden of the subsidy system in the different sectors by comparing the amount of revenues from selling energy to each sector to the amount of subsidy offered to the sector. The negative subsidy values indicate that the revenues collected from the consumers is less than the cost of energy, which means that the GECOL is not making any profit in fact the number represents the GECOL's loss which is covered by the government.

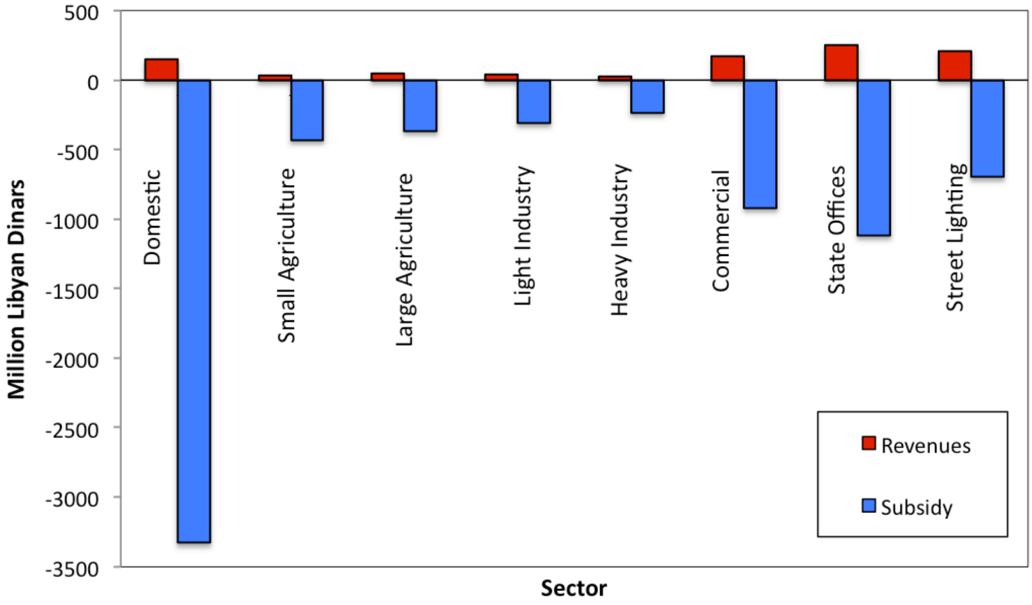


Figure 6: Subsidy and profit by the GECOL in 2012 (Agha and Zaed, 2012)

1.2.2 Solar energy geometry

Although the solar radiation incident on the Earth's atmosphere is relatively constant (Solar Constant is 1.367 kW/m^2), the radiation that reaches the earth's surface varies. The intensity of the solar radiation reaching a given point depends on its Geographical location, the orientation and the time of day and year. In order to calculate the production of electricity by a photovoltaic system, the amount of radiation reaching the panels of the system must be estimated. This section looks at some of the solar geometric concepts that are used to calculate the solar radiation received on a certain location (Malslanka, Illionis Institute of Technology, and Samodra, Sepuluh Nopember Institute of Technology). The solar geometry is also needed in order to calculate a suitable inclination angle for the photovoltaic panels in order to maximum their energy production.

Earth rotates about the axis through its two north and south celestial poles perpendicularly to the equator, but not perpendicularly to the plane of the Earth's orbit. The Earth's axis forms an angle of 23.5° with a line perpendicular to the plane of its orbit as shown in Figure 7.

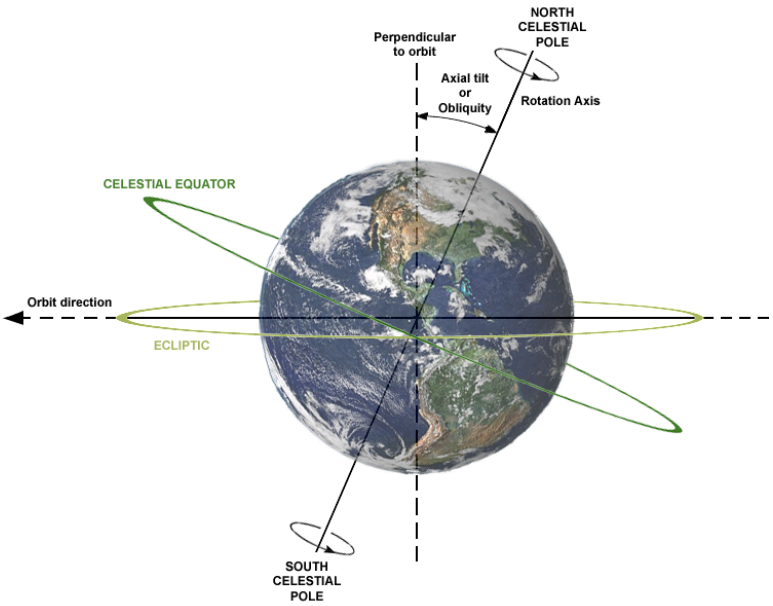


Figure 7: The Earth's axis (Maslanka, 2014)

Some of the main geometric factors that affect the amount of solar radiation reaching a specific location on earth are:

Solar time (LST)

The solar time is the passage of time indicated by the sun's location in the sky. It is time based on the rotation of the earth with respect to the sun. A solar day is the time the earth takes to rotate fully with respect to earth. Due to the variation of speed in which the earth moves in its orbit at different times of the year, and the fact that the plane of the earth's equator is inclined to its orbital plane, the length of the solar day varies throughout the year.

$$LST = LT + \frac{TC}{60} \qquad (1)$$

Where:

- LT = Local time
- TC =Time correction factor

The time correction factor, accounts for the difference of the local solar time (LST) resulting from the longitude variation within a time zone.

Declination angle (δ)

The declination angle is defined as the angle made between a solar ray extended to the center of the earth, and the equatorial plane. It changes seasonally due to the tilt of the earth on its rotation axis. On the northern atmosphere, on the occasion of the summer solstice, the sunrays make an angle: $\delta = +23.5°$ with the equatorial plane. While on the winter solstice $\delta = -23.5°$.

The sun Declination angle has the range of: $-23.5° < \delta < +23.5°$ during its yearly cycle. Figure 8 shows the Declination angles during the summer and winter solstices.

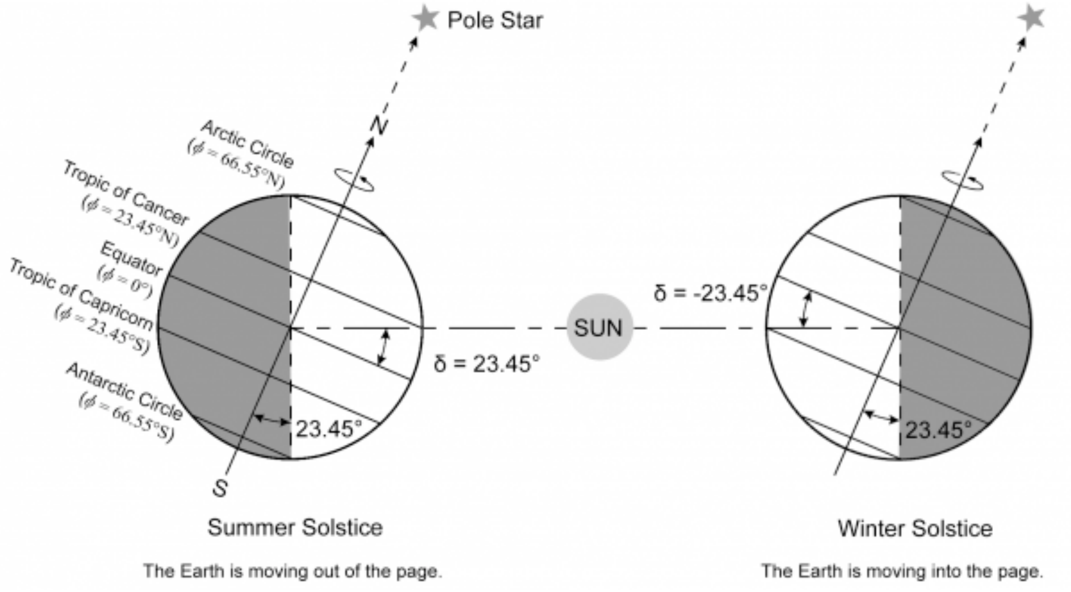


Figure 8: Declination angles in summer and winter solstices (Scientific, 2014)

Latitude (L) and longitude (LN)

The latitude is a geographic coordinate that defines the north-south position of a point on the surface of the Earth. It is expressed in degrees, and ranges from 0° at the equator to 90° at both the North and South poles. The latitude specifies the east-west position of a point. It is represented as lines parallel to the equator; there are 90 angular degrees of latitude from the equator to each of the poles. Tripoli, Libya is located 32.5 ° N. and 20.4° E.

Hour angle (ω)

The hour angle converts the local solar time into degrees in which the sun moves across the sky. It is equal to zero at noon. It is measured in positive values before noon, and in negative values after noon. Equation 2 defines the hour angle.

$$\omega = 15^\circ \times (LST - 12) \tag{2}$$

Where:

- LST = Local solar time

Elevation angle (*h*)

It is the angular height of the sun in the sky measured from the horizontal. The elevation angle is 0° at sunrise and 90° when the sun is directly overhead at noon. The elevation angle (*h*) can be calculated using equation 3.

$$\sin(h) = \sin(L) \times \cos(\delta) + \cos(L) \times \cos(\delta) \times \cos\omega \tag{3}$$

Where:

- *L*= Latitude of the site
- δ = The declination angle of the sun
- ω = The hour angle

Azimuth angle (A)

The Azimuth angle defines the direction of the sun. It is defined as the angle between the direction of the due north and that of the perpendicular projection of the sun down into the horizontal line. The Azimuth values are: 0° = due North, 90° = due East, 180° = due South, and 270° = due West. The azimuth angle can be calculated as using equation 4.

$$\sin(A) = [\cos(\delta) \times \sin(\omega)] + \cos(h) \tag{4}$$

Where:

- δ = The declination angle of the sun
- ω = The hour angle
- *h* = The elevation angle

Zenith angle (z)

The zenith angle is the angle between the sun and the vertical line. It complements the elevation angle. Figure 9 shows all of the elevation, azimuth and zenith angles.

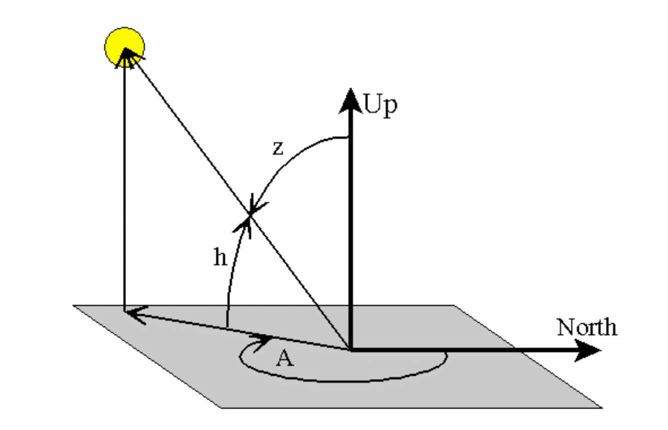


Figure 9: Zenith angle (Earth System, 2014)

1.3 Solar radiation in Tripoli

The Global horizontal and its two components; direct and diffused horizontal radiation, were obtained from the Tripoli, Libya weather files of the simulation software EnergyPlus. Figure 10 shows the average monthly radiation rate on a squared meter of a horizontal surface. The irradiance is at its highest on July where it has an average of 7.8 kWh/m^2; the highest radiation amount occurs on the 2nd of July with about 8.01 kWh/m^2. The irradiance is at its lowest in December with an average of 2.35 kWh/m^2.

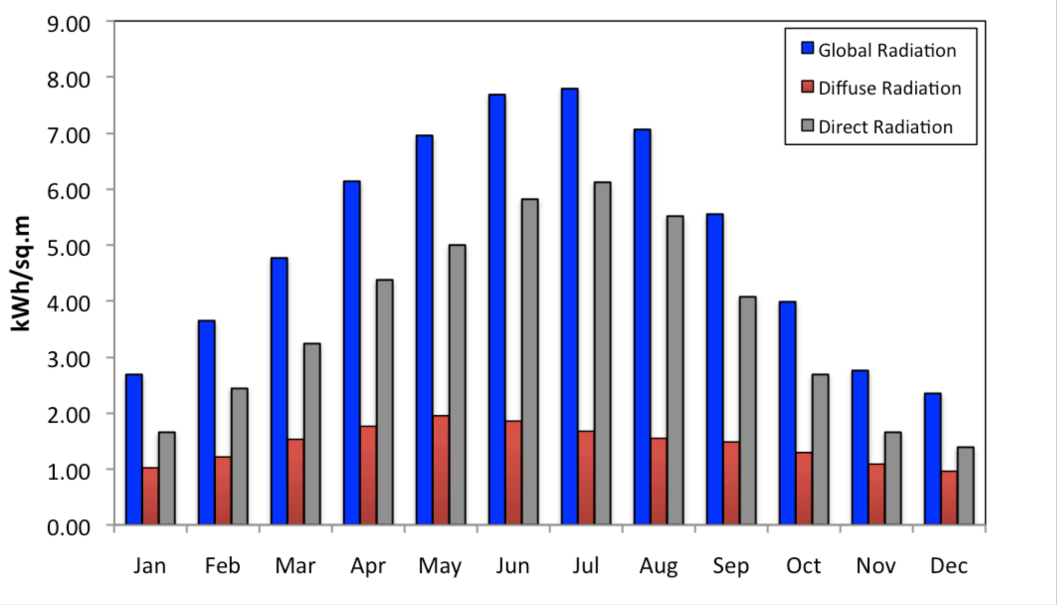


Figure 10: Monthly average radiation in Tripoli, Libya

1.4 Using solar energy for cooling

Solar energy can be used in different ways to cover a building's energy needs for cooling. This can be done either by transforming the solar energy to a thermal energy to be used in solar thermal compressor coolers, or by converting the solar energy into electricity using a Photovoltaic system, and using the resulted electricity to run a mechanical cooling system.

1.4.1 Solar absorption cooling

An absorption cooling system eliminates the need of electrical energy by replacing the need of a mechanical compressor by the use of solar energy, refrigerant liquid and an absorption chiller. A solar absorption cooler consists mainly of solar collectors, a hot water tank, a condenser, an evaporator and an absorber and a generator.

In an absorption chiller unit the evaporator and condenser are the same as in conventional systems. However the function of the mechanical compressor in the absorption cooler is replaced with a chemical absorbent (LiBr) and a heat generator (solar collectors in the case of a solar absorption cooling). A pump is also required. To achieve the cooling effects, the refrigerant goes through a cycle which, can be summarized as follows:

- Since liquids require less work to raise its pressure than that a vapor requires, the refrigerant (e.g. ammonia) is transformed into a liquid state, by passing thorough the absorber tank (e.g. Water), where it is absorbed and a solution of water and ammonia is resulted.
- A pump is used to exert work to increases the liquids pressure creating a high-pressure liquid.
- The high-pressure liquid moves into the generator where it is heated up, using the heat from the solar collectors. This causes the refrigerant to evaporate creating a high-pressure vapor.
- The high-pressure absorber liquid goes through an expansion valve to reduce its pressure. The low-pressure absorber (in its liquid state) travels back into the absorber tank.
- The high-pressure vapor of the refrigerant goes through the condenser, where is condensed into a high-pressure liquid.
- The high-pressure liquid goes through an expansion valve, to produce a low-pressure liquid lowering its boiling point by doing so.
- The low-pressure liquid goes through the evaporator, where it absorbs heat from the room, lowing by that the indoor temperature of the room. As the temperature of the low-pressured refrigerant increases, it transfers back into a low-pressure vapor.

1.4.2 Photovoltaic system powered cooling systems

A Photovoltaic system is used to generate the electricity needed to power the mechanical compressor of a classical air conditioning system. The electricity production of the PV system is due to the "photovoltaic effect", where the PV modules generate energy by converting solar radiation into direct current electricity (DC). A PV system is made up of a number of components, the main elements of a PV system are:

- **Photovoltaic panel:** there are different types of solar panels that will be described further on in this section. They are usually made of individual solar cells connected together. These cells are made from a semi-conductor material. When the sunlight strikes the surface of the solar cells, their photoelectric properties allow them to absorb a portion of this light. The energy of this absorbed light excites the electrons of the semiconductor material causing them to be knocked loose and free to move within the electric field of the PV cells.

- **Inverter:** the electricity generated by the PV system is direct current (DC), while the electricity from the grid is high voltage alternating current (AC). In order to be able to use the electricity produced by the PV system to run household equipment, the DC needs to be converted to AC by an Inverter. The inverter is connected to the solar array in a grid-tie system, while it is connected to the battery pack in an off-grid system (battery-based system).

- **Batteries:** the battery is used to store the energy produced by the PV panels and act as a constant source of electricity, when the PV panels are not producing electricity (no availability of solar radiation).

There are two different types of PV systems:

- **Battery-based systems:** The PV system operates independently from the utility grid or as a backup to the grid in case of a power outage. It requires a constant voltage source of power typically a battery bank. The excess solar energy accumulates and is stored in the battery to be used at night. One of the biggest disadvantages of this type of systems is that it requires more components and requires more maintenance and battery replacement every 5 to 7 years; this increases both the initial installation costs and the maintenance costs.

- **Grid-Tied systems:** The PV system is connecting to the building utility grid. It is a simpler system and requires the least number of components since there is no need to store any energy; the electricity is sent to the utility grid to be distributed into the different parts of the building from there. It requires less maintenance, requires no battery replacement (since none is used) and overall costs less. All of this makes it the primarily used PV system for homes and smaller structures with utility power available.

Since the purpose of the study is cover some of the electrical needs not all; for economic reasons, the system is designed to be working together with the grid. Also, since most of the cooling loads occur during the daytime, when solar radiation is available on site, it is more cost efficient to install a Grid-tied system. Figure 11 shows the components of the system:

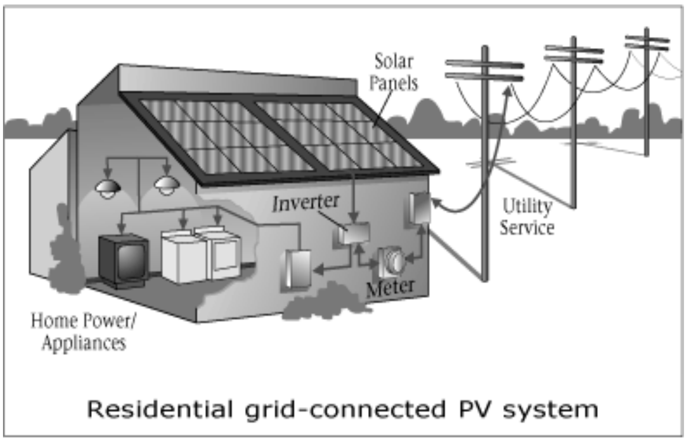


Figure 11: Grid-Tied PV system (Solar San Antonio, 2015)

PV panels

There are different types of PV panels, depending on the material that the panel is constructed with. Some of these types are:

- **Thin film PV cells (TFPC).**

These solar panels are manufactured by depositing one or more thin layers of the photovoltaic material on to a base layer that can be made of glass or a roll of flexible plastic or metal. The TFPC's efficiency is between 7-13%. The main advantage of this type of panels is their flexibility, which opens up different potential applications. Also, high temperature and shading have less impact on the solar panel performance. However, thin-film PV panels are usually not very useful for residential purposes, as they require larger roof area, which makes their space-efficiency rather low. They also tend to degrade faster than silicon based solar panels.

- **Crystalline silicon panels (c-Si)**

c- Si solar cells are the most common solar cells due to their stability and the their efficiency which ranges between 15-25% under perfect conditions. In 2011, around 95% of all shipments by U.S manufacturers to the residential sector were crystalline silicon PV panels

(U.S. Energy Information Administration, 2011). The two most common types of c-Si panels are monocrystalline and polycrystalline silicon panels:

- **Monocrystalline silicon cells (mono-Si).** They are made of the highest-grade silicon (purest silicon), which makes them the most efficient. That in return makes them more space efficient. Mono-Si panels live longer. All of this makes this type of PV panels the most expensive there is on the market.

- **Polycrystalline silicon panels (p-Si).** They are the most common type used in photovoltaic systems, especially for homeowners due to their lower costs. However, P-Si panels are less efficient than mono-Si panels. They have an efficiency of about 13-16% due to the lower grade silicon used to make the panel. Figure 12 shows the efficiencies of different types of PV panels when used in laboratory conditions.

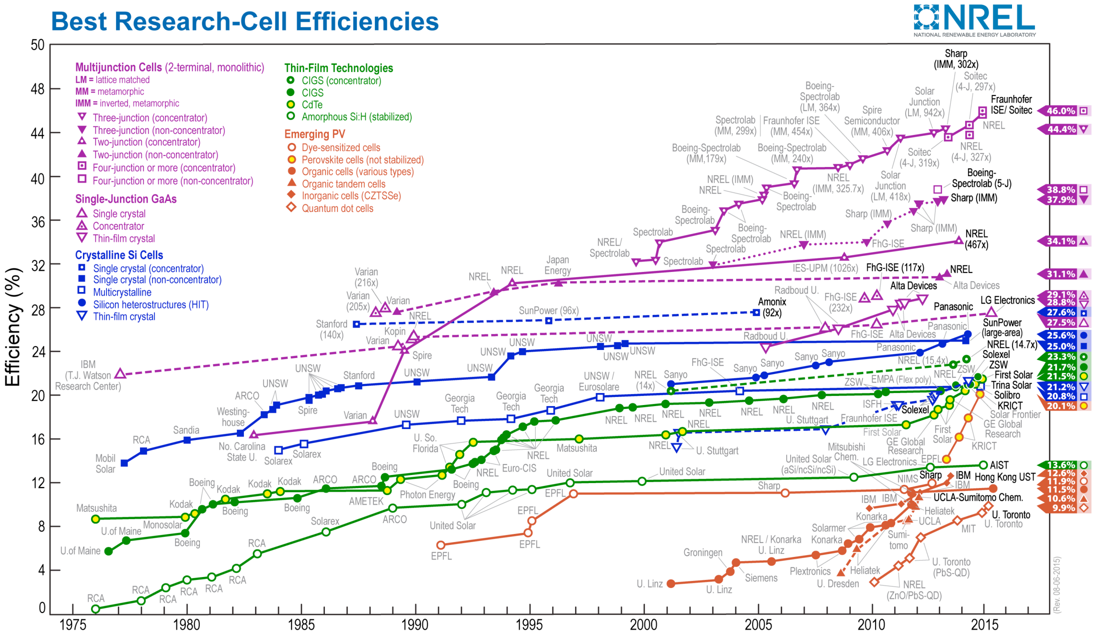


Figure 12: PV panels efficiencies (NREL, 2015)

2 METHOD

2.1 Overview

Even though Libya's geographical location makes it one of the richest with solar power, the solar energy market in Libya still remains untapped. The usage of solar energy specifically in the residential sector remains to be explored. This thesis would examine the possibility of lowering the reliance on the Grid to satisfy the electrical demands of the residential sector. This is to be done by using solar energy as a source of electricity to power the air conditioning system in residential buildings. It will look at the cost efficiency of implementing PV systems to cover the electrical demands, and the savings achieved in the grid-electricity consumption by doing so.

Two existing flat roofed housing units, with different household sizes are chosen. A suitable solar system is designed for each unit. In order to determine the size of the solar system for each house, the electrical demands of the house and specially the energy needed to run the cooling system to achieve the wanted indoor temperature needs to be computed, as well as the amount of electricity produced by the solar panels in use. A method consisting of the following steps is used to achieve the objective of the study:

- The building is modeled and simulated in order to calculate its cooling and heating loads.
- A suitable HVAC system is sized using EnergyPlus to cover the calculated demands of the building.
- The building's electricity consumption is calculated.
- The electricity production of a chosen PV panel is simulated using EnergyPlus in order to size a suitable PV system.
- Three different sizes for the PV system are suggested; depending on the portion of the electricity demands it is to cover.
- A financial analysis is carried out in order to examine the efficiency of using the PV system in two different cases, which will be discussed later on in this chapter.

2.2 Simulation of the building's demands

In order to analyze the electrical needs of the buildings, their thermal performance is simulated. A special care is given to the cooling loads of the buildings in order to design a PV system that would cover these loads.

2.2.1 Thermal modeling of buildings

A thermal dynamic simulation for each building is done to predict the thermal performance of the houses and their systems throughout the year, taking into account the behavior of the occupants and the way the buildings are operated. Specific Schedules for the usages of the houses and their systems, which can be found in the next chapter, are used for the simulation. The main two outputs of the simulation carried out in this thesis were the buildings cooling and heating loads. These loads are the amount of heat that must be removed (cooling loads) or added (heating loads) to the space by the HVAC equipments. It is defined as "the rate at which heat must be removed/added from the space to maintain a constant space air temperature" (Sam, C. M., 2012). These loads are made up of two components:

- ***Sensible load.*** It is the heat energy that causes the change of the temperature of the air in the buildings with no phase change. It is added to the space by conduction, convection and solar radiation.
- ***Latent load.*** It is the energy absorbed or released from the air during a phase change from a gas to liquid or vise-versa, which affects the humidity of the indoor environment. The cooling system needs to take into account the indoor humidity level and to remove moisture from the air in order to achieve a comfort zone for the occupants.

The heat gains and loses in a building vary depending on the heat transmission coefficient of the building materials, the way the components are assembled, the tightness of the building and of course the behavior and the activity of the occupants. This makes a numerical precise calculation an impossible goal to achieve. However, EnergyPlus uses all of the data and information of the nature of the structure and physical qualities of the building, together with approximate schedules that summaries the activity inside it and the way the building operates, in order to calculate a close estimate of the demands of the building simulated. Figure 13 shows the different possible heat gain sources in a building.

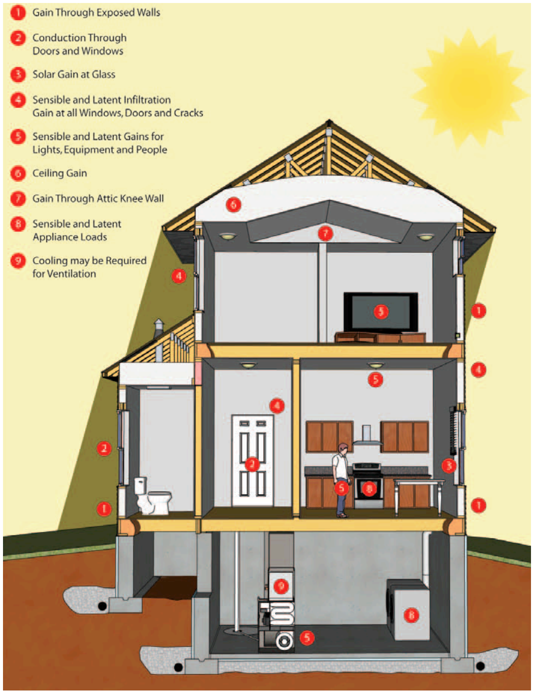


Figure 13: Possible heat gains in a building (Green Building Advisor, 2012)

The main inputs needed by EnergyPlus to simulate the cooling demands of a building are:

- **Construction and Materials.** The materials used for the layers making up the structure of each of the buildings are described in details in the EnergyPlus input data section in the next chapter.
- **Fenestration surface.** It looks at the doors and windows elements of the building.
- **Internal gains.** Internal gains contribute to the thermal performance; higher internal gains increase the cooling demands of a building during the summer period, while decreases the heating loads of the colder season. Internal gains come from the appliances used within the house including lighting, and the metabolism and activity of the occupants. Figure 14 shows examples of difference sources of internal gains.

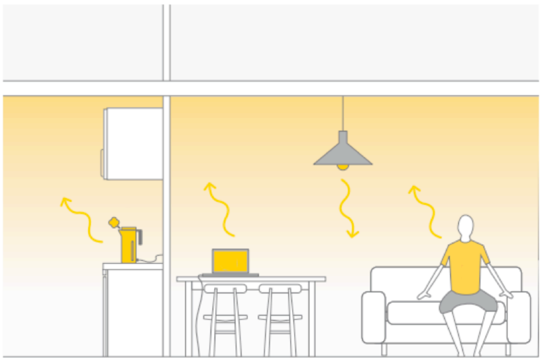


Figure 14: Internal gains (Šulskutė, 2013)

- **People.** The number of people in each space and their activity adds to the internal gains in the space. A schedule for the number of people in the different zones of each building is set in the EnergyPlus input data.
- **Lights.** The heat gain from lighting in EnergyPlus is divided into four fractions:
    - Return air fraction: which is the fraction of heat that goes into the zone return air.
    - Fraction Radiant: the heat emitted from lights that travel into the zone as long-wave radiation.
    - Fraction Visible: The fraction of heat that travels into the zone as short wave radiation.
    - Fraction of the heat from lights that is convicted to the zone air.
- **Electric Equipment.** It calculates the heat released from such equipment into the zone and how it contributes to the internal gains. An estimated schedule for the electric equipments is described in the next chapter.
- **Airflow - Zone Infiltration: Design Flow Rate.** Infiltration is the unintended airflow from the outside into the buildings though opening and closing of exterior doors, cracks around the windows, and through gaps in the buildings structural elements. The rate of infiltration depends on how tight a building envelope is. In this case, due to the characteristics of the buildings and its materials, the infiltration rate is assumed to be 0.3 1/h.

2.2.2 Air conditioning system electricity demands

EnergyPlus is used to calculate the electricity needed to run an HVAC system that would cover the loads calculated on the previous section. An HVAC with a heat pump is modeled by EnergyPlus. The following objects on EnergyPlus are required in order to size the air-conditioning system:

HVACTemplate: Thermostat.

To maintain a comfortable indoor temperature for the occupants during the summer season, the set point for cooling is set at 24°C. The set point for heating is 21°C. No setback temperature is used.

Site: Location- SizingPeriod: DesignDay

The EnergyPlus automatic sizing is used. To avoid the risk of having an over designed or an under designed cooling system, a “Design Day” object is chosen as an input parameter on which the sizing equipment for the system is based on. EnergyPlus “creates” a 24-hour profile worth of weather data (temperature, solar radiation, wind speed, etc.) that is used by the software to size and simulate the cooling system.

From the Tripoli *weather data* file, a “Design Day” object is chosen to best satisfy the cooling demands of 99.6% of the building’s loads.

HVACTemplate: Zone: PTAH

This object specifies the type of HVAC system as a Packaged terminal air-to-air heat pump with a DX cooling coil, heating coil and an outdoor air mixer.

The main input fields are:

- Zone Name: the name of the zones where cooling is needed. It states the spaces within the building that have cooling demands to be fulfilled with the cooling system.
- Template Thermostat Name: the entered name was Thermostat, which reference the already established ***HVACTemplate: Thermostat object***. It sets the temperature points which the ac system to work with.
- Outdoor Air Method: the rate of fresh out from outdoors brought into the building through the ac system. In this case DetailedSpecification is entered in the field. It means that EnergyPlus would reference another object, which defines this rate. The object is:
    - ***HVAC Design Objects: DesignSpecification:OutdoorAir***. Where the outdoor air flow Changes for the mechanical ventilation by the PTAC is set to 0.2 1/h
- Cooling and heating Coils Availability Schedule name: this is left blank, which means the HVAC system would be constantly running whenever the temperature is above 24°C (in cooling) or drops below 21°C (in heating).
- Cooling coil Gross Rated Cooling COP: this defines efficiency of the system in cooling. It is equal to the cooling coil capacity (watts) / electrical power input of the compressor and the fan. It is set corresponding to the LG ac system with a ***value of 3.***

- Heat pump heating coil Gross Rated COP: defines the heating efficiency of the system. It is set to the value of the heating COP of the ac system **3.6.**

2.2.3 Photovoltaic system modeling

In order to harvest the maximum solar energy, the panels of the PV system are fixed on the roof with a certain inclination angle that varies depending on the location of the site, in order to be exposed to the maximum amount of solar radiation. The total solar radiation on any inclined surface is the sum of the direct radiation that reached that surface, the diffused radiation on the inclined surface and the reflected radiation from the surroundings. In order to harvest the maximum radiation in Tripoli, Libya, equations 5, 6 and 7 (NASA documents, 2014) are used to calculate the three components of the solar radiation on an inclined surface.

$$DirR_{inc} = DirR_{hz} \times \frac{\cos(i)}{\sin(h)} \tag{5}$$

$$DifR_{inc} = DifR_{hz} \times \frac{1+\cos(\mu)}{2} \tag{6}$$

$$fleR = GR_{hz} \times \frac{1-\cos(\mu)}{2} \tag{7}$$

Where:

- ***$DirR_{inc}$***= Direct radiation on inclined surface
- ***$DifR_{inc}$***= Diffused radiation on inclined surface
- ***$DirR_{hz}$***= Direct horizontal radiation
- ***DiR_{hz}***= Diffused horizontal radiation
- ***fleR***= Reflected radiation
- ***GR_{hz}***= Global horizontal radiation
- ***i***= incident angle
- ***h***= elevation angle
- μ = Tilt angle

The solar radiation on surfaces with different inclination angles was calculated. Table 1 shows the monthly and annual solar radiation (kWh/m^2) that reached the different surfaces:

Table 1: Monthly radiation on tilted surfaces in Tripoli, Libya

Tilt (°)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual (kWh/m^2)
0.0	82	101	146	183	215	230	241	218	165	123	82	72	1859
22.5	109	125	164	188	205	212	226	218	180	147	105	96	1976
27.5	113	128	165	185	200	205	219	214	180	149	109	100	1967
32.5	117	130	165	182	193	196	210	208	179	151	112	103	1946
37.5	119	132	164	177	185	186	200	202	176	152	114	106	1913
42.5	121	132	162	172	176	176	189	193	173	152	115	108	1868
90	98	96	94	73	54	43	48	69	90	103	91	90	948

The PV system is to be designed in order to cover the highest electricity demands; which is assumed to occur in the summer season, therefore the inclination angle of the solar panels is chosen depending on the angle that is exposed to the most radiation during the summer period; the 2nd and 3rd quarters of the year (April to September). Figure 15 compares the amount of radiation that would reach panels with different tilt angles.

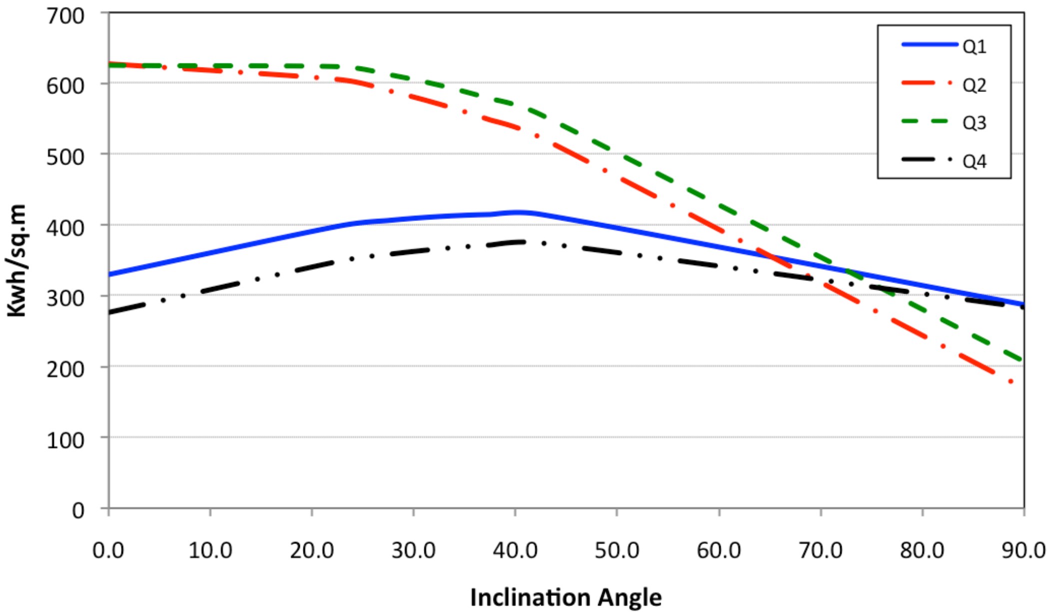


Figure 15: Radiation on inclined surfaces in Tripoli, Libya and the different quarters of the year

Figure 15, both surfaces with the inclinations of 22.5° and 0.0° (horizontal) are exposed to the highest amount of irradiance during the 2nd and 3rd quarters with around 1229 kWh/m^2 and 1252 kWh/m^2 respectively. However as shown in Figure 16, a panel with inclination of 22.5° would have a higher yearly solar radiation with around 1976 kWh/m^2 comparing to 1859kWh/m^2 if the panel was installed horizontally. For that reason the inclination angle of the PV panels is fixed at 22.5° from the horizontal surface of the roof to be installed on.

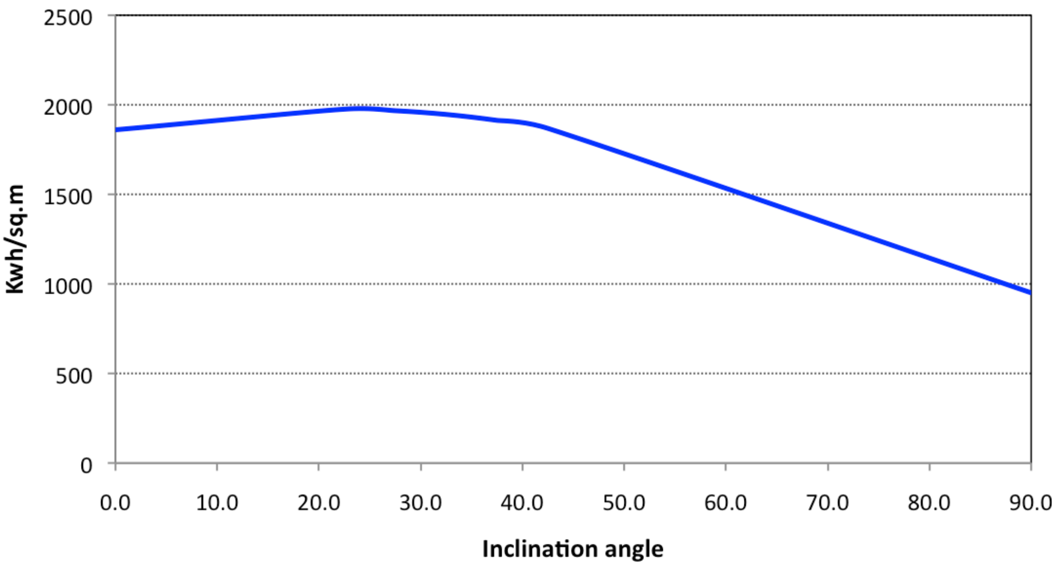
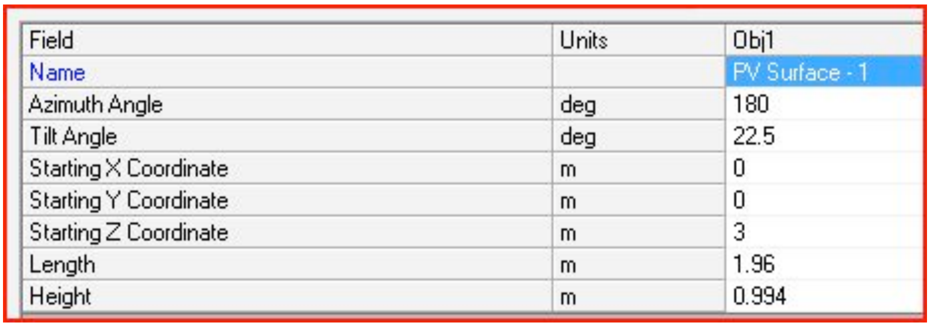


Figure 16:Annual radiation on inclined surface

The amount of maximum electricity produced by the PV system, depends on the output rate of the solar modules that build up the system, and the efficiency of the panel. The typical value is between 12% and 20%. As it is the most common to use a Polycrystalline Silicon panel for residential PV systems, the Astronergy 300 Silver Poly panel is chosen in this thesis. It is a 72- cell polycrystalline module, with maximum power of 300W. It has the dimensions of 195.6×99.4 cm. The efficiency of the panel is 15%.

In order to size an efficient PV system to produce the required electricity needed to meet the electrical needs of the building, EnergyPlus is used to calculate the electricity production of one Astronergy 300 Silver Poly panel located on the site of each building. The modeling was done in a simplified way, not taking into account any shading affects, due to the fact that all neighboring buildings were the same heights, and the high sun's location during the summer minimizes the shadows casted. The next steps were followed:

1. Identifying an object on EnergyPlus that works as a surface that defines the location and geometry of the PV array using the ***Shading: Building*** object in the ***Thermal Zone and Surfaces*** group. Figure 17 shows a screenshot of the object's required fields:



Field	Units	Obj1
Name		PV Surface - 1
Azimuth Angle	deg	180
Tilt Angle	deg	22.5
Starting X Coordinate	m	0
Starting Y Coordinate	m	0
Starting Z Coordinate	m	3
Length	m	1.96
Height	m	0.994

Figure 17: Shading: Building object in EnergyPlus

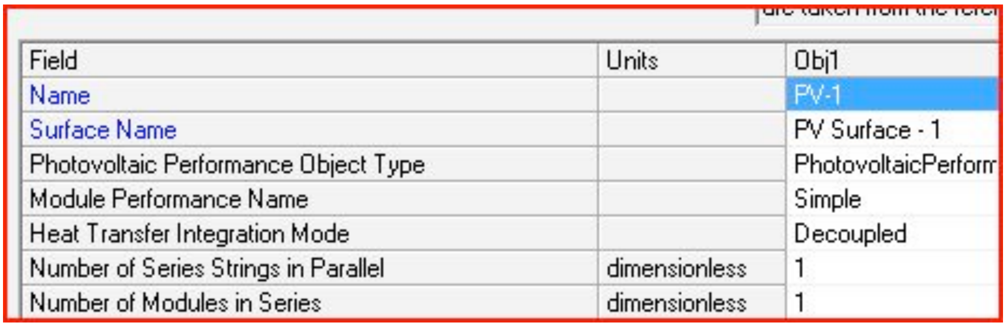
- Name: this field gives a unique name to the shading surface that would function as a mounting surface for the PV panels.
- Azimuth Angle: it is set to **180°** (the surface needs to be facing south).
- The tilt Angle: it states the optimum tilt angle for the panels. It is set to 22.5° (as determined earlier).
- Length & height: set to **1.96** meter by **0.994** meter, which is the dimensions of the Astronergy 300 Silver Poly panel that was chosen.

2. EnergyPlus is used to create an object that describes the array of PV module; this is done through the ***Electric Load Center – Generator Specification*** group:

- ***Generator" Photovoltaic***. It describes and models the module array. The following shows the required fields of the object:

- Name: defines a unique name for the PV array ***"PV-1".***
- Surface Name: it defines the name of the surface where the PV module is installed (it defined the geometry and the location of the surface). It is set to ***"PV Surface-1".***
- Photovoltaic Performance Object Type: defines the type of the PV performance model. ***"Photovoltaic Performance: Simple"*** was chosen.
- Module Performance Name: is the name given to the Photovoltaic performance object: ***"Simple".***

- Heat Transfer Integration Mode: the ***"Decoupled"*** option is chosen. It means that the modules cell temperature in the array is computed based on an energy balance to NOCT conditions.

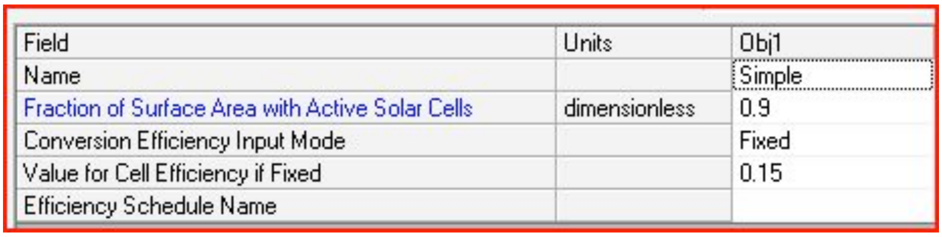


Field	Units	Obj1
Name		PV-1
Surface Name		PV Surface - 1
Photovoltaic Performance Object Type		PhotovoltaicPerform
Module Performance Name		Simple
Heat Transfer Integration Mode		Decoupled
Number of Series Strings in Parallel	dimensionless	1
Number of Modules in Series	dimensionless	1

Figure 18: Generator object in EnergyPlus

3. ***Photovoltaic Performance: Simple.*** This object is used to get an idea of the level of annual production and peak power. It takes into account the efficiency with which the surface converts solar radiation to electricity; the full geometric model for solar radiation is used in this object, including shading and reflections. The following fields are required:

   - Name: the name is only used as an identifier. It has to be unique to this module.
   - Fraction of Surface Area with Active Solar Cells: it defines the fraction of the area of the surface that will have active PV cells on it. It includes the difference between the area of the PV module and the area of the actual active cells. It is assumed that 90% works as the active cell of the panel. The value is set to "0.9"
   - Conversion Efficiency Input Mode: the "Fixed" option is chosen. It means that the efficiency of the module is constant (no need for schedule) and is to be specified in the next field.
   - Value for cell efficiency: it specifies the efficiency in which the PV module converts solar radiation to electricity. The panels used have an efficiency of "15%".
   - Figure 19 shows a screenshot of the object on EnergyPlus.

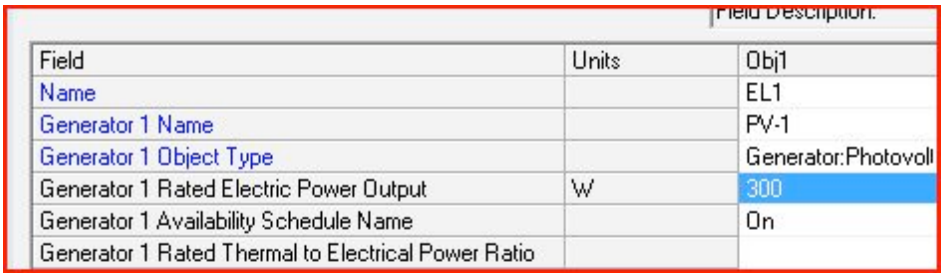


Field	Units	Obj1
Name		Simple
Fraction of Surface Area with Active Solar Cells	dimensionless	0.9
Conversion Efficiency Input Mode		Fixed
Value for Cell Efficiency if Fixed		0.15
Efficiency Schedule Name		

Figure 19: Photovoltaic performance: Simple object

4. Electric Load Center: Generators. This object is used to define the already specified PV module “PV-1”, as a generator to be included in the simulation by EnergyPlus. The following are the five important fields to be entered in the object:

   - Name: identifies the name of the generator as “EL1”.
   - Generator 1 Name: identifies which generator to be used. In this model, the ***“PV-1”*** PV module is used as the only generator.
   - Generator 1 Object type: since “PV-1” generator is PV module, the option ***Generator: Photovoltaic*** option is chosen.
   - Generator 1 Rated Electric Power Output: Astronergy 300 Silver Poly CHSM 6612P-300 is picked. It has a rated power output of 300 Watts.
   - Generator 1 Availability Schedule Name: schedule ***on***, is created for the generator. It indicated the periods in which the generator is available (in this case, during all periods of time).



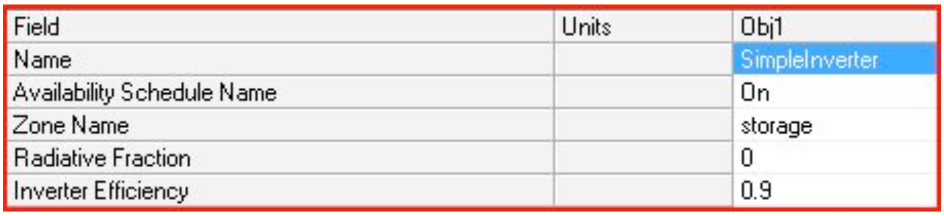
Field	Units	Obj1
Name		EL1
Generator 1 Name		PV-1
Generator 1 Object Type		Generator:Photovolt
Generator 1 Rated Electric Power Output	W	300
Generator 1 Availability Schedule Name		On
Generator 1 Rated Thermal to Electrical Power Ratio		

Figure 20: Electric load center: Generators object

5. ***Electric Load Center: Inverter: Simple.*** This object is used to model the inverter, which converts electricity from Direct current (DC) to Alternating Current (AC) that can be used in the house. The fowling input fields are required for this model:

   - Name: identifies a unique name for the inverter “***SimpleInverter”.***
   - Availability Schedule Name: it is set on ***“On”.***
   - Zone name: it specifies the zone where the inverter is located. It is located in the ***“Storage”*** zone.
   - Radiation Fraction: it contains the thermal losses from the inverter to the location zone in the form of long-wave thermal radiation. The losses in this model are set to ***“0”.***

- Inverter efficiency: it is set to ***"0.9"*** (90%).

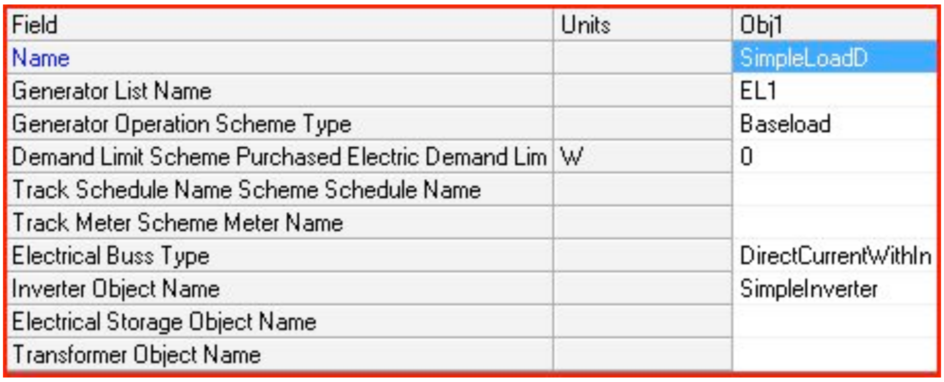


Field	Units	Obj1
Name		SimpleInverter
Availability Schedule Name		On
Zone Name		storage
Radiative Fraction		0
Inverter Efficiency		0.9

Figure 21: Electric Load center: Inverter: Simple object

6. ***Electric Load Center Distribution***. This is used to model the on-site electricity generators according to operation schedules and tracks the amount of electricity generated.

- Name: contains the name of the electric load center as ***"EL1".***
- Generator Operation Scheme type: ***"Baseload"*** scheme option is chosen. It operates the generator at its rated electric power when the generator is scheduled on.
- Demand Limit Scheme Purchased Electric Demand Limit: it determines the demand limit above which the generator meets the entire electrical load on he building minus the photovoltaic array. It is set to ***"0".***
- Electric Buss type: Since the PV system generates DC electricity this field is set ***"Current With Inverter".***
- Inverter Object Name: identifies the inverter connected to the load center. It is set to the already modeled inverter ***"SimpleInverter".***



Field	Units	Obj1
Name		SimpleLoadD
Generator List Name		EL1
Generator Operation Scheme Type		Baseload
Demand Limit Scheme Purchased Electric Demand Lim	W	0
Track Schedule Name Scheme Schedule Name		
Track Meter Scheme Meter Name		
Electrical Buss Type		DirectCurrentWithIn
Inverter Object Name		SimpleInverter
Electrical Storage Object Name		
Transformer Object Name		

Figure 22: Electric load center distribution object

2.2.4 Different photovoltaic system sizes

In order to cover some of the electricity demands of the building, more panels need be installed. Since the PV system is a Grid-tied one, not all of the house electricity needs to be supplied with the PV system, however the system is sized to at least cover the electricity needed to meet the cooling demands of the building. The next three different PV sizes are suggested:

- **PV system size 1**: it is designed to cover the cooling loads of the building; assuming that the highest electricity demands would occur during the summer period when solar radiation availability is at its highest.
- **PV system size 2**: It is designed to cover the total electrical demands of the hottest months of the year (May-October); which is also assumed to correlate with the highest PV electricity production.
- **PV system size 3**: It is deigned to cover the total annual electricity needs of the building.

The number of panels (x) needed in order to build up an efficient PV system is calculated using equation 8.

$$x = \frac{Ele_{prn}}{Ele_{pro}} \tag{8}$$

Where:

- Ele_{prn} = Electricity needed to be produced by the system
- Ele_{pro} = Electricity production of one panel.

Roof space area:

The sizing of the PV system depends on the roof area available and the costs of the installation; the roof area available restricts the size of the array. The modules cannot be installed packed together. Spacing is needed between modules to prevent shadow casting, which would affect the solar radiation reaching the solar panels, and to allow the air to cool down the modules to minimize the risks of overheating. It may also be needed to account for walking paths around and between rows of modules for easier installation and for future maintenance accessibility. For a flat roof a good rule of thumb is to allow an area of 1 square foot (0.0929 m^2) of open roof for every 10Watts (Boxwell, 2013). It is slightly on the generous side (less roof area is needed), however it is a worst-case assumption, since shadowing is not taken into account when calculating the roof area availability. The roof area needed can be calculated using equation 9.

$$Area = \frac{x}{0.01kW} \tag{9}$$

- X= the size of the PV system

2.3 Economic analysis

An analysis is carried out in order to examine the financial efficiency of installing PV systems in residential buildings. In this section the levelised costs of electricity produced by the PV system is compared to that of the grid-supplied electricity. It also looks at the payback period and the savings created when a PV system is installed.

2.3.1 Levelised Cost of Energy

"Levelised Cost of Energy (LCOE, also called Levelised Energy Cost or LEC) is a cost of generating energy (usually electricity) for a particular system. It is an economic assessment of the cost of the energy-generating system including all the costs over its lifetime: initial investment, operations and maintenance, cost of fuel, and cost of capital. A net present value calculation is performed and solved in such a way that for the value of the LCOE chosen, the project's net present value becomes zero. This means that the LCOE is the minimum price at which energy must be sold for an energy project to break even." (NREL, 2013)

Levelised costs of energy produced by the grid Grid-Electricity ($LCoE_{grid}$):

The current cost of the grid electricity production (A_0) is **14.55 US cents/kWh.** A Levelised cost of energy ($LCoE_{grid}$), looks at the future value of this cost after a period of time. It is common for costs to increase from one year to another by an escalation rate, which is assumed constant in this case. The escalation rate is the percentage at which the value of a specific goods or services in a given economy is expected to change over a period of time. The uniform rate of change defines a geometric gradient series. In order to calculate the present value of the grid electricity costs over 20 years (P(g)), equation 10 (Panneerselvam, R., 2001) is used.

$$P(g) = A_0 \times (1+g) \times \left[\frac{1 - \left(\frac{1+g}{1+i} \right)^n}{(i-g)} \right] \tag{10}$$

LCoE$_{grid}$ can now be calculated using equation 11 (Panneerselvam, 2001).

$$LCoE_{grid} = P(g) \times \left[\frac{i(1+i)^n}{(1+i)^n - 1} \right] \tag{11}$$

Where:

- *P(g)* = The present value of the capital costs of kWh over a number of years
- A_0 = the costs of 1 kWh (14.55 US cents)
- *g* = the escalation rate (2%)
- *i* = the interest rate, the rate of return per period of time, (6%)
- *n* = number of years/ life time of the system (20 years)

Levelised costs of energy produced by the PV system (LCoE$_{PV}$):

To calculate the levelised cost of energy produced by the PV system per kWh (the future value of cost by the end of 20 years), the amount of electrical energy that is produced by the system must be taken into consideration. The Levelised cost of energy is calculated using equation 12 (Panneerselvam, 2001).

$$LCoE_{PV} = \frac{T}{Q} \tag{12}$$

Where:

- *T*= The equivalent annual cost
- *Q*= Energy produced by the system.

The equivalent annual cost (*T*) is defined as the cost per year of owning and operating the PV system over its entire lifetime of 20 years. It is calculated using equation 13.

$$T = OM + A \tag{13}$$

Where:

- OM: operation and maintenance costs
- A: annualized capital payment

The annualized capital electricity costs (A), is the amount of payment due annually if the capital cost of the PV system was to be divided into equal annualized payments over the 20 years. It is calculated using equation 14 (Panneerselvam, 2001).

$$A = P \times \left[\frac{i(1+i)^n}{\left((1+i)^n - 1\right)} \right] \tag{14}$$

Where:

- P= The capital cost of the PV system (initial investment)
- i = the interest rate, of 6%
- n = number of years/ life time of the system (20 years)

The capital cost of the system (P) is calculated from the manufacturer brochure. The price is of a SolarEdge Grid-tie Systems with Astronergy Solar Panels (Astronergy 300 Silver Poly). The cost of a system consisting of 10 panels is 5535 US$ (Wholesale Solar, 2015). The cost of 1 panel is **553.5 US**$.

The National Renewable Energy Laboratory estimates the operation and maintenance costs of the PV systems as shown in Figure 23. The Operation and Maintenance costs per kW of a small system with a capacity of 10kW is **20 US$/kW-year**.

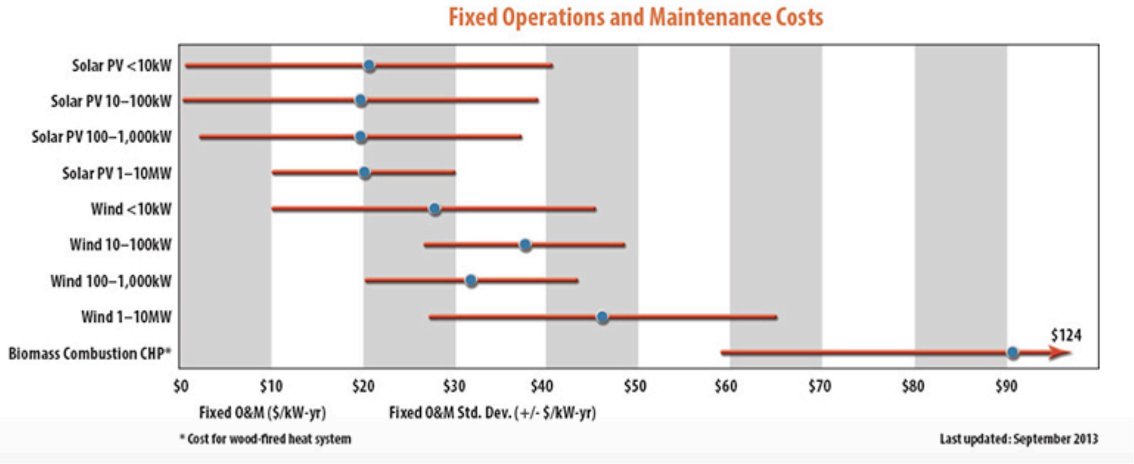


Figure 23: Operation and maintenance costs (NREL, 2013)

The operation and maintenance costs of a system per year (OM) is calculated by the equation 15.

$$OM = C \times System_{size} \tag{15}$$

Where:

- C = maintenance costs per kW
- $System_{size}$ =the capacity of the PV system (kW)

2.3.2 Grid electricity costs

In order to do a full economic analysis of the PV systems, the cost of the PV electricity production is compared to the costs of the electricity obtained from the grid. To do that, the levelised cost of energy from Grid **($LCoE_{grid}$)** must be calculated.

The current price of grid-electricity is 14.55 US cent/kWh. Assuming that the escalation rate is 2%, and the interest rate is 6%, the present value of the cost over the period of 20 years *P(g)* can be calculated using equation 10:

$$P(g) = 14.55 \times (1 + 0.02) \times \left[\frac{1 - \left(\frac{1 + 0.02}{1 + 0.06} \right)^{20}}{(0.06 - 0.02)} \right]$$

$$P(g) = 199.119$$

The present value of the cost of 1 kWh over 20 years is 199.05 US cents. The $LCoE_{grid}$ is calculated using equation 11:

$$LCoE_{grid} = 199.119 \times \left[\frac{0.06(1+0.06)^{20}}{(1+0.06)^{20}-1} \right]$$

The levelised cost of electricity is **17.36 US cents per kWh.**

Due to the subsidy the government pays 89% of the electricity costs. The levelised cost of electricity covered by the government is **15.45 US cents per kWh.** The consumer pays the rest of 11% of the costs (**1.91 US cents per kWh)**.

2.3.3 Payback period

As a part of the economic analysis of the PV systems, the payback period of each system is calculated in order to identify how cost-efficient it is to implement the usage of Photovoltaic systems to generate electricity in the residential sector.

The payback period can be defined as the period of time in which the initial capital cost of the system is to be recovered from the cumulative cash flow that results from the savings achieved by reducing the amount of electricity bought from the grid and replacing it with the electricity generated from the PV system (investment). The year in which the net cash flow reaches zero is called the Payback period. The sum of the revenues achieved by the savings due to the usage of the PV system from the payback period year onwards is the total profit due to installing the system. Due to the escalation rate (2%) in the grid electricity prices, the annual savings (achieved by reducing the amount of grid electricity) is not constant. The payback period for each system is calculated in two cases:

Case 1:

This case looks at the current situation in Libya. It takes into account the electricity subsidy already existing in Libya. It examines whether it makes sense financially for the consumer to install a photovoltaic system, given the low price he/she pays for electricity under the existing subsidy system, where the consumer only pays 11% of electricity costs (1.6 US cents/kWh)

Case 2:

To lower the amount of money spent by the public treasury on domestic electricity, a theoretical case is proposed. The unreasonably high subsidy applied to the residential sector's electricity costs is canceled. In this case the consumer pays the total cost of electricity supplied from the grid (14.55 US cents/kWh).

In order to further encourage the consumer to invest in a PV system, the government can offer a grant to those homeowners who decide to invest in a PV system. In this case, the government would not offer any subsidy on the grid-based electricity, but only offers a set percentage to cover some of the costs of the PV system. It is expected that in this case the government would save some money, by replacing the total electricity costs it covers under the current policies of the country, by offering a grant for the installment of PV systems. The amount of savings (S_{gov}) is calculated as using equation 16.

$$S_{gov} = TC_{sub} - C_{PV} \tag{16}$$

- S_{gov} = Savings for the government
- TC_{sub} = Total electricity costs covered by the government over a period of time in which the PV system is to be used (89% of the building's electrical demands)
- C_{PV} = Capital costs of the PV system covered by the government.

The total electricity costs covered by the government (TC_{sub}) is calculated using equation 17. It is determined for each house by calculating the amount of money it costs the public treasury to cover its share of the electrical costs over 20 years under the current subsidy taking into account the escalation rate of 2%.

$$TC_{sub} = \left(K_{wh} \times P_{kWh}\right) \times \sum_{n=1}^{n} (1.02)^{n-1} \tag{17}$$

- K_{Wh} = Annual electrical demand of the house in kWh
- P_{kWh} = Cost of kWh covered by the government (0.129 US$)
- Escalation rate 2%
- n = number of years

3 CASE STUDY BUILDINGS

The residential housing units in Libya are mostly constructed similarly. They have flat roofs, and due to the climate conditions of the area insulation materials are often not used. The windows are single glazed, which contributes to heat gains in the hot climate. The walls are usually constructed using concrete blocks. In this thesis, two cases are examined, one where the walls of the structure are not insulated, and a second where insulation is applied to the concrete external walls.

3.1 Al-Mrayed house

The building is a one level single-family house with an area of 206 m^2. The house has a flat roof. It is located in a suburban area with sufficient sun exposure due to the fact that all the surrounding buildings have a similar shape and height, eliminating any shadows that are casted by the neighboring buildings. A family of six people occupies the house. The long axis of the house is in the East-West orientation. Figure 24 is a plan showing the distribution of the spaces and the orientation of the house.

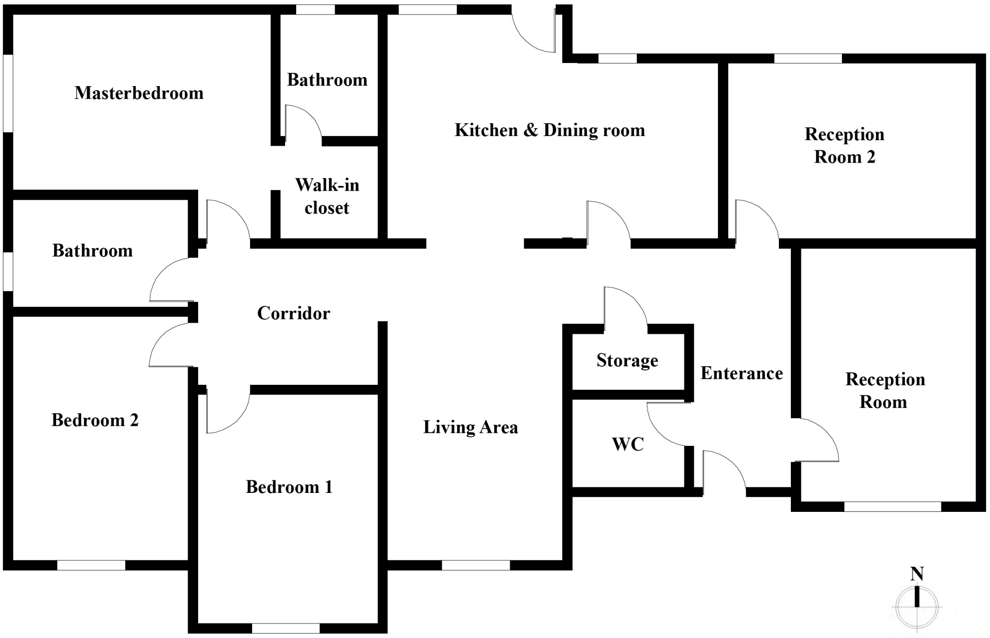


Figure 24: AL-Mrayed house Plan

First step in order to calculate the energy demands of the house was to create a model of the structure using SketchUp, in order to generate the different thermal zones and the geometry of the building.

3.1.1 EnergyPlus input data

To simulate the building using EnergyPlus software, the model is imported into EnergyPlus where further characters that determine how the building behaves were added to the model:

Construction and materials

In this section the construction materials of the different elements are set, Table 2 shows the materials in which the different elements of the structure are constructed of and the U-values of those elements:

Table 2: Building elements' materials of House 1

Element	**Layers and materials of elements**	**U-Value (W/m^{2}K)**
Exterior Doors	50mm Wood	2.953
Interior Doors	25mm Wood	--
Exterior Walls	200mm 2-core concrete block (limestone), 6.4mm cement	2.961
Interior Walls	6.4mm cement board, 200mm 2 core concrete block, 6.4 cement	--
Ceiling	19mm gypsum, 200mm heavyweight concrete	2.693
Floor	Terrazzo, 200mm heavy concrete	3.567
Windows	6mm Clear glass	5.778

Table 3 shows the thermal conductivity of the materials used. Thermal conductivity measures how easily heat flows through the material, independent of the thickness of the material in question. The lower the thermal conductivity the better thermal performance of the material is.

Table 3: Thermal conductivity of materials used in House 1

Element	**Thermal Conductivity λ (W/mK)**
50mm Wood	0.15
25mm Wood	0.15
200mm 2-core concrete block (limestone)	1.13
19mm gypsum	0.16
6.4mm cement board	0.58
200mm heavyweight concrete	1.95
Terrazzo	1.8
6mm Clear glass	0.9

People

The number of people in each space is identified. A schedule is used to determine the frequency and the length of the period in which each space is occupied. Table 4 shows the occupancy of each room.

Table 4: Occupancy schedule of House 1

Room	**Number of people**	**Days of occupancy**	**Hours of occupancy**
Living Area	6 people	All Days	09:00 – 22:00
Guest reception	14 people	Weekends	18:00 – 23:00
Master Bedroom	2 people	All Days	21:00 – 09:00
Bedroom 1	2 people	All Days	21:00 – 09:00
Bedroom 2	2 people	All Days	21:00 – 09:00
Dining Room	6 people	All Days	20:00 – 21:00

Table 5 shows the thermostat set points.

Table 5: Thermostat set points

Thermostat	**Set Point temp (°C)**	**Days**
For Cooling	24	All Days
For Heating	21	All Days

Electric equipment

This section models the electrical equipment. The design level in Watts is used to sum up the maximum electrical input to all the equipment in a given zone. Table 6 shows a schedule of the electric equipments input.

Table 6: Electric equipments Input (Watts) in zones in House 1

Zone	**Design Level (Watts)**
Bedroom 1	200
Bedroom 2	200
Master Bedroom	240
Kitchen	800
Living Area	540
Dish washer	600
Fridge	150
Guest Reception	200

Table 7 shows the schedule in which the electric equipment is used:

Table 7: Electric Equipments Schedule in House 1

Equipments	**Days of operations**	**Hours of operations**
Kitchen equipments	All Days	07:30-08:00/12:00-14:00/18:30-17:00
Fridge	All Days	24:00 hours
Dish washer	All Days	19:00 – 21:00
Living room equipments	All Days	10:00 – 21:00
Lighting house	All days	10:00-22:00
Bedroom equipments	All Days	22:00-24:00
Reception Room equipments	Weekends	18:00 – 23:00

3.2 Giamali house

The building is a one level single-family house with a staircase leading to the roof. It has an area of 186m^2. A family of four people occupies the house. It has a flat roof and insulated external walls. Figure 25 is a plan of the house showing the distribution of the spaces and the orientation of the house.

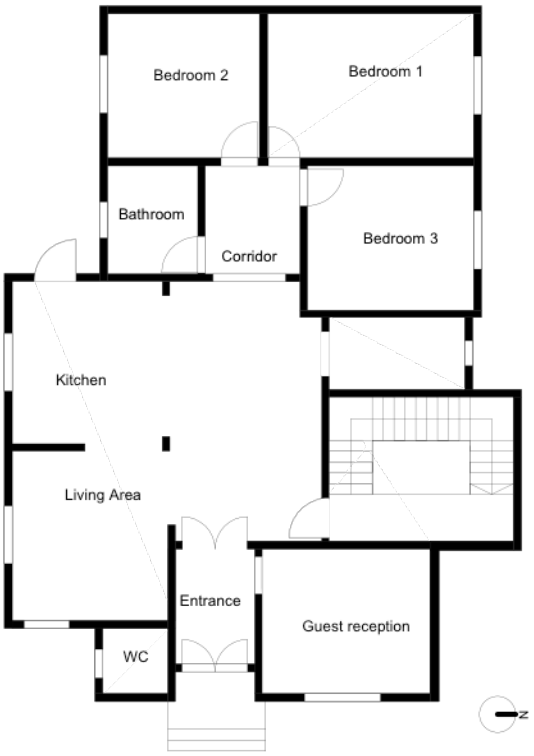


Figure 25: Plan of the Giamali House

The same steps used in the previous simulation are followed in order to calculate the energy demands of the house. However, there are some differences concerning the occupants and the materials of the building that needed to be taken into account.

3.2.1 EnergyPlus input data

Construction and materials

In this section the construction materials of the different elements are set. Table 8 shows the materials for the building elements, and the U-value for each structural element.

Table 8: List of materials in House 2

Element	**Layers and materials of elements**	**U-Value (W/m^2K)**
Exterior Doors	50mm Wood	2.953
Interior Doors	25mm Wood	--
Exterior Walls	200mm concrete block (filled), 25mm insulation board, gypsum or plaster board	0.779
Interior Walls	Gypsum, 200mm concrete block (filled), gypsum	--
Ceiling	Gypsum board, 200mm heavyweight concrete, 25mm stucco	3.552
Floor	Terrazzo, 200mm heavy concrete	3.567
Windows	3mm Clear glass	5.894

Table 9 shows the thermal conductivity of the materials of the

Table 9: Thermal Conductivity of materials of House 2

Element	**Thermal Conductivity λ (W/mK)**
50mm Wood	0.15
25mm Wood	0.15
200mm concrete block (filled)	0.72
25mm insulation board	0.03
Gypsum or plaster board	0.58
200mm heavyweight concrete	1.95
Terrazzo	1.8
25mm stucco	0.72
3mm Clear glass	0.9

People

Table 10 shows the number of people in each space, and the time of occupancy.

Table 10: Occupants in different zones of House 2

Room	**Number of people**	**Days of occupancy**	**Hours of occupancy**
Living Area	4 people	All Days	09:00 – 22:00
Guest reception	10 people	Weekends	18:00 – 23:00
Bedroom 1	2 people	All Days	21:00 – 09:00
Bedroom 2	1 people	All Days	21:00 – 09:00
Bedroom 3	1 people	All Days	21:00 – 09:00
Dining Room	6 people	All Days	20:00 – 21:00

Table 11 shows the thermostat set points.

Table 11: Thermostat set points in House 2

Thermostat	**Set Point temp (°C)**	**Days**
For Cooling	24	All Days
For Heating	21	All Days

Electric equipments

Table 11 shows the maximum electricity input to equipment in each zone. While Table 7 shows the schedule of operations of the equipments.

Table 12: Electric equipments (Watts) in House 2

Zone	Design Level (Watts)
Bedroom 1	100
Bedroom 2	170
Bedroom 3	75
Kitchen	800
Living Area	540
Dish washer	600
Fridge	150
Guest Reception	210

4 RESULTS

4.1 AL-Mrayed house

4.1.1 Simulation of building's energy demands

The thermal simulation of the building shows that the highest electrical loads occur during the summer period; the electrical demands of the house reaches its peak in July with a value of **2409.48 kWh**. Although the building has both cooling and heating loads, the simulation shows that the cooling loads are higher due to the nature of the climate in Tripoli, Libya and the internal gains of the building. Using EnergyPlus, the cooling loads of the house were calculated and the following monthly loads were obtained as shown in Figure 26. The highest cooling demands occur in July with a value of **3659.36 kWh**.

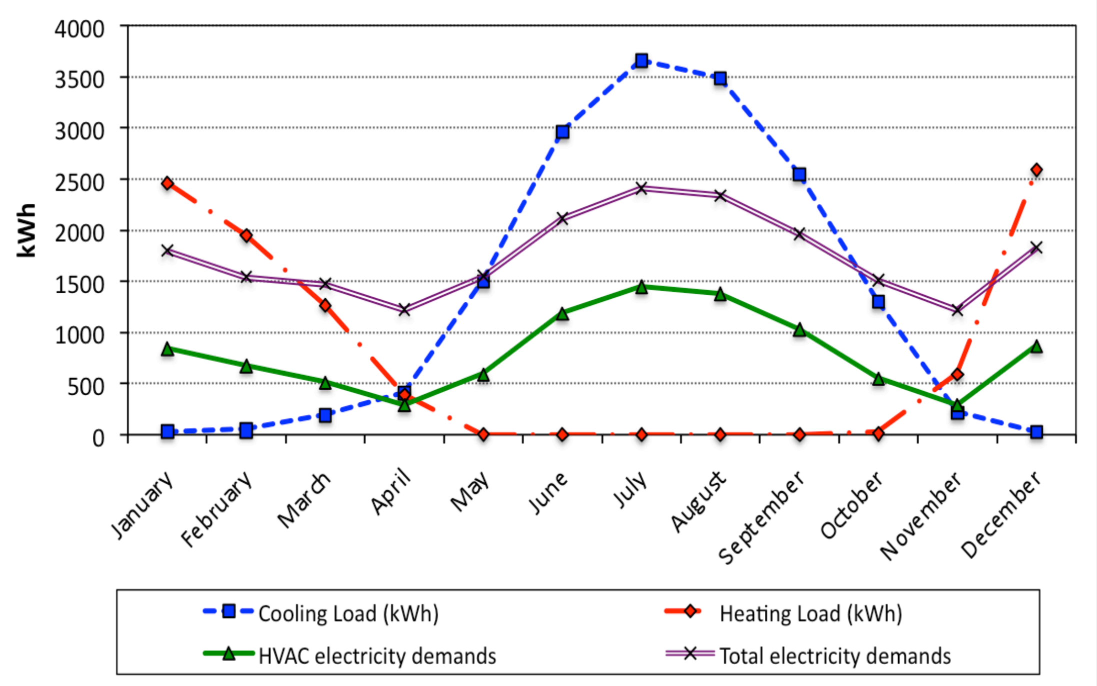


Figure 26: EnergyPlus Calculated monthly Loads in House 1

Figure 27 shows the relationship between the total of the building's electrical demands and the cooling loads of the house. It is noticeable that they both peak in the period from June to September.

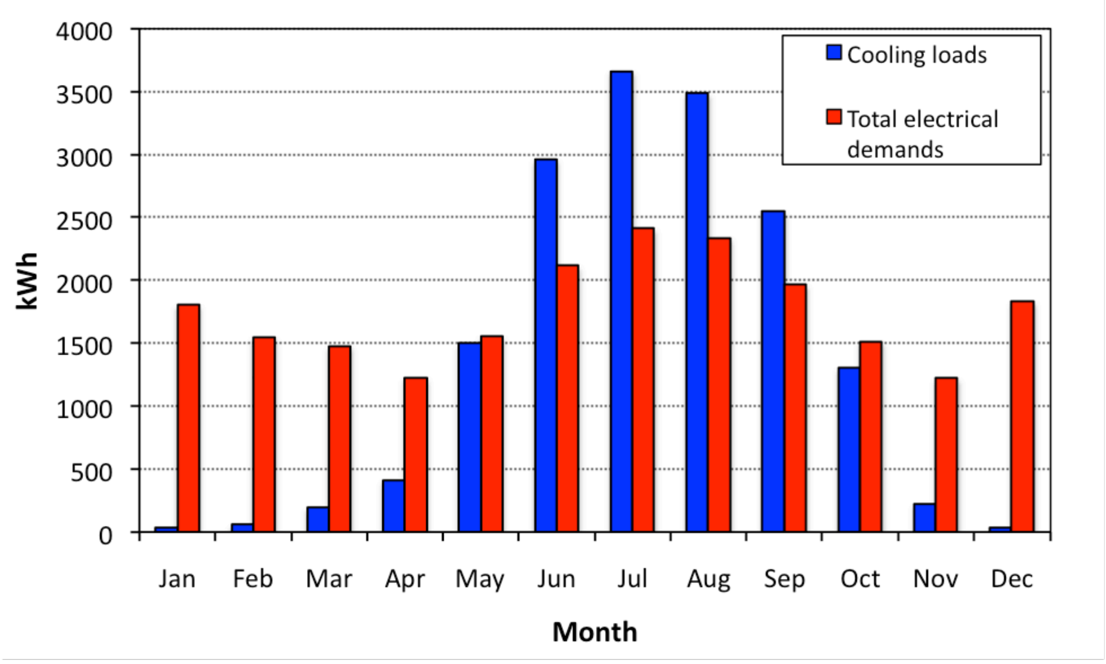


Figure 27: Electric demands and cooling loads of House 1

The electric demands for cooling and heating are calculated by EnergyPlus. Figure 28 shows the electric demands for the HVAC system and the total electric demands of the house.

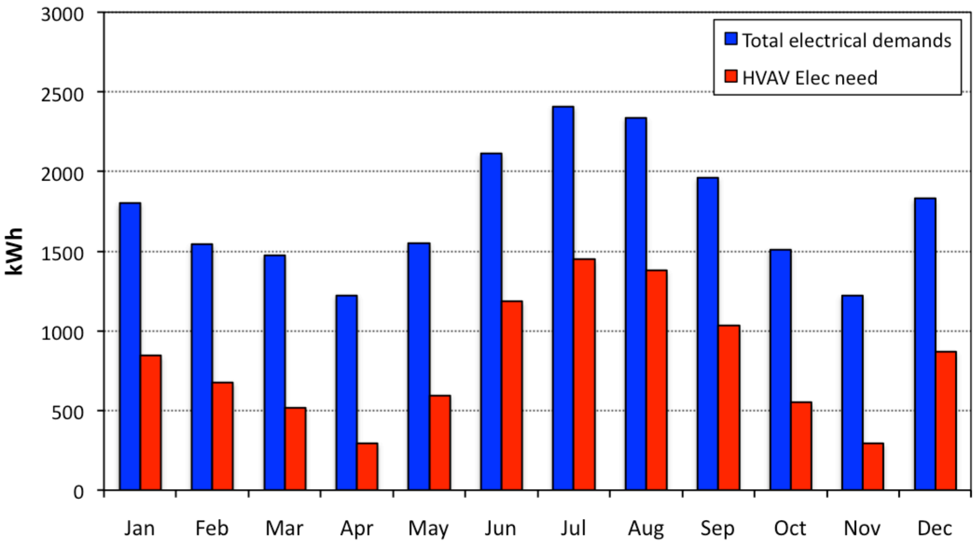


Figure 28: Electric demands of House 1

The total electricity demands of the house are calculated to be **20980.25 kWh.** Figure 29 shows the percentages of electricity used for cooling and that for heating to the total electrical consumption of the building as a whole:

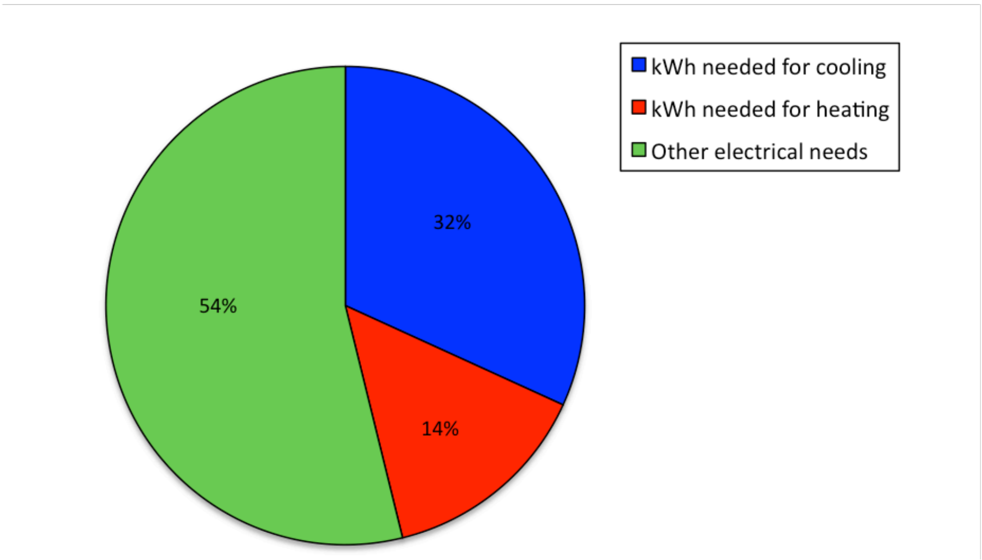


Figure 29: Electrical consumption percentage in House 1

The total electricity demand for heating with an HVAC system with a heating COP of 3.6 is calculated to be **3008.74 kWh**. While the electricity needed for cooling with a system of cooling COP of 3 is **6674.70 kWh**.

4.1.2 Building grid-electricity cost to government.

The total electricity demands of the house are calculated by EnergyPlus to be **20980.25 kWh**. Under the subsidy system the government pays 89% of the electricity costs (0.129 US$/kWh). The total costs the public treasury pays for the total electrical demands of the house over 20 years (TC_{sub}) is calculated using equation 17.

$$TC_{sub} = (20980.25 \times 0.129) \times \sum_{n=1}^{20} (1.02)^{n-1}$$

$$TC_{sub} = 65759.67 US\$$$

4.1.3 Photovoltaic system sizing

EnergyPlus estimated the electricity produced by the chosen module under the conditions of the house's specific location and the amount of solar radiation available. The Electricity production of one Astronergy 300 Silver Poly panel ranges from **24.41 kWh** in December to its maximum in kWh to **54.71 kWh** in July. The annual production of the panel is **481.64 kWh**. Figure 30 shows the monthly production of one panel. The highest production of electricity coincides with the maximum electricity demands of the house. This verifies the assumption that the most electricity overload occurs in the summer period, which makes the idea of sizing the PV system around the summer loads a valid one.

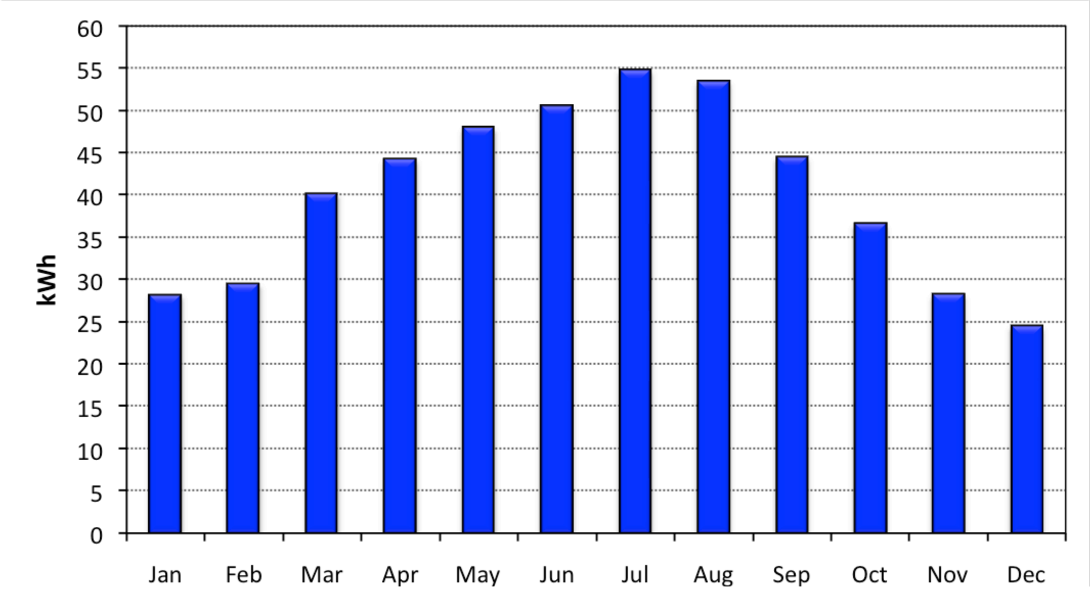


Figure 30: Monthly kWh production per panel in House 1

The number of panels that make up the systems is calculated using equation 8. Table 13 shows the number of panels needed for each of the three systems.

Table 13: The three proposed PV system sizes in House 1

	Electricity demand (kWh)	**No. Of Panels**	**System Size (kWp)**
PV system size 1	6674.70	14	4.2
PV system size 2	11885.13	25	7.4
PV system size 3	20980.25	44	13.1

Table 14 and Figure 31 show the roof area required by each PV system. It is noticeable that the roof area available is much bigger than that which is needed by any of the systems; the largest system would only cover about 60% of the total roof area. Giving the low tilt of the panels (22.5°) and the high position of the sun, the distance between panels in order to eliminate shading casted by the panels would not as big as to exceed the rest of the 40% of roof area available. This renders any further detailed analysis for the roof area unnecessary.

Table 14: Roof area needed for the proposed PV systems in House 1

	System size (kWp)	**No. Panels**	**Area (m^2)**	**% Of area covered**
PV system size 1	4.2	14	39.02	18.9%
PV system size 2	7.4	25	68.75	33.4%
PV system size 3	13.1	44	121.7	59.1%

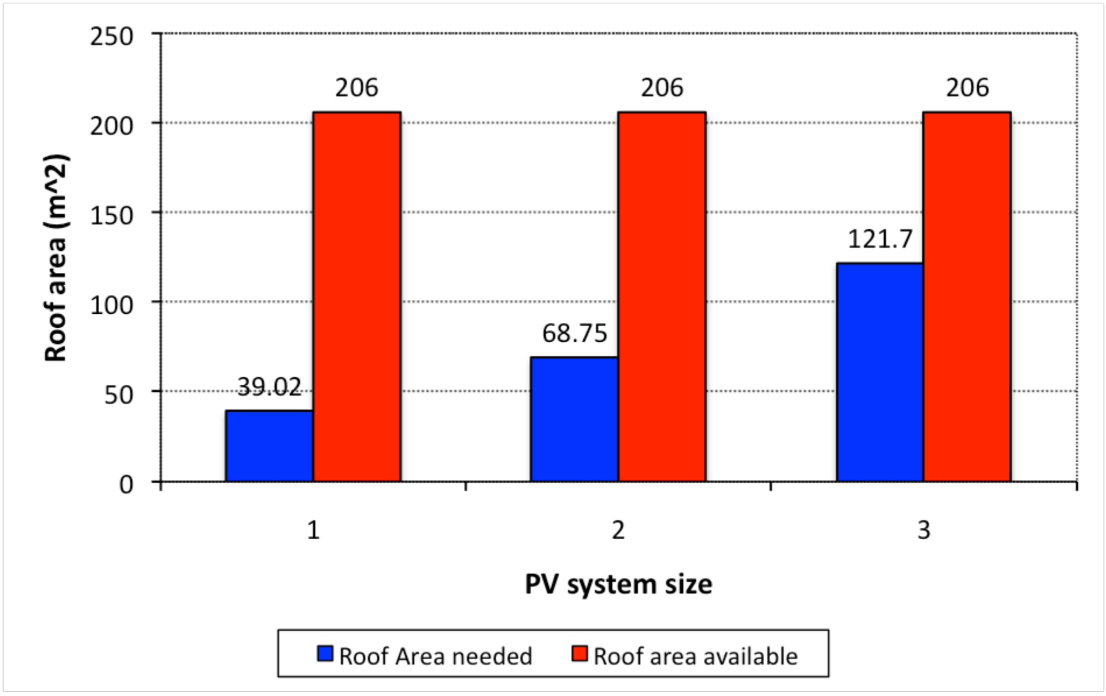


Figure 31: Roof Area of House 1

4.1.4 Capital costs of the PV systems

The capital cost of the PV system (*P*) is calculated by multiplying the numbers of panels needed for the system by the cost of one panel (553.5 US$). Due to the lack of an existing local market for Photovoltaic's' technology, the system would be imported from abroad and an importing tax fee of 10% is applied. Table 15 shows the capital costs of the three proposed systems.

Table 15: Capital costs of the PV systems suggested for House 1

System size	No. Panels	Capital costs with 10% importing taxes (US$)
4.2 kWp	14	8523.90
7.4 kWp	25	15221.25
13.1 kWp	44	26789.40

4.1.5 Grid electricity demands when using PV systems.

The produced electricity by the PV system is used to cover some of the house electrical needs. Reducing by that the electricity bought from the grid; in case that the production of a PV system does not cover the total electrical demands of the house, any shortage would be supplied from the grid.

Table 16 shows the annual electricity that need to be supplied from the grid when using the three proposed systems.

Table 16: Electricity annual production of the PV systems and the annual electricity purchased from the grid in House 1

PV system	Annual Production (kWh)	Annual Building demand (kWh)	Annual electricity from grid (kWh)
4.2 kWp	6742.92	20980.25	14237.33
7.4 kWp	12040.93	20980.25	8939.32
13.1 kWp	21192.03	20980.25	-211.78

4.2 Giamali house

4.2.1 Simulation of building's energy demands

As it was in house 1, the highest electrical demands coincide with the period in which the cooling load of the house is at its maximum. This occurs in July, where the cooling load gets as high as **3183.75 kWh**. EnergyPlus calculated the loads of the house and the monthly loads were obtained. Figure 32 shows that the monthly demands of the house.

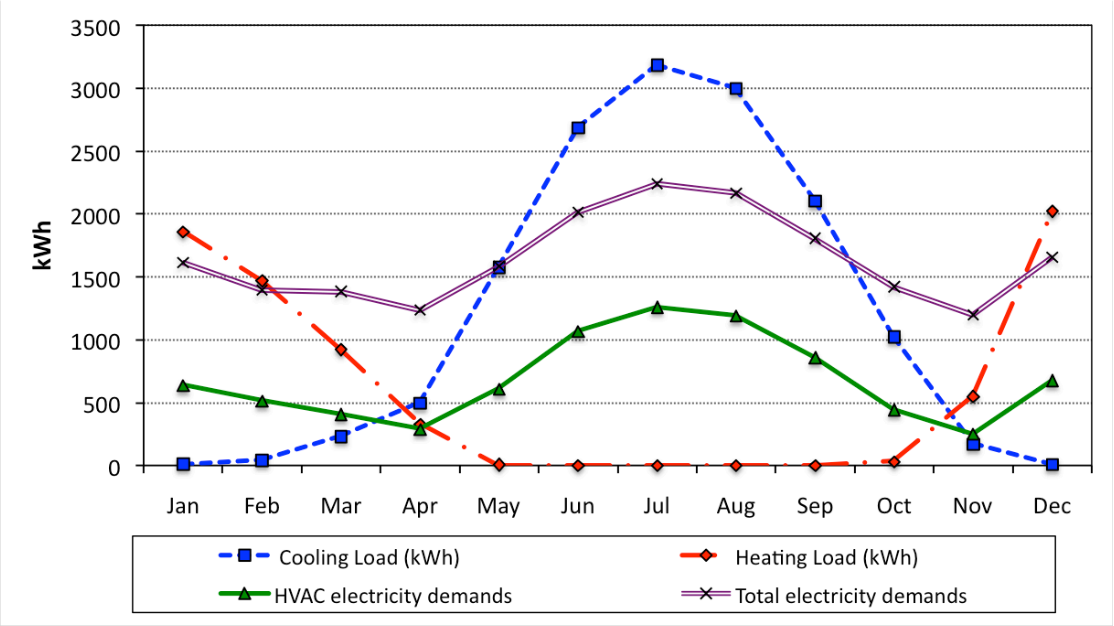


Figure 32: EnergyPlus calculated monthly loads in House 2

Figure 33 shows the total building's electricity demands and the cooling loads that must be covered by the HVAC system.

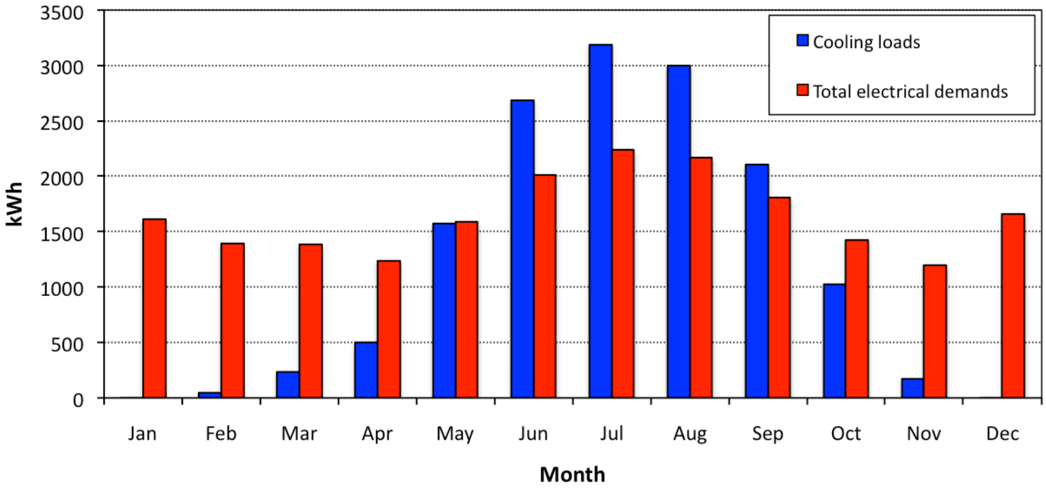


Figure 33: Electric demands and the cooling loads of House 2

The electric demands for cooling and heating are calculated by EnergyPlus. Figure 34 shows the electric demands for the HVAC system and the total electric demands of the house.

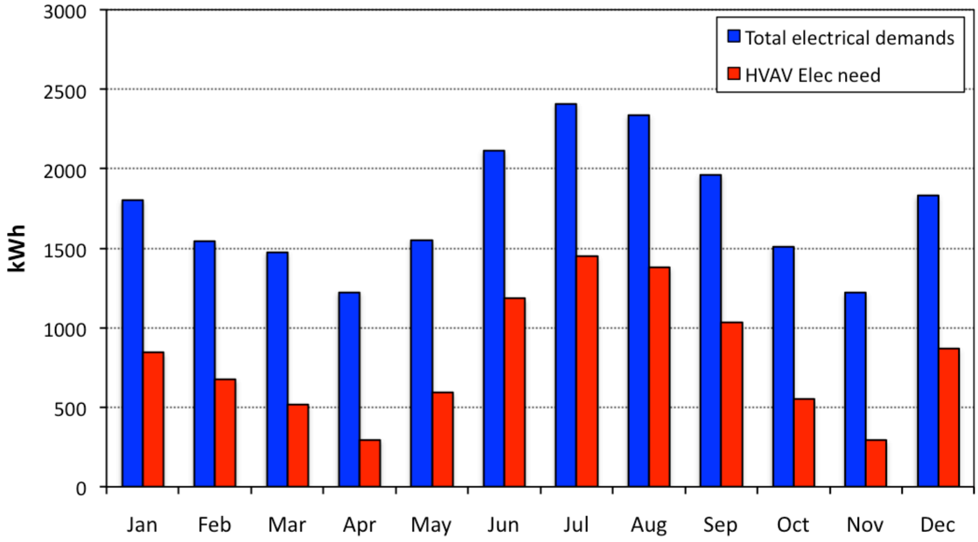


Figure 34: Electric demands of House 2

The total electricity demand of the house as calculated by EnergyPlus is **19703.52 kWh.** The total electricity demand for heating is **2360.04 kWh**. While the electricity needed for cooling is **5812.59 kWh.** Figure 35 shows the percentages of electricity used for cooling and that for heating from the total electrical consumption of the building as a whole.

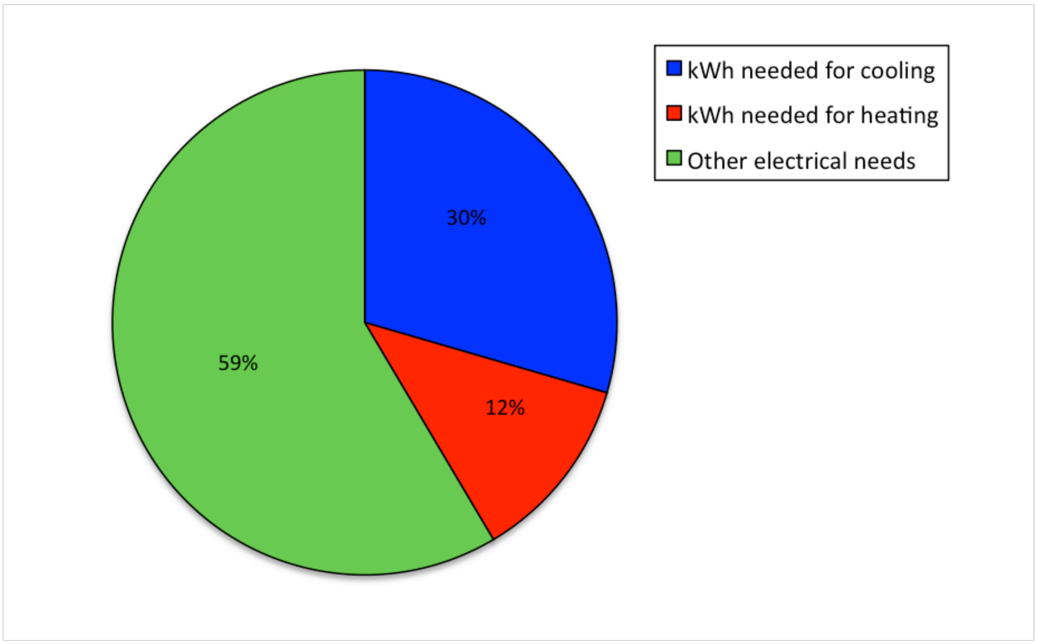


Figure 35: electric consumption percentage in House 2

4.2.2 Building grid-electricity cost to the government

The total electricity costs covered by the government under the subsidy system and without the installation of a PV system in the house (TC_{sub}) is calculated using equation 17.

Table 17: Grid electricty costs for House 2

Annual electricity demand (kWh)	Costs of 1 kWh for government (US$)	Escalation rate	Number of years
19703.52	0.129	2%	20

$$TC_{sub} = (19703.52 \times 0.129) \times \sum_{n=1}^{20} (1.02)^{19}$$

$$TC_{sub} = 61757.94 US\$$$

4.2.3 Photovoltaic system sizing

The same Panel is used for the PV system of this house. EnergyPlus simulated the PV panel to calculate the estimated electricity produced one Astronergy 300 Silver Poly panel. The electricity produced by the inverter of the PV system from one-panel ranges from **24.39kWh** in December to its maximum of **54.58 kWh in July**. The total annual production is **481.11 kWh**.

The three suggested PV sizes are shown in Table 18.

Table 18: The proposed PV system sizes for House 2

	Electricity demand (kWh)	No. Panels	System Size (kWp)
PV system size 1	5812.59	12	3.6
PV system size 2	11226.31	23	7
PV system size 3	19703.52	41	12.3

The same method was applied to calculate the roof area needed for house no.2 (Giamali House). The available roof area is about 186m^2. Table 19 shows the calculated areas required.

Table 19: Roof area available for the proposed PV systems for House 2

	System size (kWp)	**No. Panels**	**Area (m^2)**	**% Of area covered**
PV system size 1	3.6	12	33.45	18.0%
PV system size 2	7	23	65.03	35.0%
PV system size 3	12.3	41	114.27	61.4%

Figure 36 shows that the roof area of the house ia big enough to accommodate the different options of system sizes. The biggest sized PV system (12.3 kWp) needs about 61% of the total roof area of the house.

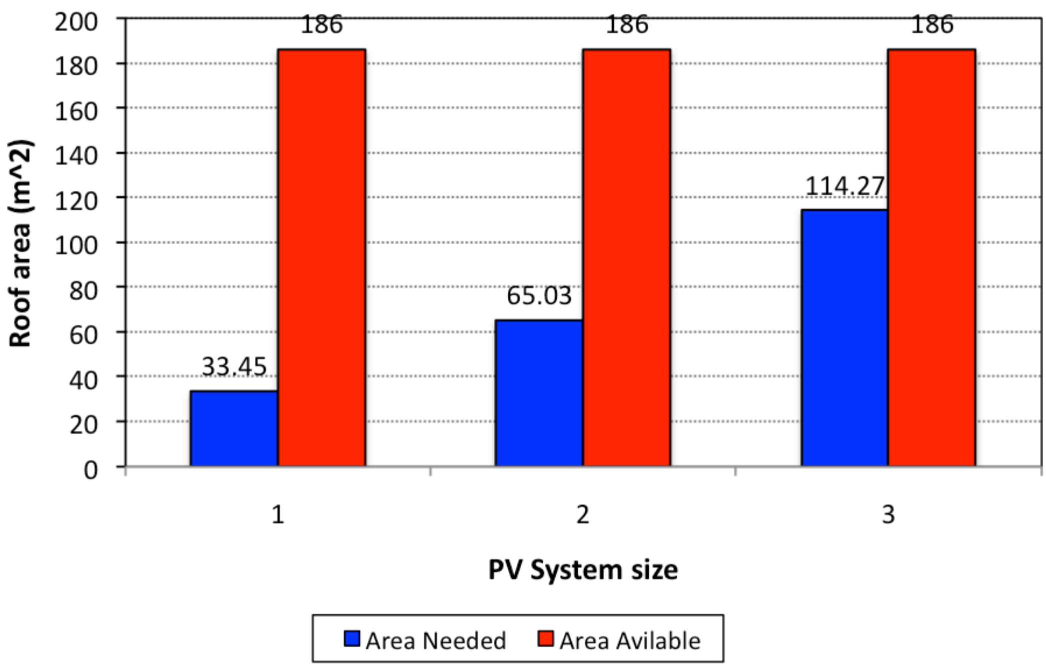


Figure 36: Roof area in House 2

4.2.4 Capital costs of the PV systems

Table 20 shows the Capital costs of the three PV systems sized for the house.

Table 20: Capital costs for the PV systems suggested for House 2

System size	No. Panels	Capital costs with 10% importing taxes (US$)
3.6 kWp	12	7306.2
7 kWp	23	14003
12.3 kWp	41	24962.9

4.2.5 Grid electricity demands when using PV systems.

The amount of electricity purchased from the grid is equal to the difference between the electricity demand of the building and the electricity produced by the PV system. Table 21 shows the annual electricity that needs to be supplied from the grid when using the three proposed systems.

Table 21: Electricity annual production of the PV systems and the annual electricity purchased from the grid in House 2

PV system	Annual Production (kWh)	Annual Building demand (kWh)	Annual grid electricity (kWh)
3.6 kWp	5773.37	19703.52	13930.15
7 kWp	11065.63	19703.52	8637.89
12.3 kWp	19725.68	19703.52	-22.16

4.3 Economic analysis

Due to the facts that the price per panel does not change with the system size, the costs of operation are calculated per 1kW at a price of 20 US$/kW, and that the avoided costs of electricity is based on the calculations of electricity produced per panel, a general case was used to calculate the payback period of implementing a PV system. The general case is also used to calculate the levelised costs (LCoE) of energy produced by the PV systems.

4.3.1 Levelised costs of energy produced by the PV systems ($LCoE_{PV}$)

As shown previously in equation 12, the levelised costs of energy produced by a PV system ($LCoE_{pv}$) is dependent on its annualized costs and the energy produced by the system. The annualized costs as shown in equations 13 and 14, is dependent on the constant values of operations costs, price of panels, and constant interest rate of 6%. It is clear that the $LCoE_{pv}$ is independent to the size of the PV system chosen. For that reason the $LCoE_{pv}$ is calculated using the general case of a system of 10 panels. Table 22 shows the calculations of the levelised costs of energy by the system

Table 22: Levelised costs of energy produced by the PV system

	Capital costs (US$)	OM (US$/year)	A (US$/year)	T=(A+OM) (US$/year)	LCoE (US¢/kWh)
10 panels system	5535	60	530.82	590.82	12.27

The levelised cost of energy produced by the PV system is the same for all of the proposed PV system sizes, and it is equal to **12.27 US cents**.

4.3.2 Payback period.

The same general 10 panels PV system is used to calculate the Payback periods for each of the suggested cases.

Case 1:

This case looks at the payback period of using a PV system under the current subsidy system applied in Libya. The homeowner only pays 11% of the actual cost of the electricity supplied from the grid. Table 23 shows a summery of the capital costs and the electricity production from the general PV system. It also shows the price the consumer pays for the electricity purchased from the grid and the escalation rate of the price of electricity (which is assumed constant throughout the 20 years).

Table 23: Electrical Demands and Costs for case 1

PV system costs (US$)	PV production (kWh/year)	Grid- electricity costs (US$/kWh)	Escalation rate
6088.5	4816.37	0.016	2%

Figure 37 shows that the Payback period is 106 years. This means that for the consumer it is rather inefficient to install a PV system, due to the very low prices that the homeowner pays for electricity under the subsidy system.

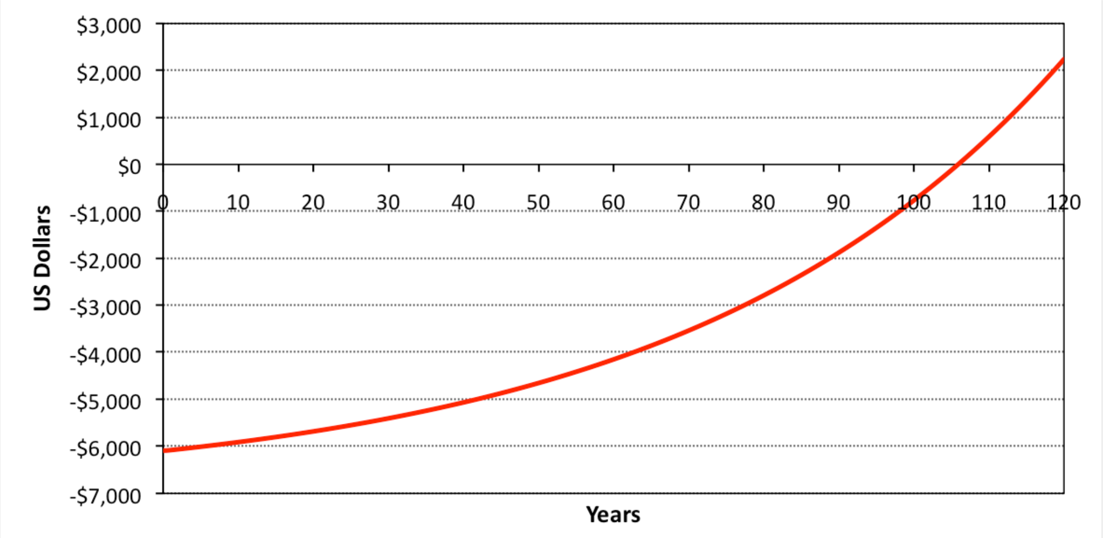


Figure 37: Payback Period under current subsidy (case 1)

For the consumer, to be encouraged to install a PV system, a payback period that lies within the lifetime of the PV system (20 years) must be achieved. This can be realized by offering a grant that ensures that. The government can offer the homeowner a grant in the form of a set percentage of the total cost of the PV system. Figure 38 shows different grant percentages. It is clear that in order to achieve a somewhat realistic and beneficial payback period under the high electricity subsidy system, the consumer would have to pay as low as 5% of the system cost. It makes no sense for the government to pay 95% of the PV system costs along with the 89% of the grid-supplied electricity.

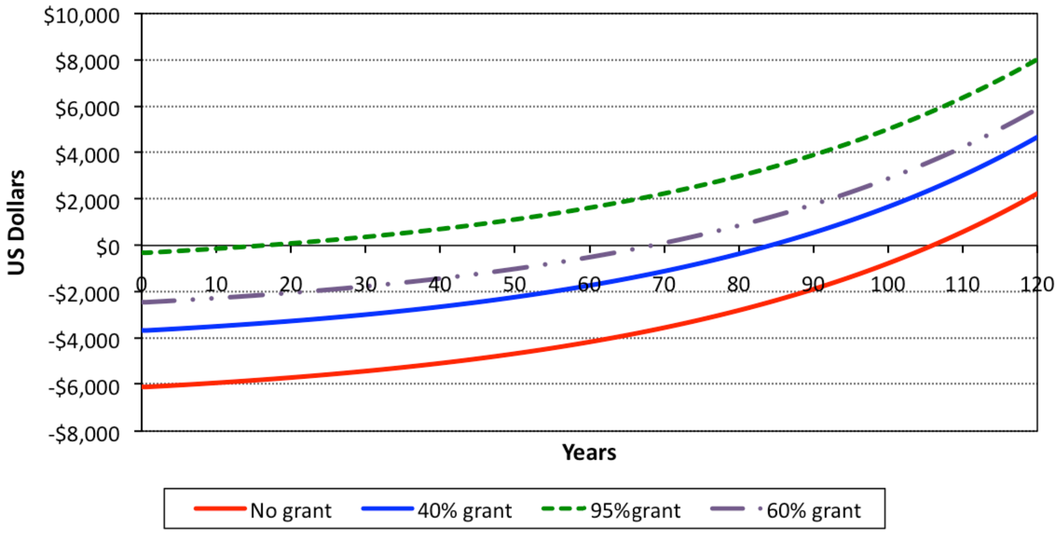


Figure 38: Payback periods under different grant values (Case 1)

Case 2

In this theoretical case, the unrealistically high electricity subsidy in Libya is canceled, and the homeowner would be demanded to pay the full price of electricity supplied from the grid. Table 24 shows a summery of the capital costs, the electricity production of the PV system, the price the consumer pays for the grid-electricity and the escalation rate.

Table 24: Electricity demands and costs for case 2

PV system costs (US$)	**PV production (kWh/year)**	**Grid- electricity costs (US$/kWh)**	**Escalation rate**
6088.5	4816.37	0.145	2%

Figure 39 shows that the Payback period is 9 years. It means that it is efficient for the consumer to install PV system in this case; where it lowers the amount of the electricity bought from the grid under the actual electricity price. By the end of the lifetime of the PV system (20 years) the consumer would have gained a profit by reducing the amount of electricity that needs to be supplied from the grid.

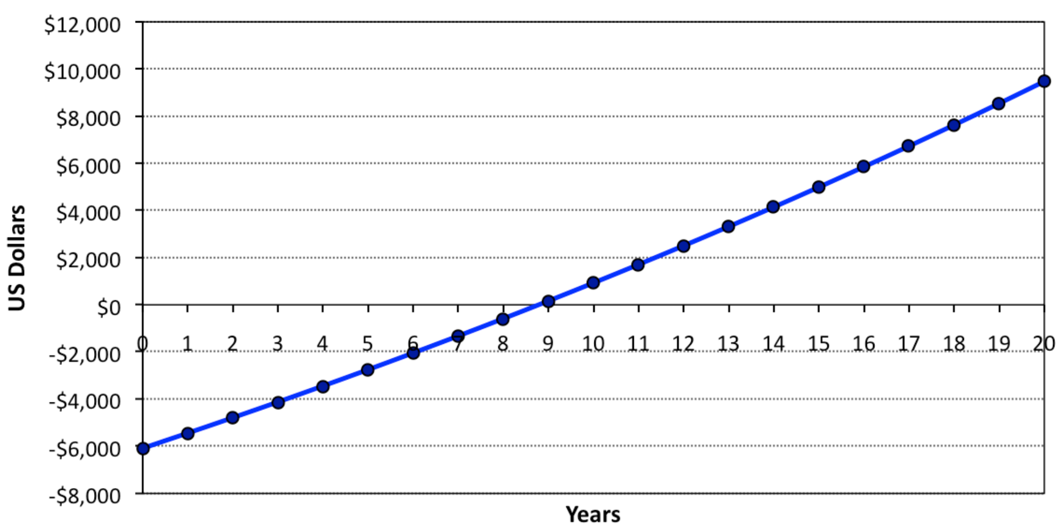


Figure 39: Payback period with no electrical subsidy

The Payback period can be reduced even further, and the homeowner's profit realized after 20 years can be increased, by implementing the grant policy in this case as well. Figure 40 shows different percentages of grants that can be offered by the government and how it affects the Payback period of the PV system. With a grant of 30% the payback period drops to 7 years. A grant of 50% drops the payback period to 5 years. The profit also increases as the value of the grant offered increases; when the payback period is reached earlier on, the profit starts cumulating at an earlier point within the 20 years.

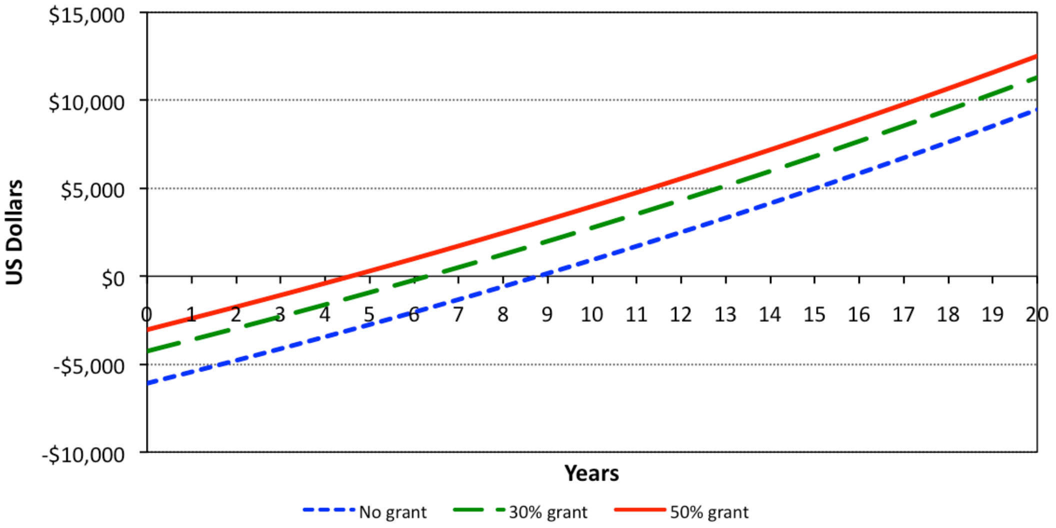


Figure 40: Payback periods for different values of grant

5 DISCUSSION

5.1 Capital costs

Figure 41 compares the capital costs of the three proposed PV systems in House 1 (AL-Mrayed house) that were designed to cover the electrical demands of the AC system. It is noticeable that the maximum sized system, which was designed to cover the total annual electrical demands of the house, has the highest capital costs of 26789.4 US Dollars. While the smallest size, which was designed around the electricity needed to run the cooling system is the cheapest, where it costs only 8524.9 US Dollars.

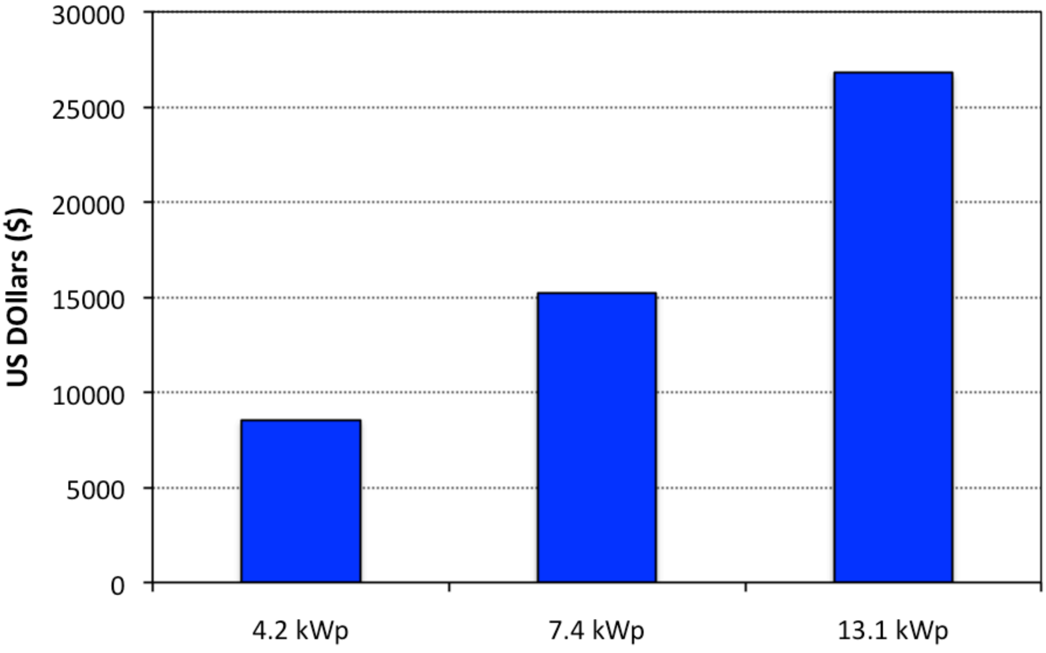


Figure 41: The capital costs of the PV systems in House 1

Figure 42 shows the capital costs of the PV systems suggested to be installed in House 2 (Giamali House). It is also clear that the biggest sized system would cost more.

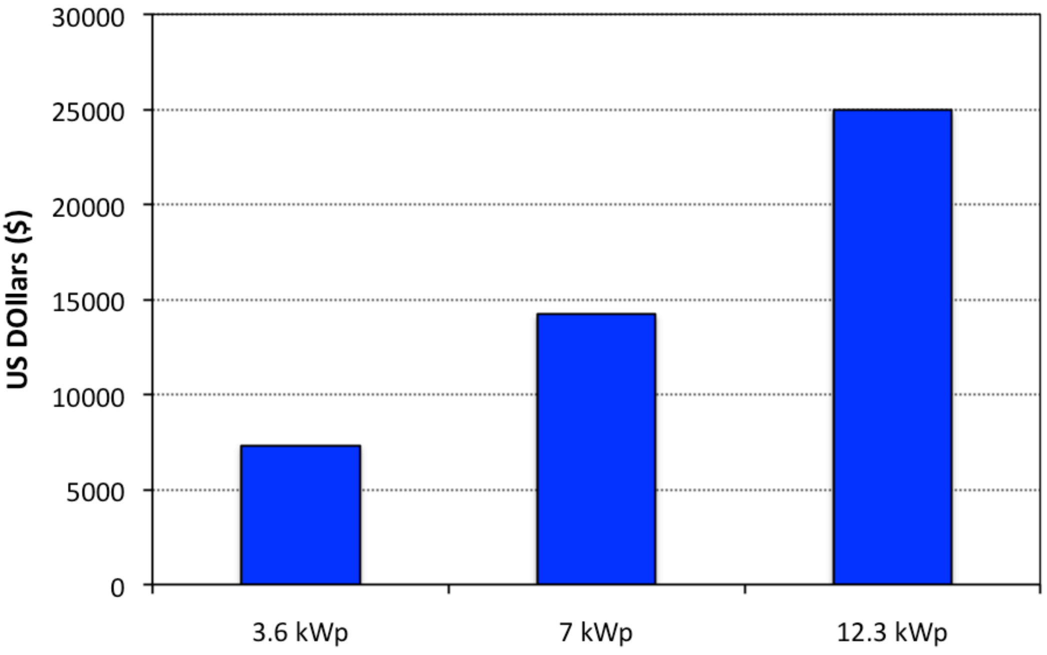


Figure 42: Capital costs of the PV systems in House 2

Although the smallest systems cost the least, they also produce the least electricity, which means the portion of electrical demands it covers is the least. The consumer would have to pay the price of the electricity supplied from the grid in order to cover the remaining electrical demands. Table 25 shows the amount of electricity needs to be supplied from the grid when installing the three systems in House 1.

Table 25: Costs of electricity bought from the grid in House 1

PV system	Annual electricity from grid (kWh)	Grid electricity Cost with subsidy (0.016 US$)	Grid electricity Cost with no subsidy (0.145US$)
No PV	20980.25	335.68	3042.14
4.2 kWp	14237.33	227.79	2064.41
7.4 kWp	8939.32	143.03	1296.20
13.1 kWp	--	--	--

Table 26 shows the amount of electricity needs to be supplied from the grid when installing the suggested PV systems for House 2.

Table 26: Costs of electricity bought from the grid in House 2

PV system	Annual electricity from grid (kWh)	Grid electricity Cost with subsidy (0.016 US$)	Grid electricity Cost with no subsidy (0.145US$)
No PV	19703.52	315.26	2857.01
3.6 kWp	13930.15	222.88	2019.87
7 kWp	8637.89	138.21	1252.49
12.3 kWp	--	--	--

5.2 Levelised cost of energy

Figure 43 shows that the levelised cost of electricity produced by the PV system (**12.27 US¢/kWh**) is lower than the levelised total cost of electricity supplied from the grid (**17.36 US¢/kWh**). However, due to the subsidy on electricity, the consumer only pays 11% (**1.91 US¢/kWh)** making it the cheaper source of energy for the homeowner.

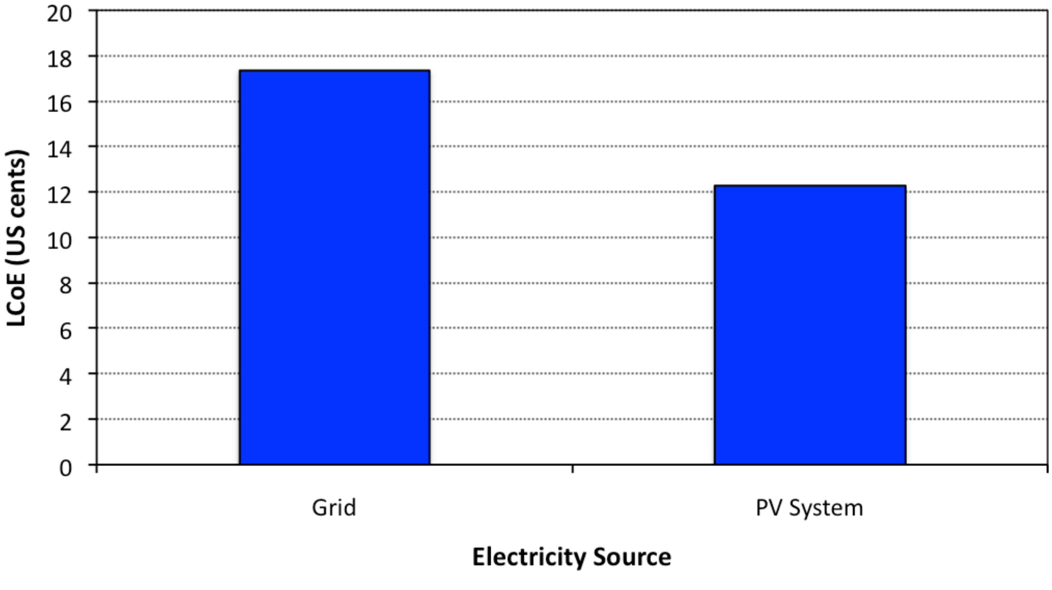


Figure 43: LCoE for the different sources of energy

The Levelised cost of energy estimates the value of costs at the end of the lifetime period of the PV system (20 years). Even though both prices; the price of electricity generated by the PV system and the price of fossil fuel based electricity are subjected to the same escalation and interest rates, the values of the costs of the PV based electrical energy remains cheaper in the next 20 years. This encourages the notion of implementing Photovoltaic systems as a source of electricity in a country with an abundant solar energy and high costs of fossil fuel generated electricity production. However for the homeowner, the LCoE calculations only validates the investment in a PV system if the subsidy on electricity was lifted, which would change the electricity tariff and demands the consumer to pay the full price for the grid-based electricity.

5.3 Payback period

From the results of calculating the payback period of the PV system, it is apparent that for the homeowner, the installation of a photovoltaic system is invalid under the normal conditions of the electricity sector's policy in Libya. The price that the residential consumer pays for electricity is too low, that it would take more than 5 times the lifetime of a PV system in order to start making a profit. In a way to encourage the homeowner to invest in a PV system a percentage of the cost of the PV system needs to be granted by the public treasury. However, when the option was examined, it was noticed that in order to drop the payback period to a period that is within the lifetime the PV system, the government would have to carry a huge burden of paying about 95% of the capital costs of the system. This would only increase the costs burden on the public treasury; as it would still be obliged to cover the 89% of the price of the electrical needs that the PV system would not cover.

In the second case, a theoretical scenario was examined. The subsidy on electricity is canceled. The consumer is obliged to pay the total price of electricity (0.145 US$/kWh). Due to the high costs of electricity, the installation of PV system would realize a sizeable profit by the end of its lifetime of 20 years. The consumer would also reach a payback period for the system in about half way the lifetime of the PV system (in year 9).

In this case, another scenario was examined, where the government would offer a grant to the homeowner in a form of a set percentage of the total costs of the PV system in order to encourage people further to turn to solar energy as a source of electricity. The higher the percentage of the grant, the lower the payback period is for the consumer and the more profitable the PV system is. It is also noticed that government would achieve some savings by replacing the high electricity demands with a grant for the PV system.

Although the grant costs the government, it still creates a profit for the public treasury. The savings achieved by the government is calculated using equation 16**.** Table 27 shows the government's savings when installing the three proposed PV systems in House 1 (Al-Mrayed House) where the total electricity costs covered by the government under the subsidy system over 20 years is calculated by equation 16 to be **65759.67 US$.**

Table 27: Government's Savings for House 1

Grant %	4.2 kWp Savings (US$)	7.4 kWp Savings (US$)	13.1 kWp Savings (US$)
30%	63202.50	61193.30	57722.85
50%	61497.72	58840.92	52364.97

Table 28 shows the government's savings when installing the three suggested PV systems in House 2 (Giamali House).

Table 28: Government's savings for House 2

Grant %	3.6 kWp Savings (US$)	7 kWp Savings (US$)	12.3 kWp Savings (US$)
30%	59566.08	5755.88	54269.09
50%	58104.84	54756.17	49276.52

The homeowner would also gain some profit in case 2, where h/she pays the full price of the grid-based electricity. The profit is realized by cutting down in the grid-electricity purchases throughout the life lifetime of the PV system in use (20 years). This profit varies depending on the size of the PV system installed. Table 29 shows the profits achieved in House 1, under the different grant percentages.

Table 29: Consumer's Profit over 20 years in House 1

Grant %	Payback period (Years)	4.2 kWp profit (US$)	7.4 kWp profit (US$)	13.1 kWp profit (US$)
0%	9	13265	23736	41738
30%	7	15822	28302	49775
50%	5	17527	32346	55133

Table 30 shows the Profit realized in the house examined in case study 2 (Giamali House).

Table 30: Consumer's Profit over 20 years in House 2

Grant %	Payback period (Years)	3.6 kWp profit (US$)	7 kWp profit (US$)	12.3 kWp profit (US$)
0%	9	11348	21701	38772
30%	7	13540	25902	46260
50%	5	15001	28703	51253

It is clear that in all cases, and under all percentages of the grant offered by the public treasury, the PV system creates a profit for the consumer. The profit correlates positively with the size of the PV system; the bigger the size of the system is, the less annual electricity is bought from the grid under the actual price of 0.145 US$/ kWh. The profit also increases with the increase of the value of the grant offered by the government; the grant decreases the initial investment costs for the consumer.

Regardless to the fact that the higher percentage of the grant offered, the lower the savings achieved by the governments are (as seen in Table 27 and Table 28), It is obvious that the government still in fact creates a profit by replacing the electricity subsidy with a set value for a grant. It would also help in encouraging the homeowners to invest in this untapped market of solar energy, which has huge potentials in a country like Libya.

5.4 Electricity production and demand balance

In both houses studied in this thesis, the largest PV systems were designed in a way that they cover the annual electrical demands of the house. In House 1 (Al-Mrayed house), the 13.1kWp PV system produces a total annual energy of 21192.03 kWh, which is more than the house's annual demand as calculated previously (20980.25 kWh). Figure 44 shows the electricity demand of the house and the electricity produced by the PV system. Although the electricity production is higher or lower than the electricity demanded at different points throughout the year, the total annual production covers the total annual demand of energy and creates a small surplus as shown in Table 31.

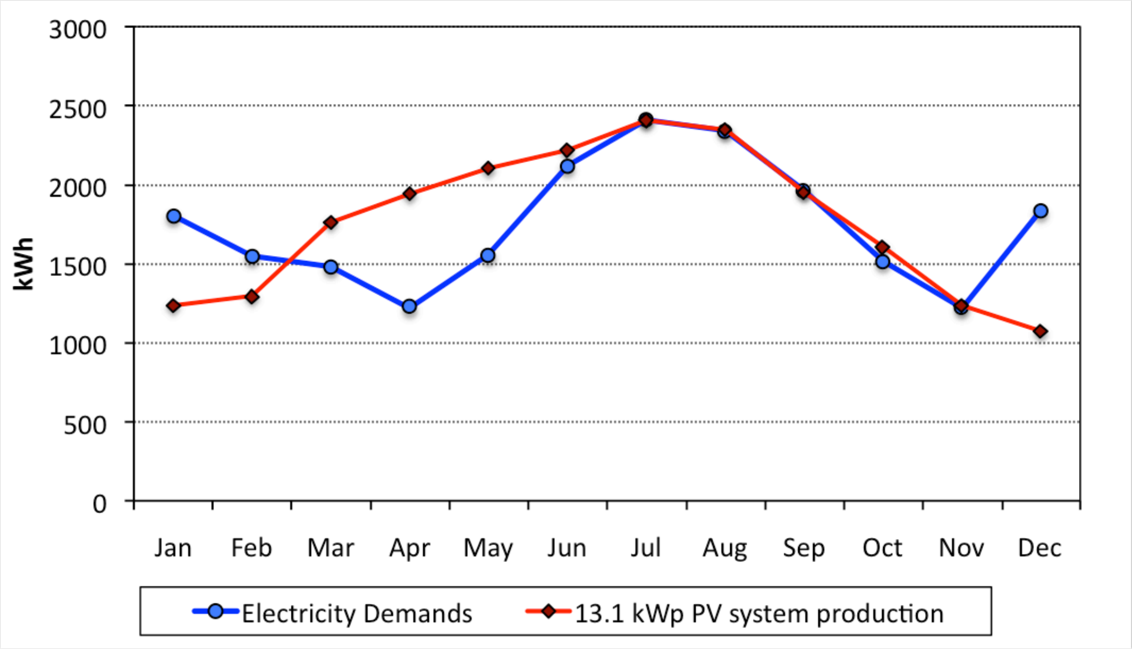


Figure 44: 13.1 kWp PV system energy production in House 1

Table 31: Demand and Production balance for house 1

13.1 kWp PV system Annual production (kWh)	The annual electricity demand (kWh)	Annual surplus of Energy (kWh)
21192.03	20980.25	211.78

Figure 45 shows the electricity demand of house 2 (Giamali House) and the electricity produced by the 12.3kWp PV system on a monthly base. Table 32 shows that the PV system's production covers the annual electricity demand of the house (19703.52 kWh) and creates a very insignificant surplus.

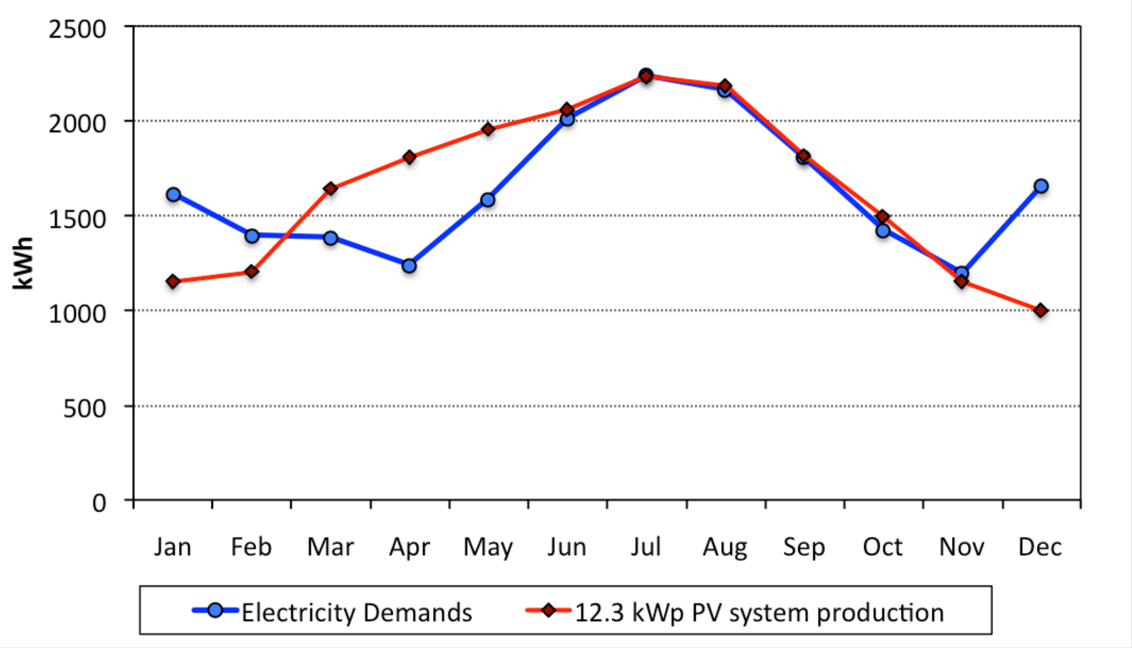


Figure 45: 12.3 kWp PV system energy production in House 2

Table 32: Demand and Production balance for house 2

12.3 kWp PV system Annual production (kWh)	The annual electricity demand (kWh)	Annual surplus of Energy (kWh)
19725.68	19703.52	22.16

The houses can be categorized as zero-energy buildings (ZEB). There are different criteria that define a zero-energy building. The houses in this thesis use the energy produced on site by the Photovoltaic systems, to cover their demands without the need of purchasing electricity from an outside source. Although the PV systems produce an annual surplus of electricity, this production is so small that it can be neglected. It can be said that the energy provided by the on-site renewable energy source is equal to the energy used by the building, which creates a net zero site energy.

6 CONCLUSION

This thesis examined the possibility of using photovoltaic technology to generate the electricity needed in classical single-family houses in Libya. The loads of the houses and their annual electricty demands were simulated. The annual electricty needs of this type of house is estimated to be around 20000 kWh. Different PV system sizes were designed to cover different portions of the total electrical demands of the houses. One system was designed in order to cover the total annual demands of the buildings. The study shows that it is possible to cover the whole annual Electricity demands of this type of house by installing a PV system with a size that ranges between 12.3 kWp 1nd 13.1 kWp. A system this size would only occupy about 60% of its roof area.

The thesis also looked at the cost efficiency of implementing these photovoltaic systems to generate electricity on site. Using PV systems in Libya is still not as widely spread, as it should be, given the fact that the country is located on one of the richest regions with solar energy. One of the main reasons that are holding back people from using solar energy as an alternative source of energy, specifically in the residential sector, is the cost of the technology. Since the government pays 89% of the electrical bill, investing in a PV system, from the homeowner’s point of view, is not economically valid. As shown in this study, the consumer would never reach the payback period in which he/she recovers the initial costs of the PV system within its lifetime of 20 years. This is true even if the PV system costs are partially granted by the government; the government would need to pay a huge percentage of the capital costs in order to drop the payback period to a reasonable number.

The only way for the homeowner to create a profit and achieve a realistic payback period within the PV system's lifetime of 20 years, is if the consumer was obliged to cover all costs of the electricity supplied from the grid by lifting the subsidy system applied in Libya. In this theoretical case, the government would be saving in the costs it used to pay for the grid electricity under the subsidy policy. In order to encourage the homeowners to invest in the PV technology to cover their electrical demands, it is suggested that the government offers a grant to cover some of the capital costs of installing a PV system. Although the grants would cost the public treasury, it would still be able to create a profit by replacing the high electricity subsidy given to the residential consumers, with a more reasonable grant that helps the consumers in investing in a PV system in order to reduce the fossil fuel based electricity purchased from the grid. From this thesis, it is clear that this scenario would create the most profit for the homeowners and by doing so encourages them to invest in a cleaner source of energy.

7 INDEX

7.1 List of figures

7.2 List of tables

8 LITERATURE

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